ASSESSING THE IMPACT OF EROSION AND SEDIMENT YIELD FROM FARMING AND FORESTRY SYSTEMS IN SELECTED CATCHMENTS OF SOUTH AFRICA

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Water Research Commission

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EXECUTIVE SUMMARY

INTRODUCTION

Natural ecosystems provide key functions for the sustainable economic development of societies. However, in many regions of the world, in particular in developing countries, such landscapes have suffered extensive degradation with consequential negative implications for ecosystems health, potentially jeopardizing the capacity of ecosystems to deliver various life-supporting services.

Concerns with regards to long-term sustainability and high environmental costs support the need for an increased understanding of the processes and consequences of land degradation. Land degradation is not limited to an impact on water resources and agricultural production (crop and animal); the living system of the soil also provides a range of ecosystem services that are essential to the well-being of the agricultural sector and society. Initially focusing on the water resource, Payment for Ecosystem Services (PES) systems now focus on land-water interactions and highlight that catchment rehabilitation is key to sustained water supply and water quality. As different soil erosion processes occur at various spatial and temporal scales, the assessment of soil erosion at the landscape scale has long been recognized to be a difficult issue in the environmental sciences. Micro-plots can be used to inform on the contribution of splash and rain-impacted flow on sediment mobilization, however they can significantly either overestimate or underestimate the overall soil water erosion (e.g., Govers and Poesen, 1988; Le Bissonnais *et al*., 1998). Multi-scale research studies are a promising approach to detect and quantify the relative contribution of erosion processes (e.g. splash, sheet, concentrated flow, stream bank and stream bed mobilization) that dominate at various spatial scales (de Vente and Poesen, 2005; Poesen and Hooke, 1997; van Noordwijk *et al*., 2004; Verbist *et al*., 2010).

Soil erosion not only involves the loss of fertile topsoil, reduction of soil productivity and reduction in crop yield over time, but also causes water management problems, in particular in semi-arid regions such as South Africa where water scarcity is frequently experienced. It must be noted that soil erosion cannot be prevented but must be limited. Previous WRC studies highlighted that a better understanding of erosion processes will contribute to changing the behaviour of farmers by adopting conservation farming practices. Incorrect land use practices including overgrazing of natural grasslands is one of the major contributing factors to erosion and increased sediment yield. It must be mentioned that the lack of understanding of properties of sensitive soils with cultivation and grazing and uncontrolled veld fires and other management practices are some of the contributing factors to erosion. Anticipated wide-spread changes in land use and climate variability are likely to exacerbate all of the above-mentioned concerns. Recommendations from previous reports suggested that future studies should focus on the connectivity of sediment delivery pathways and develop precautionary measures to limit the direct discharge of sediment into streams. Attention should be afforded to quantification of sediment detention, retention or reaction to specific controls in stream networks, including farm dams, wetlands and buffer strips.

AIM and OBJECTIVES

The primary aim of this research was to improve the understanding of the processes of erosion and sediment yield for different combinations of landuses (*viz*. grassland, woodlands, agricultural crops/pastures, orchards and forest plantations) and scales for traditional and commercial agricultural production systems at selected sites within catchments for further application and extrapolation.

The specific objectives of the project were to:

1. To evaluate erosion and sediment dynamics with particular attention to: a) Sediment sources, sinks, pathways and associated mechanisms; b) Sediment associated NPS impacts with particular emphasis on phosphates; c) Erosion and sediment delivery rates.
2. To determine controlling factors of sediment dynamics for different landuses with consideration of: a) Climate/weather patterns and variability; b) Combination of landscape elements on fluxes of sediments; c) Landuse and management practices.

To modify and improve existing models available in South Africa and internationally for extrapolation of erosion and sedimentation impacts for different scenarios.

METHODS

Runoff plots were established in each of the landuse types, *viz*; commercial plantations (black wattle), commercial (sugarcane) and subsistence (maize – till vs minimal till) crops, and grasslands (planted pasture and natural). Within each land use type 1 m x 1 m (1 m^2) micro-plots and 5 m × 2 m (10 m^2) runoff plots were installed adjacent to each other at three landscape or topographic positions along a slope gradient. Three replicates per position were installed at each site. A single plot at each of the three different slope positions were connected to a pipe which first fed into a tipping bucket mechanism was installed on a single 5 x 2 m plot to ensure that the temporal response of each individual plot location (in terms of overland flow) was measured after the onset of a rainfall event. The design and procedure for collecting each sample remained constant and frequency of site visits depended on the frequency and intensity of rainfall events. At each plot runoff and sediment were collected for analysis. Micro-plots provided information on the contribution of rain splash and rain-impacted flow on sediment / nutrient mobilisation, whilst the larger plots measured sediment / nutrient movement via surface overland flow.

Rainfall data were obtained from manual rain gauges which were located adjacent to the runoff plots. These were installed to measure the spatial variability of rainfall within the study sites, and to determine amount of interception and nutrient concentration in the rainfall that could impact runoff results. To gain accurate measurement of rainfall for the area, rainfall data were retrieved from locally placed Automatic Weather Stations (AWS), which provided temporal data of each rainfall event, allowing for event duration to be calculated.

Water and sediment samples were collected after rainfall events and used to assess water and sediment quality of the runoff. The water quality constituents are the Nitrates-Nitrogen ($NO^{3-}N$), total phosphorus (P), Dissolved Organic Carbon (DOC) and Particulate Organic Carbon (POC). POC was defined as the fraction of carbon which had been bonded onto soil particles and then subsequently eroded, POC included any organic matter which had been eroded. DOC was defined as the fraction of carbon which has been dissolved into solution by rainfall and soil water. Water samples were collected in the field by taking 500 ml samples and stored in a cooler box on-site. Once back at the laboratory, samples were stored in a fridge, which was kept at a constant temperature of 4 °C until completion of analysis. Furthermore, water repellence was measured at all sites.

Rainfall simulation was used in the Okhombe valley to study cattle path erosion and in a workshop held in the area for the community members.

Two models were run, using data collected during previous research in the region and the present project, ArcSWAT and MIKE SHE. MIKE SHE was set up and run at Two Streams. Much of the focus was compiling input data to form a comprehensive hydrological model that could be used for more detailed sediment modelling studies. ArcSWAT was set up and run at both Two Streams and Fountainhill Estate. The *status quo* was modelled allowing for a comparison between landuse types and specific land management. Not only did the model provide detailed spatial and temporal data, a platform was created that would be ideal to test various landuse and management scenarios.

RESULTS

Soil Loss and Sediment Yield at Two Streams

Sediment concentration and soil losses significantly decreased with an increase in plot scale from 1 m^2 to 10 m^2 plots, suggesting significant soil loss from the 1 m^2 plots which implies that splash erosion is important in such systems. This is likely due to a proportion of the soil material being detached and transported (along a five-meter length) as a result of splash and rain-drop impact.

Positive correlations were observed between landscape positions (slope gradient) and both unit-area runoff and soil losses. These findings are concordant with studies where slope gradient was identified as the main driver of runoff generation at a global scale (Chaplot *et al*., 2007; Mutema *et al*., 2015b; Mhazo *et al*. 2016; Prosdocimi *et al*. 2016). Notably, measured soil organic matter (i.e. SOC and N content and stocks) correlated positively to unit-area runoff but negatively to soil losses, implying greater runoff with low detachment and sediment transportation.

Soil organic carbon stocks (r = -0.82) and soil vegetation cover (r = -0.51) were found to be strong inhibitors to soil erosion (soil loss) under sugarcane cultivated soils. Soil organic carbon stocks and soil surface vegetation cover are closely related, due to the accumulation of organic matter from crop residues.

Soil Loss and Sediment Yield at Fountainhill Estate

The highest runoff recorded within the 1 m^2 plot was 25 l/m^2 under maize tillage, followed by maize under no tillage (10,43 l/m^2). These findings were further illustrated on 10 m^2 plots where 155 l/m^2 of runoff was recorded under maize tillage between May 2018 to December 2018. Maize under no-tillage had a lower runoff value of 19.8 l/m^2. The lowest runoff record within the 1 m^2 plots was under pasture where 0 l/m^2 was consistently recorded. Runoff from the natural grassland plots were comparatively low with the lowest recorded runoff on 7 December 3018 (0.68 l/m^2). However, within the 10 m^2 plots, natural grassland had the 2nd highest runoff (44 l/m^2) for 3 rainfall events, whereas, pasture experienced one runoff event (4 May 2018) of 25 l/m^2 and no runoff was recorded for the following rainfall events.

Rainfall Simulation at Okhombe

The community members quickly gained the concepts of slope gradient and basal cover from the rainfall demonstrations. The community began to understand why mitigation measures worked and to identify sites where various mitigation techniques would work more effectively than other techniques. The understanding of the driving factors of land degradation provide the community with an applied understanding of the problem faced by the area and renewed energy and ideas to combat land degradation.

Hydrological and Sediment Yield Modelling

The MIKE SHE set-up for the study site, is to date the most exhaustive and holistic hydrological modelling approach taken for the Two Streams sub-catchment, supplying insight into the dominant hydrological processes in operation and the overall water use of the hydrological system.

The ArcSWAT model can be used effectively in South Africa, particularly eroded areas of KwaZulu-Natal. The SWAT model simulated flows well and with greater complexity. In addition, the management component in SWAT is very detailed and relevant to the Two Streams site.

The spatial sediment yield at Two Streams shows that, in contrast to the surface runoff, the plantation areas exhibit more runoff than the sugarcane. The spatial sediment yield at FHE shows that, like Two Streams, the plantation areas exhibit more sediment loads than the maize. The area under pastures had a particularly low sediment yield, similar to the natural grassland areas. The two maize treatments had high amounts of sediment yield, with the till treatment exhibiting the greatest amount of sediment yield.

It is clear from the results that the SWAT model is a suitable hydrological model for examining the impacts of different land-uses in catchments in South Africa and can provide high resolution temporal and spatial output data. The SWAT-CUP calibration interface provides a useful tool to determine the sensitivity of input parameters, improve the simulation efficiency and provide an indication of the model uncertainty.

DISCUSSION AND CONCLUSION

Soil erosion is a significant problem in South Africa with an annual soil loss of 400 million tonnes (Meadows and Hoffmann, 2003). This threat has both on- and off-site impacts that negatively influence the natural ecosystems. This study provided an insight to soil erosion and nutrient loss and transportation. There was a strong focus on the forestry sector and going forward post-harvest and field preparation for next crop measurements need to be done as one expects the rate of soil erosion to increase. It is paradoxical as we require the forestry sector as an important contributor to the economy of the region, but we have to accept the consequential environmental harm. We need to manage this by understanding and hence modelling predicted outcomes. Our models are only as good as the data we receive and thus the need for such a study as this provides high spatial and temporal data to populate these models.

The key driver of soil erosion, is rainfall intensity as high rainfall intensity resulted in greater soil erosion, so mitigation measures need to be put in place that reduces the amount and intensity of rainfall on the surface, this study has shown that tree cover was effective in rainfall interception and the associated litter reduced the intensity of rainfall. The data set from the present study may be used in the future to populate soil erosion models, so that future climatic conditions can be modelled and mitigation measures can be put in place to reduce soil erosion and nutrient loss.

RECOMMENDATIONS FOR FUTURE RESEARCH

At the completion of any research project there are, one hopes, many unanswered new research questions that have arisen as a consequence of a particular project. This project is certainly no exception as new field-, laboratory- and model-based questions / ideas arose as the work was carried out. The use of plots to collect sediment for analysis and, although we made a few minor refinements in the field, they are well versed and recognised, and allow comparison across projects. At the initiation of the project the primary concern was identifying suitable sites for measurements. We feel there could be a stronger role for historical aerial photography and the use of remote sensing techniques. One of the students (Nosipho Machaya, MSc, Environmental Science) developed a GIS mapping approach to identifying potential erosion sites which were then groundtruthed and Bangani Dube (MSc, Soil Science) incorporating (with Lyndon Riddle, PhD student) the use of drone technology.

This resulted in a methodological paper which Mr Riddle intends to develop. We accept the drone technology is still very much a new innovation however, on a large scale, we can certainly perceive a mapping function for the technology. A similar argument can be made for the rainfall simulation experiment – for demonstration purposes and to start a discussion / workshop / community engagement / raining exercise it worked extremely well. However, as a field-based approach, although it has been cited and extensively used, we felt that under South African conditions and if for no other reason the amount of fresh water that was required to adhere correctly to the recognised international standards of methodology to allow for comparison, it was too environmentally costly. By way of example we used the simulator to demonstrate, to a community group, surface runoff on grassed versus cattle paths.

One of the main motivating points for working at the selected sites was the ability to use existing research infrastructure and work at sites that had long-term data sets – this is crucial in any modelling project. It is imperative that these sites continue to be monitored. We lack many long-term research sites in South Africa and with the ever-increasing difficulty of sourcing funds it will be increasingly difficult to maintain long-term sites. Few funders are prepared to fund for an extended time period and it has to be the role of the South African Observation Network (SAEON) or Universities to commit to maintaining certain sites, after funds for the initial project have ceased. This is a difficult situation, Universities do not have the funding, external funders seek short-term projects and we have a transient population of post-graduate students. However, we do need these long-term sites and, included in this discussion, must the continuation and maintenance of long-term climatic records and, where possible, instillation of new long-term automatic weather-stations.

Throughout this project this point has been raised and we have been aware of the need to ensure that whatever approach we adopt, can continue after the funding phrase and, if for no other reason, to monitor for a full life-cycle of a plantation to be able to monitor from harvesting, post-harvest treatment, re-planting, growth and harvest.

We have been fortunate and working with MONDI and the Fountain-Hill Trust we have developed a relationship that will continue beyond the life of this existing project, we will continue to monitor the sites and the idea is to use the site as field-based laboratories for generations of students. As educators this is an important outcome for us and will continue the good work already carried out in multiple WRC reports in the region and maintain the existing strong relationships with local industry and farming communities.

With regards to the modelling aspect, two areas of development arise for us. The first is to obtain the necessary environmental parameters to allow ArcSWAT to be more user-friendly. SWAT is a suitable model and has been used successfully in this project. However, it has taken more time than anticipated as many of the default variables / value s/ measurements are not set of South Africa conditions. One of the reasons for choosing this model is the software allows one to input site specific environmental information. What we require is databases that have SA scenarios and we can then choose the necessary values from a dropdown menu that has been set-up for SA conditions. This is a long-term objecting and although it is doubtful it would be considered as a single research project, there should be some co-ordination between projects and site-specific environmental data inputted into a central file (custodianship unknown) to develop these data files. A similar scenario exists for MIKE SHE, however this is more complex as it requires software development as plug-ins to the existing model framework.

Encompassing all these ideas we must sound a note of caution. Yes, we make a call for research and training sites and the necessity that they continue, however the research must be relevant and necessary (not always easy to define this we appreciate!) training sites, research and must not become a researchers 'play-ground' and attempt new technologies merely for the sake of it – thus, we need to ensure the research questions are relevant to the needs of the disciplines? The role and integrity of the reviewing process must be maintained, as must the role of the reference committees which, we have experienced in this and other WRC funded projects, is dwindling due to competing demands on expert's time.

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CONTENTS

FIGURES

TABLES

ABBREVIATIONS

ACRU	The Agricultural Catchments Research Unit
AWS	Automatic weather station
BSI	Bare Soil Index
CSIR	Council for Scientific and Industrial Research
DAFF/DOA	Department of Agriculture, Forestry and Fisheries
DBH	Diameter at Breast Height
DOC	Dissolved Organic Carbon
DWS/DWAF	Department of Water Affairs & Sanitation
FAO-56	Food and Agriculture Organisation, paper no. 56
GCM	General Circulation Model
GIS	Geographic Information Systems
GLASOD	The Global Assessment of Human-induced Soil Degradation
HRU	Hydrologic Response Unit
HRU	Hydrological Response Unit
K	Potassium
LAI	Leaf Area Index
MAP	Mean Annual Precipitation
MUSLE	Modified Universal Soil Loss Equation
N	Nitrogen
NO3	Nitrate
NPS	Non-Point Source Pollution
P	Phosphorus
PAR	Photosynthetically Active Radiation
PAW	Plant Available Water
POC	Particulate Organic Carbon
RUSLE	Revised Soil Loss Equation
SOC	Soil Organic Carbon
SWAT	The Soil and Water Assessment Tool
SWB	Soil Water Balance
TM	Thematic Mapper
TOC	Total Organic Carbon
USDA	US Department of Agriculture
USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project
WRC	Water Research Commission
SWAT	Soil Water Assessment Tool
PES	Payment for Ecosystem Services

1: INTRODUCTION

1.1 Background and motivation

Natural ecosystems provide key functions for the sustainable economic development of societies. However, in many regions of the world, in particular in developing countries, such landscapes have suffered extensive degradation with consequential negative implications for ecosystems health, potentially jeopardizing the capacity of ecosystems to deliver various life-supporting services.

Concerns with regards to long-term sustainability and high environmental costs support the need for an increased understanding of the processes and consequences of land degradation. Land degradation is not limited to an impact on water resources and agricultural production (crop and animal); the living system of the soil also provides a range of ecosystem services that are essential to the well-being of the agricultural sector and society as a whole. Initially focusing on the water resource, Payment for Ecosystem Services (PES) systems now focus on land-water interactions and highlight that catchment rehabilitation is key to sustained water supply and water quality. While flow detachment and transport by splash occur at local level, larger surface areas are required for sedimentation to be the dominant process. As different soil erosion processes occur at various spatial and temporal scales, the assessment of soil erosion at the landscape scale has long been recognized to be a difficult issue in the environmental sciences. Micro-plots can be used to inform on the contribution of splash and rain-impacted flow on sediment mobilization, however they can significantly either overestimate or underestimate the overall soil water erosion (e.g., Govers and Poesen, 1988; Le Bissonnais *et al*., 1998). Plots of several m^2 are useful tools to evaluate interrill erosion however they provide little information on the dominant erosive processes and their interactions (Chaplot and Le Bissonnais, 2003). Therefore, multi-scale research studies are a promising approach to detect and quantify the relative contribution of erosion processes (e.g. splash, sheet, concentrated flow, stream bank and stream bed mobilization) that dominate at various spatial scales (de Vente and Poesen, 2005; Poesen and Hooke, 1997; van Noordwijk *et al*., 2004; Verbist *et al*., 2010). Recent soil erosion mapping and modelling studies conducted by DAFF and the ARC-ISCW suggest that large parts of South Africa consist of highly erodible soils with widespread soil erosion evident.

Soil erosion not only involves the loss of fertile topsoil, reduction of soil productivity and reduction in crop yield over time, but also causes water management problems, in particular in semi-arid regions such as South Africa where water scarcity is frequently experienced. It must be noted that soil erosion cannot be prevented but must be limited. Siltation of storage dams is acknowledged to be a major problem in South Africa and better understanding of erosion and sediment yield is important to limit the cause of siltation. As an example, due to siltation, the storage capacity of the Welbedacht Dam near Dewetsdorp in the Free State reduced rapidly from the original 115 to approximately 16 million cubic meters within twenty years since completion in 1973. From a health perspective, the silt often acts as a host for pathogens. Phosphates are also linked to sediments contributing to eutrophication of dams and estuaries. Sediments in water furthermore increases the wear and tear of nozzles and hydraulic pumps for irrigation. Previous WRC studies highlighted that a better understanding of erosion processes will contribute to changing the behaviour of farmers by adopting conservation farming practices. Incorrect land use practices including overgrazing of natural grasslands is one of the major contributing factors to erosion and sediment yield. It must be mentioned that the lack of understanding of properties of sensitive soils with cultivation and grazing and uncontrolled veld fires and other management practices are some of the contributing factors to erosion. Anticipated wide-spread changes in land use and climate variability are likely to exacerbate all of the above-mentioned concerns. Further recommendations from previous reports suggested that future studies should focus on the connectivity of sediment delivery pathways and develop precautionary measures to limit the direct discharge of sediment into streams. Attention should be afforded to quantification of sediment detention, retention or reaction to specific controls in stream networks, including farm dams, wetlands and buffer strips.

Areas of impact where this project has contributed to the WRC knowledge tree:

1. Human capital and development in water and science sectors. The project team consists of black and white, male and female members and both black and white, male and female post-graduate students were trained as part of this research project. The outcomes are MSc thesis, field-based training for post-graduate students and a number of workshops, reported as deliverables, in which post-graduate students, both directly linked to the research and others, were trained in research skills, report and academic paper writing, and grant applications.
2. Sustainable development solutions. The project has contributed to operational solutions for sustainable use of soil and water resources for different landuse types, viz plantations, commercial and subsistence cropping and grassland predominantly through field-based data collection used to develop and validate appropriate models. Controlling and minimising erosion could potentially result in more carbon and nutrients remaining within the soil profile. Deceasing the losses by water erosion will, in the long-term, protect both the natural resources and improve ecosystems services for the production of food, enhanced bio-diversity and improved human health.
3. Empowerment of communities was carried out within the Okhombe Valley region of the Natal Drakensberg. This has been an on-going long-term relationship over a number of WRC funded initiatives. In this particular situation we undertook a number of rainfall simulation experiments the degraded grassland. These experiments became experiential learning initiatives with community members being pro-actively involved and then we took the set-up to a local school and had a one-day workshop with the community demonstrating and discussing soil erosion processes with a particular focus on cattle path erosion. Cattle path erosion has long been recognised as a major concern in the region by the community and is very evident in the surrounding mid-slopes due to daily migration of cattle up / down the surrounding slopes for grazing. This was followed with in-field active participatory involvement in setting up and running the rainfall simulation under different 'ground conditions' to demonstrate soil erosional processes. Thus, ensuring that the project contributed to community empowerment and capacity building at a rural scale.
4. Informing policy and decision making. The results on best management practices, identified through the models, can potentially inform active policies in the field of agriculture, forestry and water. The guidelines for modelling practices will be of benefit to a larger group of end users through extrapolation of findings and should provide country wide benefits.
5. New products and services for economic development. Much information is available regarding the prevention and reduction of erosion. However, an assessment of the effectiveness of these remedial and preventative measures is necessary before costly implementation proceeds.

1.2 Aim and Objectives

The primary aim of this research was to improve the understanding of the processes of erosion and sediment yield for different combinations of landuses (*viz*. grassland, woodlands, agricultural crops/pastures, orchards and forest plantations) and scales for traditional and commercial agricultural production systems at selected sites within catchments for further application and extrapolation.

Specific 1. To evaluate erosion and sediment dynamics with particular attention to: a) Sediment sources, sinks, pathways and associated mechanisms; b) Sediment associated NPS impacts with particular emphasis on phosphates; c) Erosion and sediment delivery rates.
Specific 2. To determine controlling factors of sediment dynamics for different landuses with consideration of: a) Climate/weather patterns and variability; b) Combination of landscape elements on fluxes of sediments; c) Landuse and management practices.

Specific 3. To modify and improve existing models available in South Africa and internationally for extrapolation of erosion and sedimentation impacts for different scenarios.

2: KNOWLEDGE REVIEW

2.1 Introduction

Water availability is predicted to be the single greatest and most urgent development constraint facing South Africa with poor water quality in rivers and streams exacerbating the issue for water users (Nilsson and Malm-Renöfält, 2008). The national water resources strategy (DWAF, 2004) estimates that, at current usage and price levels, available water resources will be unable to meet demands by 2025. According to Turpie *et al*. (2008) surface water is heavily committed for use, water is imported from neighbouring countries, and the limited groundwater resources do not offer much of a reprieve. In the future, the growth in human population will lead to an increased need for food and forest production, which will lead to an increased competition for water between different water users (Clulow, 2007).

More than 70% of South Africa is affected by varying intensities of soil erosion (Ighodaro *et al*, 2013), the most dominant agent being water. Water erosion occurs predominantly from precipitation through rain-splash, un-concentrated flow as sheet erosion. The erosional processes depend on a combination of interactive effects of erosion factors, namely rainfall erosivity, soil erodibility, slope steepness and slope length, crop management, and support practice. Although soil erosion is a natural process, it is often accelerated by human activities such as clearing of vegetation by overgrazing. “Loss of fertile topsoil and reduction of soil productivity is coupled with serious offsite impacts related to increased mobilisation of sediment and delivery to rivers” (Le Roux *et al*., 2008, 305). Eroded soil material leads to the sedimentation of reservoirs, also an increase in water pollution due to suspended sediment concentrations in streams (Le Roux *et al.*, 2008). The water quality in many rivers and reservoirs have been degraded by an increase in suspended sediment

Changes in land use have been recognized as capable of accelerating soil erosion these include; land use, land use change, planning and land management (Laker, 2004). It is that unless there is an adoption of better land management practices, approximately 140 million hectares of high-quality soil, in Africa and Asia, would have been degraded as a result of soil erosion by 2010 (Ighodoro *et al*, 2013). This highlights the danger of soil erosion activities and the need for appropriate soil management practices, and a concerted effort in the fight against its effects

In South Africa, KwaZulu-Natal has large areas of moderate to extremely high potential erosion risk (90%) but relatively low actual erosion risk (18%) due to existing vegetation cover. Dangers of erosion are inherent when changes in land use practice are made. Much of the Eastern Cape, Limpopo and KwaZulu-Natal Provinces are under severe threat of erosion. Natural forests, maintained as nature reserves, can be stable against erosion (Laker, 2004), but planting of commercial forests can promote erosion.

Due to the interrelated nature of the research this chapter is divided into ten sections all linked to soil erosion with a primary focus on soil erosion in South Africa. The sections are; defining soil erosion and sediment yield, explaining the types of erosion, outlining the factors that determine the rate of soil erosion, describing overland flow and how soil erosion varies temporally and spatially, considering the implications of soil erosion, the threat of climate change, the impact of soil erosion on forestry and water catchments, strategies that could possibly mitigate soil erosion and finally, modelling soil erosion.

2.2 Soil Erosion and Sediment Yield

Soil erosion is a physical process of soil degradation and is the most common type of land degradation (Morgan, 1988). According to Le Roux *et al*. (2008) soil erosion can be defined as the detachment and transportation of soil particles from one location to another, the degree of soil erosion ranges from splash erosion to the alarming stage of gully formation. The process of soil erosion can be described as a loss of nutrient rich clay and organic matter, which impoverishes the upper top soil and leads to the upper soil layers being removed through erosion. The intense and increased pressure on the land to provide goods and services leads to its degradation and loss of its productive capacity. Land degradation is the loss in ability of the land to create benefits from the land use that falls under a specified form of land management (Meadows and Hoffman, 2003). Erosion results in the degradation of a soils productivity in a number of ways: it reduces the efficiency of plant nutrient use, damages seedlings, decreases plants' rooting depth, reduces water-holding capacity, decreases permeability and infiltration rates and increases runoff. It is estimated that approximately seventy-five billion tons of fertile soil are lost from agricultural systems each year (Pimentel and Burgess, 2013). The Food and Agriculture Organization (FAO) estimate that approximately five to seven million hectares of productive topsoil are lost annually through erosion while other estimates state losses of more than ten million hectares per year (Sun *et al*., 2014).

In South Africa, erosion is a problem which is worsening according to the Land Degradation Assessment in Dryland Areas (DA, 2008) and unless erosion mitigation and control efforts are encouraged the situation will continue to worsen. Approximately three hundred to four hundred million tons of soil are estimated to be lost annually in South Africa (Ning, 2006). The State of Environment Report of South Africa calculates that soil erosion costs at two billion rand annually which includes off-site costs for purification of silted dam water (Le Roux *et al*., 2008).

The on-site effect of erosion is a reduction in soil quality through the removal of topsoil and the loss of nutrients and applied fertilizers. In addition, soil erosion has the potential to remove light-weight organic matter and organic residues which reduces the water holding capacity of the eroded soils making them less suitable for plant grow. (Fournier, 2011). Off-site, some of the sediments can be trapped by the vegetation in the riparian zone before reaching the stream. Sediments which enter the watercourses may block drainage ditches and stream channels and silt reservoirs and dams. Sediments delivered to the stream can significantly increase the turbidity of water and deteriorate downstream water quality through increased eutrophication which leads to increased water purification costs. Eroded particles, in particular the smaller size fractions such as clays, silts and organic matter have high specific surface areas and charge densities, thus increasing the potential for adsorption of nutrients, agrochemicals and heavy metals onto sediment.

According to Miller *et al*. (2009), concentrations of pollutants in sediment are highly dynamic because of transformations between particulate and solute phases, which exacerbates water quality problems associated with sedimentation. Sharpley *et al*. (1981) described sediment as a multiple stressor in terms of water pollution as concentrations of pollutants such as phosphorus can be higher in sediments than in the original soil. A study carried out by Abagale *et al*. (2012) in Northern Ghana found that soil and nutrient (N, P, K) loss and loss of organic carbon and organic matter were greater on non-vegetated areas of farmlands than on those that had been vegetated. They observed that erosion and soil nutrient loss rates increased with quantity of rainfall over a period of time and with rainfall intensity. According to Ngcobo *et al*. (2012), nitrogen (N) and phosphorus (P) dynamics have not been adequately assessed in South Africa. This is particularly relevant in the predominantly agricultural and rural catchments of the country where non-point source pollution (NPS) is widespread. The mechanisms that govern sediment yield, N and P distribution are anticipated to change under conditions of higher temperature and rainfall, however the magnitude and direction of that change is not well understood.
Since erosion takes place predominately on land that is being utilized, the limited amount of high potential agricultural land is at high risk of degradation as a result of erosion (Morgan, 1988). South Africa's population is growing at just under two percent per year and to feed the growing population, food production needs to increase (WWF, 2009). The loss of productive agricultural soil as a result of erosion threatens food security and sustainable development and thus requires attention. According to Rickson (2014), forestry operations such as timber harvesting, road constructions, clear-cut logging and burning of forest residues have significant impacts on catchment sediment yields reducing the water quality for downstream users.

2.2.1 Types of soil erosion

The degree of soil erosion ranges from splash erosion to gully formation. The agents that transport the soil comprise those which contribute to the removal of a relatively uniform thickness of soil and those which concentrate their action in channels. The former consists of rain splash and surface runoff in the form of shallow flows of infinite width, sometimes known as sheet flow but more correctly categorized as overland flow, while the latter covers water flow in small channels, known as rills or deep channels known as gullies (Morgan, 1988).

Sheet erosion, which is a uniform removal of soil from the surface, is the second phase of the erosion process after rain splash. As erosion becomes increasingly severe, rill erosion begins (Toy *et al*., 2002). According to Ritter (2012), rill erosion results when surface water runoff concentrates and forms small yet well-defined channels. While it is widely accepted that rills are initiated at a critical distance downslope, where overland flow becomes channelled (Morgan, 1988), rill erosion can occur on steep land and on land that slopes more gently.

Sealing and crusting have been reported to increase soil erosion by enhancing surface runoff and the detachment of soil particles from the soil surface (Le Bissonnais and Singer, 1993; Wakindiki and BenHur, 2002). Soil crusting refers to the formation of a thin layer at the soil surface which is characterized by reduced porosity and high penetration resistance whilst surface sealing is the initial phase or wetting phase in crust formation (Valentin and Bresson, 1998). Surface crusting, particularly on bare surfaces, is driven by raindrop impact however compaction of the soil affects the formation of a crust (Neave and Rayburg, 2007).

2.2.2 Processes determining the rate of soil erosion

Soil erosion process consists of two main phases; the detachment of individual particles from the soil mass and the transportation of these particles by erosive agents such as running water and wind. When there is no energy to transport the particles a third phase occurs, deposition (Salles and Poesen, 2000). Rain splash is the most common detaching agent which occurs through raindrops hitting the bare soil surface, which has the ability to loosen and detach the soil particles. If rain splash had considerable impact then soil particles may be thrown through the air over distances of several centimetres. Soils that are continually exposed to heavy rainfalls are considerably weakened and erosion is most prominent in areas with high levels of rainfall (Prasuhn, 2012).

Soil is broken up by various weathering processes; mechanical weathering which takes place when rocks are broken down by physical force and chemical weathering which breaks down the bonds holding the rocks together, causing them to fall apart and to form smaller and smaller pieces. Chemical weathering is more common in locations where there is abundant water. Soil is broken-up by alternate wetting and drying, freezing and thawing action, wind, tillage processes and by trampling of people and livestock. (Prasuhn, 2012). All these processes loosen the soil, allowing it to be removed by the agents of transport, which act and contribute to the removal of a relatively uniform thickness of soil. These agents are split into two main groups: the first group consists of rain splash, surface runoff sometimes known as sheet flow or better defined as overland flow. The second group covers water flow in small channels, known as rills (Morgan, 1988). According to Ritter (2012) rills are shallow drainage lines less than 30cm deep, which develop when surface water concentrates in depressions or low points and erodes the soil.

The factors which influence the rate at which soil erosion occurs are wind and rainfall intensity, soil erodibility, topography, vegetation cover, soil management practises and conservation measures. According to Morgan (1988), factors which affect erosion can be grouped into three categories: energy, resistance and protection. Energy refers to the potential ability of rainfall, runoff and wind to lead to erosion. This category is described by the term erosivity. Fundamental to the resistance category is the erodibility of the soil which depends on its mechanical and chemical properties while the category protection focuses on factors relating to plant cover. Vegetation cover provides varying levels of protection by intercepting the impact of rainfall and reducing the velocity of runoff and wind (Morgan, 1988). Vrieling *et al*. (2014) point out the high variability of rainfall erosivity and vegetation cover through space and time and concluded that spatial and temporal variability of erosivity need to be accounted for, in combination with vegetation cover, when monitoring soil erosion.

2.2.2.1 Rainfall intensity and runoff

The severity of erosion depends upon the quantity of soil material supplied by detachment and the capacity of the eroding agents to transport it. The two forms of energy available for erosion are potential and kinetic energy (Morgan, 1988). Raindrops physically break-down soil aggregates and disperse the soil material which increases the susceptibility of the suspended material to be transported by runoff. Rainfall has high energy and soil detachment through splash erosion contributes significantly to soil erosion. The raindrops erosive energy is proportional to its size, whilst the rate of soil erosion and the amount of soil eroded is proportional to the quantity of runoff. Runoff occurs when the rainfall intensity exceeds the infiltration rate of the soil. The amount of runoff is greater during short duration high intensity storms which provide sufficient energy to detach and disperse soil aggregates. The amount of runoff generally increases with increasing soil compaction and soil crusting and decreases with increasing plant canopy and basal cover. Erosion caused by long-lasting low intensity rainfall can, however, cause significant soil loss when accumulated over time (Fournier, 2011).

2.2.2.2 Soil erodibility

Soil erodibility refers to the ability of the soil to resist erosion and is based on the soil’s physical and chemical properties (Bissonnais, 1996). Soils with a higher organic matter content have an improved structure and relative faster infiltration rate and thus show greater resistance to erosion due to reduced runoff. Tillage practices that lower organic matter content, destroy soil structure and compact soil surface can significantly increase soil erodibility. According to Morgan (1988), silt loams, loams, fine sands and sandy loams are the most detachable. Finer particles are more difficult to erode due to the cohesiveness of the clay minerals of which they are comprised, unless they have been previously detached and, as a result, loss their cohesion, in which case they can then be moved at low shear velocities. Aggregate stability also depends on the type of clay mineral present.

2.2.2.3 Topography

Soil erosion by water is proportional to the steepness and length of the slope due to the greater accumulation of volume and velocities of surface runoff. Water erosion, in particular gully erosion, occurs on level land where flow accumulation is high (Morgan, 1988).

2.2.2.4 Vegetation

Fournier (2011) described vegetation cover as the most significant factor determining the severity of the soil erosion process. Vegetation cover and litter provide protection to the soil surface against the impact of erosive energy from raindrops while plant roots bind the soil particles into aggregates resulting in improved soil structure with high infiltration rates and less surface runoff (Mohammed and Adam, 2010). Residual roots provide channels that help to improve the hydraulic conductivity of the soil. Bare soils and soils with little vegetative cover or crop residues are highly susceptible to soil erosion. However, the erosion reducing effectiveness of vegetation or litter depends significantly on the type, extent and quantity of cover (Podwojewski *et al*., 2011). The effectiveness depends on how much vegetation cover is available at various periods during the year, relative to the amount of erosive rainfall that falls during these periods. In addition, the spatial distribution of vegetation along the slope has a significant impact on catchment sediment yield. Groundcover is the most important form of vegetation cover to reduce erosion, in particular in forestry plantations as it reduces the impact of rain splash and flow.

2.2.2.5 Soil Management

Good management practices such as planting along the contours and mulching can significantly reduce the energy of surface runoff and thus sediment transport. Fournier (2011) considered several soil management practices as adequate to reduce or prevent soil erosion: the prevention of the direct impact of raindrops on soil through mulching and plant cover, the management of soil surface in a way that the infiltration rate is improved and surface runoff is minimised, the shortening of the slope length to reduce surface runoff accumulation and the diversion of excess runoff in a controlled manner through waterways and graded channels. Poor land management practices, on the other hand, such as the inappropriate placement of roads or unsuitable timber extraction methods, in particular in areas prone to soil movement, can lead to high levels of soil erosion (McGarry, 2011).

2.2.3 Spatial and Temporal Variations of Runoff

In landscapes, there are spatial and temporal variations of water and nutrient fluxes and this can be useful for improving land management (Laznik *et al*., 1999). There have been various studies conducted to improve understanding of rainfall-runoff processes and many hydrologic studies to improve understanding of hydrologic processes (Beven, 1989). Yet there is still a need to improve methods to describe runoff generation mechanisms occurring over hillslopes. This will lead to increased knowledge of how catchments generate flow and how runoff generation mechanisms impact on nutrient and sediment transportation. Soil erosion rates measured at one scale are not representative for sediment yield at another scale level (De Vente and Poesen, 2005).

There are two different mechanisms used to describe overland flow generation (Horton, 1933; Hewlett and Hibbert, 1967). The first mechanism is Hortonian flow, which occurs when rainfall intensity exceeds the infiltration capacity of the soil. The second is when saturation exceeds surface runoff (this is when the perched water table rises, saturating the whole soil profile and ultimately creates a seepage face at the soil surface). Saturation excess overland flow occurs typically in areas where saturation occurs (i.e. bottomlands and seepage faces) (Sen *et al*., 2010; Van de Giesen *et al*., 2011). As a result, runoff will vary spatially and there is a need to improve the understanding of spatial and temporal variations of runoff (Sen *et al*., 2010; Van de Giesen *et al*., 2011). It is important to note that weather has temporal variability, in particular, rainfall and that soil erosion and nutrient totals can, in some circumstances, be dominated by a few extreme events (Renschler and Harbor, 2002).

Surfaces in a catchment differ in response to rainfall and thus it cannot be assumed that there is uniform overland flow generation within a landscape. Overland flow generation is a spatially-variable process and is complicated to a large degree by temporal variation (Bergkamp, 1998; Cammeraat, 2004). Overland flow generated within a catchment is influenced by the interaction between; topography, soil and land cover, rainfall event characteristics, soil surface conditions, antecedent soil moisture conditions, infiltration rates, soil hydraulic properties and the depth to water table (Casenave and Valentin, 1992; Hernandez *et al*., 2003). It is important to investigate the soil surface characteristics (environmental factors) which control the generation of overland flow. Groundcover was found to enhance infiltration and ultimately decrease the amount of overland flow generated (Bartley *et al*., 2006; Bautista *et al*., 2007; Podwojewski *et al*., 2011). There is a general trend of increasing sediment yield with increasing spatial scale (De Vente and Poessen, 2005).

Vegetation on the soil surface has an inverse relationship to generation of runoff. Sanjari *et al*. (2009) stressed that the linkages between the soil surface characteristics and the generation of overland flow is multi-factoral. Bergkamp (1998) states that effective infiltration rates on grassland hillslopes vary with rainfall intensity and flow depth, due to the interaction between rainfall, runoff, and vegetated microtopography. Environmental factors vary temporally and spatially, as such, this affects overland flow generation.

2.2.4 Global Climate Change

A plethora of studies have been undertaken to investigate the impact of climate change on the hydrological cycle, whilst few have been conducted to examine the impact of climate change on water erosion. This is predominately due to the high uncertainty associated with climate change modelling caused by the coarse scale of General Circulation Models (GCMs). Climate change is likely to worsen the impact of water erosion through its effects on rainfall intensity, soil erodibility, vegetative cover and patterns of land use (Nearing *et al*., 2005). The GCMs can provide a range of climate scenarios, however these alone are not sufficient to predict future erosion risk, particularly as GCMs are currently poor predictors of changes in rainfall intensity and surface wind-speed. In addition, to improve the regional reliable of GCMs, accurate and reliable databases of parameters such as vegetation cover, soil properties, land use, and management systems, are required (Nearing *et al*., 2005).

With respect to climate change and erosion, much will depend on the future pattern, intensity, and seasonality of rainfall events. It is important to emphasize that the threats of increasing intensity will lead to an increase in erosion. Enhanced biomass production and increased vegetation cover and soil organic matter content resulting from elevated CO_2 concentrations could potentially have a positive effect that could lead to a decline in soil erosion risk (Brinkman and Sombroek, 1996). However, the more widely predicted higher temperatures, low rainfall and soil moisture suggest that few areas will receive benefits from global climate change. Instead, projected declines in levels of soil organic matter and the weakening of soil structure will make soils increasingly prone to erosion. Modelled estimates of the effect of climate change on soil erosion depend on assumptions regarding the frequency and intensity of precipitation (Phillips *et al*., 1993). Future erosion risk is more likely to be influenced by an increase in population density, the intensive cultivation of marginal lands and the use of resource-based and subsistence farming techniques than by changes in climate (Nearing *et al*., 2004).

2.2.5 Soil Erosion and Forestry

Forest ecosystems constitute an important component of the global carbon cycle holding 1240 Pg C (Dixon, *et al*. 1994; Lal, 2005), with most of the carbon (67%) being held in the soil, I particular in the top-soil, while (33%) is contained in the aboveground biomass. Consequently, any disturbance of forests has the potential to negatively impact the global carbon cycle. South Africa’s forest resources are classified into three forest types, i.e., indigenous forests, savanna woodlands and commercial timber commercial forests. All three types play an important environmental role in soil protection and act as carbon sinks, thereby mitigating the effects of climate change. South Africa’s natural forests are highly fragmented and represent the smallest forest biome (Mucina *et al*., 2007), the savanna woodlands form the bulk of South Africa’s forest land, covering approximately thirty-nine million hectares (DAFF, 2015), the majority of this biome occurs in communal areas. In addition to its protective functions, wooded savanna provides a variety of forest goods and environmental services on which rural poor communities depend. Basic demand, particular for fuel wood, pose a threat to the sustainability of these biomes and it is evident that forest degradation and deforestation is taking its toll in the woodland biome (DEA, 2012). Commercial timber forests occupy an area of 1.27 million hectares in South Africa (Godsmark, 2014), predominantly in high rainfall areas which are characterised by frequent high intensity storms and are mostly located in relatively steep or hilly terrain where the potential for erosion is high. Large proportions of commercial forests are on marginal, highly erodible land and erosion is a major hazard to operations (Musto, 1994).

In stable natural forest ecosystems, where soil is protected by vegetation, erosion rates are relatively low. Tree leaves and branches intercept and diminish rain and wind energy (Pimentel and Kounang, 1998), thus the systems are generally undisturbed and their soils are covered by litter. However, during thinning or harvesting operations in particular in commercial forestry (read plantations), skid paths develop along which the logs are moved to the road side and, in general, any form of harvesting at the end of the timber rotation involves a considerable disturbance and exposure of the soil surface (Scott *et al*., 1998). It can thus be assumed that for long periods of time commercial forests have the ability to provide protection against soil erosion, however they can become sources of erosion and sedimentation when disturbed by thinning and harvesting operations and by site preparation for subsequent tree establishment.

The erosion-protective action of a commercial forest is dependent on the development stage of the forest. Oliveira *et al*. (2013) evaluated soil, nutrients and organic carbon losses caused by water erosion in *Eucalyptus* forests at different development stages. They found that soil loss decreased with increasing age of the trees. The loss was influenced by soil type and planting system. Furrow planting caused greater soil loss than pit planting and higher losses in nutrients and carbon. According to Swank and Johnson (1994), forest management activities such as forest cutting and harvesting interrupt the natural recycling of nutrients and there is concern that nutrients released may affect downstream uses or reduce site productivity. Small scale catchment studies have produced a large body of information on stream water quality changes in response to forest management, particularly clearcutting. Changes in stream water nutrient concentrations following cutting vary considerably between localities, even within a physiographic region. Sediment load, dissolved nutrient concentrations are affected by forest management activities (Binkley and Brown, 1993). Changes in these parameters vary, depending on forest ecosystem, management activity, e.g., harvesting and associated logging methods, site preparation methods and stand improvement between initial re-establishment and harvesting which may involve the use of fire, herbicides or fertilizer. A major concern in harvest and regeneration practices is the impact on stream sedimentation (Campbell and Doeg, 1989). McGarry (2011) has suggested a soil erosion monitoring programme which employs simple, globally applicable and field-usable indicators and measurements to obtain qualitative and quantitative information regarding soil erosion in commercial forests or on recently deforested sites.

Early South African studies on soil erosion under commercial forestry by Sherry (1954, 1961, 1964), conducted in the province of KwaZulu-Natal, showed that fires in afforested areas can affect soil erosion rates, a result confirmed later on by Norris (1993) in the same province and by Scott and Van Wyk (1990) and Scott *et al*. (1998) in the Western Cape province. The study by Scott *et al*. (1998) showed that high intensity wildfire in timber commercial forests in the late dry season caused significantly increased sediment yield due to the formation of fire-induced water repellency in the burned soils. Only small increases in sediment yields were observed following prescribed burning of catchments covered in fynbos. The study remarked on the significance of riparian zones in keeping sediment delivery ratios to watercourses low.

2.2.6 Impacts of Soil Erosion on Catchments

The extraction of freshwater for industry, agriculture or cities places the health of aquatic ecosystems and the lives they support at risk (Postel, 2000). With the ever-expanding population it is crucial to find sustainable solutions to fulfil humanities water demands sand too protect the life-support functions these aquatic ecosystems provide. The functions include: water as a provisional service, regulatory service and cultural services, functions vital for human well-being and important is sustaining freshwater-dependant ecosystems. Soil erosion impacts negatively on the natural water storage capacity of catchments areas, service of man-made dams, quality of surface water, aesthetic landscape beauty and ecological balance (Doody *et al*., 2012). The suspended sediments in streams affect water use and ecosystem health. Furthermore, the loss of soil or sediments from land surfaces reduces not only the productivity of agricultural and forestry ecosystems but also leads to silting of dams and eutrophication of water bodies. Off-site impacts include; increased flooding due to reduced river channel capacities and the deterioration of river health because of increased turbidity and pollution with pesticides and fertilisers contained in the sediment-laden flows (Van Zyl and Lorentz, 2004).

Sediments are rich in nutrients, such as phosphorus and nitrogen, which lead to eutrophication of the receiving water bodies and promote excess growth of algae. Areas of excessive algae growth, called algae blooms, deplete oxygen in the water resulting in the death of aquatic animals. According to Le *et al*. (2014), these algal blooms can cause severe water quality problems such as unpleasant odours, dissolved oxygen depletion, increased pH and dissolved organic carbon concentrations and reduced transparency. Several of the bloom forming species (e.g. *Microcystis* sp.) can release toxins which have adverse impacts on livestock, wildlife and human health. The main cause of eutrophication is phosphorus (P) which is transported in solution with eroded soil from agricultural land that applies fertilizers (Ekholm and Lehtoranta, 2012).

The effect of agricultural systems on sedimentation and P loss is reflected in the results of a long-term study carried out by Bechmann *et al*. (2005) who monitored two sub-catchments in Norway under different agricultural management. They observed that the mean annual concentration of suspended sediments in a stream situated in a cereal-growing area with mixed livestock production was 20 times higher than that of the corresponding stream in a grass and dairy cow production system. While suspended sediment losses and losses of total P increased significantly during the monitoring period in the former sub-catchment, a significant downward trend in total P loss was observed in the latter.

Agriculture is currently the main source of sediment input into rivers (Rickson, 2014). According to Collins and Anthony (2008), there is a widespread concern for the environmental problems associated with erosion and subsequent sediment transport into water catchments. Sediment represents a carrier of nutrients, trace and heavy metals, micropollutants and pathogens. High suspended sediment loadings encourage accelerated channel bed siltation and the siltation of reservoirs. Sediment deposition in lakes and rivers increases water turbidity making it difficult for light to penetrate the water, causing problems for aquatic plants that require sunlight for photosynthesis (Palmer *et al*., 2000).

2.2.7 Strategies to Reduce Soil Erosion

Global concerns regarding environmental disturbances as a consequence of erosion call for concerted efforts to improve the management of ecosystems to minimise soil, nutrient and soil organic carbon (SOC) losses and reduce sedimentation.

According to Van Zyl and Lorentz (2004), it is becoming increasingly better understood that erosion control should be linked to both soil (on-site erosion) and water (off-site sedimentation) conservation initiatives. Several countries have incorporated 'clean water strategies' into agricultural policies, legislation and programmes (Parry, 1998). Ekholm and Lehtoranta (2012) mention that methods such as the establishment of buffer strips, riparian zones and wetlands and the construction of settling ponds are recommended for the protection of water and thus the reduction of P loads and eutrophication. They suggest, however, that the link between erosion and aquatic eutrophication is more complex than previously thought and needs to be examined from a wider perspective than merely accounting for the loading and bioavailability of soil-bound P. When studying the effect of soil erosion and its control, not only the processes occurring in the water phase should be considered but also those which take place after the soil particles have settled to the bottom which are driven by microbes in the aquatic sediments (Ekholm and Lehtoranta, 2012).

Erosion is a natural process which cannot be stopped. It can, however, be minimized to an acceptable rate. The maximum acceptable rate of erosion is known as the soil loss tolerance. According to Morgan (1988), a mean annual soil loss of 1.1 kg/m^2 is generally accepted as the maximum permissible, however values as low as 0.2 to 0.5 kg/m^2 are recommended for particularly sensitive areas where soils are shallow and highly erodible. Although preservation efforts should aim to reduce soil loss to those acceptable values, this objective may be under some circumstances unrealistic, in particular in mountainous areas which receive high rainfall. The recommendations on soil loss tolerance are however based on agricultural considerations and ignore problems of pollution and sedimentation, in particular nitrogen, phosphorus and organic matter, and pesticides leave a field either in solution in the runoff or attached to sediment particles (Morgan, 1988). In South Africa, there is an increasing move towards more sustainable ways of living and food production. Farmers have at their disposable a number of conservation practices which can significantly decrease soil erosion rates (WWF, 2009). Combining a number of these practices is often more effective. The ideal goal is to reduce the soil loss rate to 6.7 t/ha/yr. This is approximately the rate at which soil can rejuvenate itself (DA, 2008).

Soil conservation measures can range from covering the soil to protect it from rain splash, improving the infiltration capacity of the soil to reduce runoff, improving the aggregate stability of the soil and increasing surface roughness to reduce the velocity of runoff and wind (Morgan, 1988). Agronomic or biological measures utilize vegetation to reduce soil erosion and afford protection to the soil. Introducing vegetation cover is generally the preferred method since it is comparatively cheap to implement and reduces the impact of rain splash, increases infiltration, reduces runoff volume and decreases wind and water velocities. Mechanical or physical methods (for example contour bunds, terraces, waterways, silt fences) attempt to control the energy available for soil erosion. Mechanical methods are effective in controlling the transport phase but do little to reduce soil detachment and are costly to install and maintain. Agronomic measures combined with sound soil management, can reduce erosion in the soil detachment and transportation phases (Morgan, 1988).

Akbarimehr and Naghdi (2012) suggest two methods to reduce erosion and sediment movement on forest roads and skid trails and prevent off-side impacts: post-harvest water diversion through the use of drainage culverts on forest roads and water bars on skid trails, and the rehabilitation of forest roads and skid trails through the establishment of vegetation cover.

For conservation measures to be efficient and cost effective, the identification of areas susceptible to erosion, which have the potential to be the main sources of sediment, is critical. The conservation practices must be closely related to the nature of the erosion problem and must consider the intricacy of the erosion process. Sumner (1995) states that strategies for erosion control in areas where accelerated erosion presents a problem to land management can only be achieved through an understanding of the soil erosion processes and their interaction with different conservation practices.

2.3 Soil Erosion Measurement Techniques

Sediment yield is said to be a direct measure of geomorphic activity and is defined as the quantity of sediment removed from a watershed per unit area over a time period (Griffiths *et al.*, 2006). Changes in sediment yield can reveal important ecosystem responses to human activity, climate, and erosion and weathering rates. Sediment yields can be analysed in two ways, namely soil loss (mg. m^{-2}) and sediment concentration (mg. l^{-1}) (García-Ruiz *et al*., 1995). According to Lane *et al*., (1997) the watershed area relative to the total discharge of sediment is referred to as sediment yield in mass/area/time. Vegetation cover, rainfall seasonality, surface materials, soil disturbance and topography caused by land use, strongly affect sediment yield (Griffiths *et al.*, 2006).

Limited knowledge exists on processes which drive the changes in sediment flux as runoff moves through channels, hillslopes and the landscape. Only a fraction of the sediment eroded in a basin will accumulate at the catchment outlet and be represented by sediment yield (Fryirs, 2013). The issue was first identified by Walling (1983) and termed 'the sediment delivery problem'. The use of applying sediment delivery measurements is not as valuable as many researchers suggest, as the ratio of sediment yield to total erosion is uncertain, and total erosion is as difficult to estimate as sediment yield (Osterkamp and Toy, 1997). Only a fraction of the amount of eroded material will reach the basin outlet as some of the sediment may be permanently or temporarily deposited on the down-slope, the base of the slope or in the slope floodplain, furthermore, gully and streambank erosion are often not considered (Osterkamp and Toy, 1997).

Soil erosion monitoring can be carried out on-site (at plot level) and off-site (at sub-catchment and catchment levels). The advantages and limitations of these two monitoring approaches are currently the subject of debate (Hartanto *et al*., 2003). Many studies on soil erosion have been conducted at sub-catchment or catchment levels. Although this approach can better describe the response of a catchment to certain management practices, instream monitoring is expensive and time consuming as monitoring should include a calibration period. On-site monitoring is generally easier to conduct and less costly. This type of monitoring is best suited to observing soil erosion processes and soil disturbances. Periodical sampling is usually adopted to estimate nutrient losses; however, it often underestimates nutrient losses as storm events are more critical for nutrient losses, in particular in the subtropics (Tang *et al*., 2008).

Erosion monitoring can be conducted at a plot (on-site) or catchment/sub-catchment (off-site) scale, however, the results associated with each method are debatable (Hartanto *et al*., 2003). Data from erosion plots contain much variation due to measurement and natural causes (Nearing *et al*., 1999; Cerdan *et al*., 2010). In terms of the performance and suitability of a field experiment design using runoff plots, crucial issues to be addressed are; the disturbance of natural conditions, complexity of ecosystem interactions, temporal and spatial scales, and representation of natural conditions (Boix-Fayos *et al*., 2006). However, there is a demand for knowledge generation and to obtain soil loss data of good quality to understand soil erosion processes at different scales (Bagarello and Ferro, 2004). Erosion plots are useful in providing estimates of erosion on different farming practices and on different crops, nevertheless, in terms of interrill and rill erosion on short slopes, plots should be reliable (Boardmann, 2006). In-stream catchment monitoring is considered expensive and time consuming, while on-site monitoring is simple, inexpensive to conduct, and is considered the appropriate method for recording soil disturbances and processes on-site (Hartanto *et al*., 2003).

The detachment and transport of soil particles resulting from the impact of raindrops or rain splash is usually considered an important first step in the chain of processes leading to loss of soil and subsequent sediment transport (Mouzai & Bouhadef 2003). Once detached, sediment is easily movable by overland flow which may often lead to the development of rills and later gullies or dongas. An assessment of rain splash detachment is therefore important in recognizing areas potentially vulnerable to accelerated soil loss so that corrective action can be initiated.

2.4 Flow Paths and Storage Mechanisms

The relationship that exists between soil profile morphology and soil water regimes facilitates the identification of flow-paths in a hillslope (Le Roux *et al*., 2011), a pre-requisite for quantifying flow rate of water in hillslopes. Soil water regimes play a major role in soil forming processes, which in turn result in the formation of specific soil properties (Soil Survey Staff, 1999). Soil water regimes are controlled by both flow-paths and flow rates (Le Roux *et al*., 2011). Many soil properties influence the hydrological behaviour of soil profiles, which are also influenced by their position in the hillslope. Therefore, deducing the hydrological behaviour of soil profiles in hillslopes, can lead to better conceptualization of hillslope processes (Van Tol *et al*., 2011).

Soils in most of the commercially afforested areas in KwaZulu-Natal are generally strongly to slightly acid and are highly leached (Musto, 1994). In the Seven Oaks area of the KwaZulu-Natal midlands where the study site is situated, soils with dominantly red and yellow-brown dystrophic, apedal B horizons, under dominantly humic A or orthic A horizons have been identified as one of the major groups of soils with Natal Group sandstone as parent material (Turner, 2000; Le Roux *et al*., 2013). Humic soils are widespread on cool, moist and elevated tablelands in this region as a result of exposure to the easterly rain-bearing winds (Turner, 2000). They are generally associated with old land surfaces in the humid, eastern sea-board region of South Africa, especially in Kwazulu-Natal, the Pondoland coast and along the eastern escarpment region of Mpumalanga (Fey, 2010). The orthic A soil zones are located in slightly drier climates or at altitudes a little lower than the corresponding humic zones (Turner, 2000). However, the orthic topsoil group can also form in the moist, humid climate (Turner, 2000).

The dominant flow-path in these soils can be described qualitatively, based on their morphology, as vertical and recharging into the deep groundwater systems (Van Tol *et al*., 2011; Kuenene *et al*., 2011, Ticehurst *et al*., 2007). They do not show evidence of redox morphology (the process that causes the red coloured Fe coatings on soil particles (Fe^{3+} oxides) to dissolve into the soil solution, resulting in the grey soil colour (low chroma). Other hydrological soil types classified based on profile morphology are interflow soils and responsive soils (Van Tol *et al*., 2011). Interflow soils are associated with subsurface lateral flow-paths at either A/B horizon or soil/bedrock interface. Responsive soils are limited in their storage capacity as they are either shallow on impermeable bedrock or are close to saturation during rainy periods, resulting in the generation of overland flow after a rain event (Van Tol *et al*., 2011).

A simple conceptual framework of hillslope hydrologic pathways (Figure 2.1) has also been used to evaluate the tropical rainforest soilscapes following detailed measurements of saturated hydraulic conductivity (K_s) on different slope units (Elsenbeer, 2001).

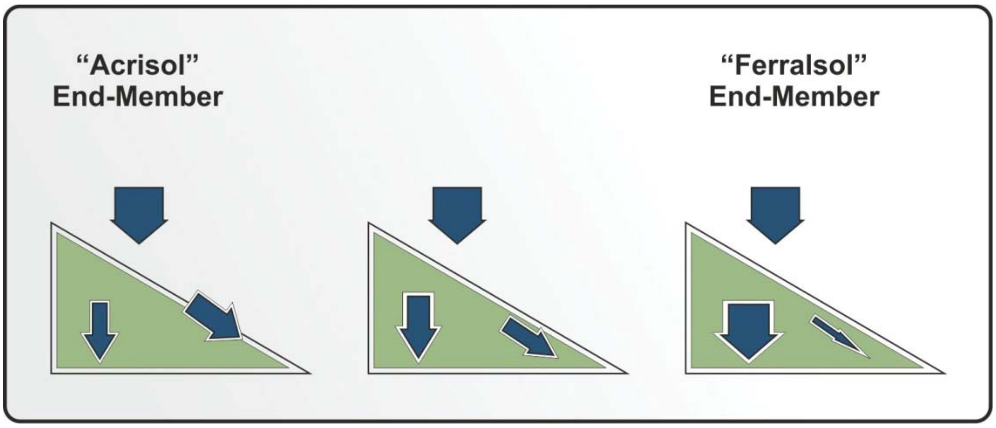

Figure 2.1 The influence of hydrological soil types on hydrologic flow paths in tropical rainforests soilscapes (Elsenbeer, 2001). The size of the arrow indicates the dominance of flow in each soilscape

The dominating vertical flow-path in Figure 2.1 is in a Ferralsol soilscape, which is similar to the hillslopes on the Mondi Mistley-Canema estate in the Seven Oaks district where Two Streams is located. The Acrisol soilscape is characterized by predominantly lateral and vertical flow paths (Figure 2.1). Ferralsols are red and yellow weathered soils whose colours result from an accumulation of metal oxides, particularly iron and aluminium (Van der Watt & van Rooyen, 1995). Acrisols are soils having a B horizon with illuvial accumulation of clay and low base saturation (Van der Watt & van Rooyen, 1995). The underlying permeable bedrock facilitates infiltration of water in the recharge soils (Van Tol *et al.,* 2011). Because of the high leaching status of most of Kwazulu-Natal soils under high rainfall, the degree of weathering of rocks can be high and very deep (Fey, 2010). The red apedal subsoils of the Kwazulu-Natal often extend to at least two or three meters before kaolinised saprolite is encountered (Fey, 2010).

Criteria for classifying hillslope hydrological responses in South Africa (Figure 2.2) into different classes have been developed based on hydrological soil types (Van Tol *et al*., 2013). The soil classes are determined by the type and position of the hydrological soil types in a hillslope (criteria), indicated by different shades on the bars and serve as the basis for the hillslope classification.

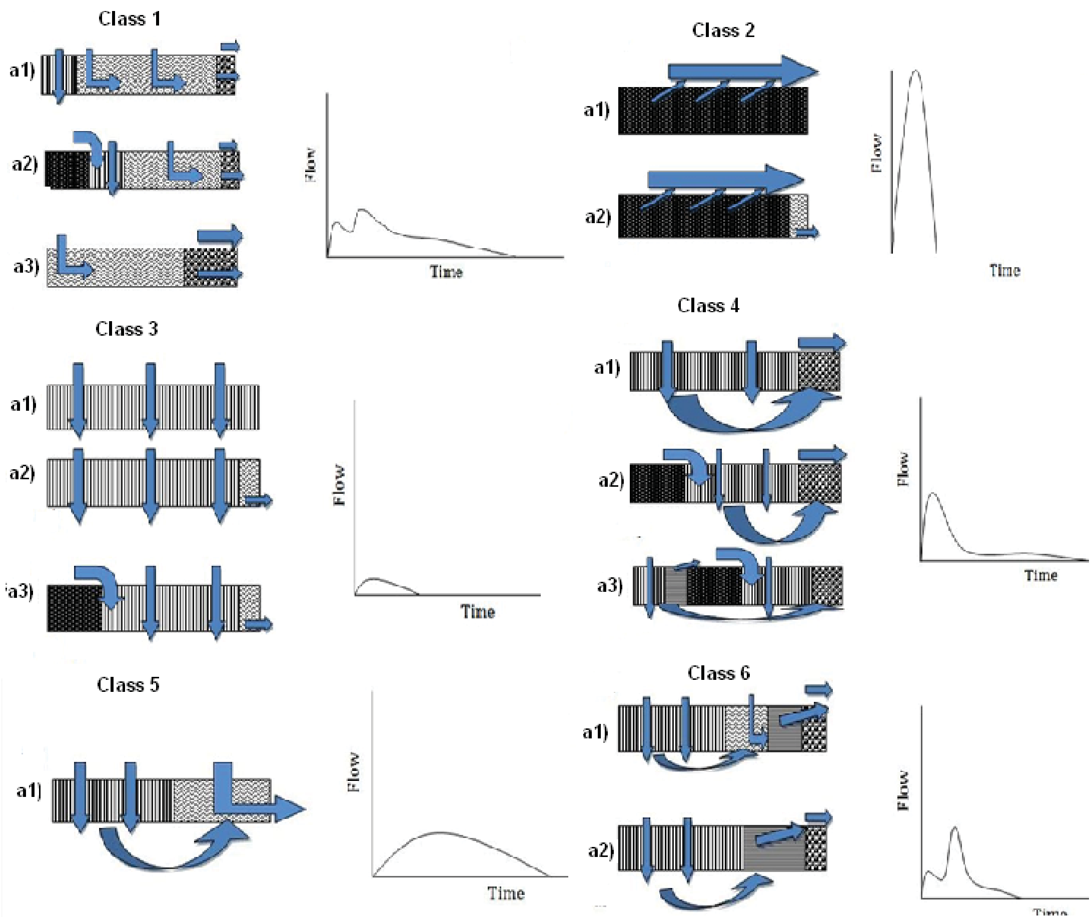

Figure 2.2 Conceptual flow models of 6 different classes accompanied by anticipated hillslope hydrographs. Bars without inclination or differences in slope length represent hydrological soil types and arrows indicate dominant flow-paths in the hillslope (After Van Tol et al., 2010)

The distribution of soils along different hillslopes dictates the type of flow-path direction (Figure 2.2). For example, class 1 (a1) and (a2) combines all hydrological soil types which in turn facilitates vertical, interflow and overland flow along the hillslope. The anticipated hydrograph shown for class 1 will have peaks and long recession as a result of different hydrological soil types. The hydrograph will be completely different if the hillslope is dominated by the overland flow path, i.e. class 2 in Figure 2.2.

2.5 Erosion and Sediment Yield Models

Arguably one of the most important components of a scientific simulation model is that it should be as easy as possible to understand in light of the assumptions and mechanisms represented in the simulator, so that critical evaluations can be made of the predictions (Thornley, 1998). Models in the public domain are promoted and explained differently, resulting in model comparisons being more difficult. Numerous models developed for a variety of uses are available. As such a predicament exists as to which model or sub-model is best suited for the intended use. Some models are designed and developed for specific purposes, while others are more general and integrated in their applicability (Schulze, 2007). Model complexity is a major determinant as to which model is selected, as the input data available, time constraints and budget influence model selection. Furthermore, the level of detail on processes, spatial disaggregation and temporal disaggregation should be considered (Schulze, 1995).

2.5.1 Concept of Hydrological Models

Comparisons of simple and complex models provide insights on the model structure to make a suitable model selection. According to Schulze (1995), models of differing complexity range from simple formulae to complex physiologically-based models. The advantage of simple models is that simple and readily obtainable inputs are required in order to provide estimations (Schulze, 1995). Simple models cannot be expected to provide a detailed estimation, but may be accurate in terms of general large-scale modelling. Simple models should not be used for extrapolation of estimates under different conditions from the ones under which these models were developed, nor for risk analysis (Schulze, 1995). More complex models can provide accurate estimates of hydrological components in comparison to simple models, provided that quality information is readily available and time and money are not limited. “The development of complex models from the processes of analysis, assembly of data, model construction and validation, take up costly resources in the form of skilled man hours and computer time” (Schulze, 1995, AT19-3).

Many hydrological models have been developed each with their own objectives and capabilities (Merritt *et al*., 2003; Aksoy and Kavass 2005; Gassman *et al*., 2009; Devi *et al*., 2015). For example, the SWAT was developed to examine and predict the movement of water and sediment, and was tailored to model agriculture production and chemical circulation related to agriculture (Devi *et al*., 2015); whilst the PRMS was developed to assess impacts of precipitation, climate and land use on catchment response (Legesse *et al*., 2003).

The primary purposes of a hydrological model are to understand hydrological processes and the implications of making certain assumptions about the nature of the real-world hydrological system, and to predict hydrological system behaviour (Moradkhani and Sorooshian, 2009**;** Devi *et al*., 2015). Hydrological models are used to provide predictions of different factors such as climate and climate change (Legesse *et al*., 2003; Teutschbein and Seibert, 2010, 2012; Pohl *et al*., 2017; Zhang *et al*., 2008) and LULC and LUCC (Zhang *et al*., 1999; Xu and Singh, 2004; Siriwardena *et al*., 2006; Vanclay, 2009; Warburton *et al*., 2012; Isik *et al*., 2013; da Silva *et al*., 2018; Toohey *et al*., 2018). Each hydrological model has its own unique characteristics and considers its own inputs, depending on the purpose of the model and the detail at which hydrological processes are investigated (Merritt *et al*., 2003).

The model input requirements depend on the processes considered by the model, the complexity at which processes are considered, the scaling capabilities of the modelling software and the model use or user requirements (Moradkhani and Sorooshian, 2009; Devi *et al*., 2015). In general, there is no best fit hydrological model for all applications (Merritt *et al*., 2003). Choosing the most appropriate model will depend on what the model will be used for (Merritt *et al*., 2003; Aksoy and Kavass, 2005). Each model has its own advantages and limitations, and some require high detail information, which is on occasion not easily available or not economically feasible (Merritt *et al*., 2003). Detailed reviews of catchment modelling have been provided by Merritt *et al.* (2003), Aksoy and Kavass (2005), and Devi *et al*. (2015).

Models can be categorised to facilitate understanding of model capabilities. Generally, models are broadly classified into three groups: empirical, conceptual and physically-based (Legesse *et al*., 2003; Merritt *et al.*, 2003; Devi *et al*., 2015), but can also be categorised based on spatial or temporal capabilities. Spatially, models can be distinguished as lumped, semi-distributed or distributed (Merritt *et al.*, 2003; Aksoy and Kavass, 2005; Devi *et al*., 2015) and temporally as static and dynamic (Merritt *et al*., 2003; Devi *et al*., 2015), where static models exclude time whilst dynamic models include time. Temporally, models can also be classified as event based and continuous, where event-based produces outputs only for specific time periods while continuous produces continuous outputs (Merritt *et al*., 2003; Devi *et al*., 2015). The different model categories are elaborated on in the coming paragraphs.

In South Africa, models such as the Agricultural Catchments Research Unit (ACRU), the Soil Water Assessment Tool (*SWAT*), Système Hydrologique Européen (SHE) model group and WAVES are just some of the models used in South Africa. Due to the available data at the site of interest, the recent development of the ArcSWAT GIS interface and the sediment and nutrient information required for the project, SWAT was chosen as the most appropriate model to use. The input required for ArcSWAT is spatially explicit soils data, land use/management information, and elevation data to drive flows and direct sub-basin routing (Arnold and Fohrer, 2005). ArcSWAT lumps the parameters into hydrologic response units (HRU), effectively over-riding the underlying spatial distribution. These HRUs are grouped according to the topography, soils (type/structure/depth/chemical properties), land use and slope (Figure 2.3).

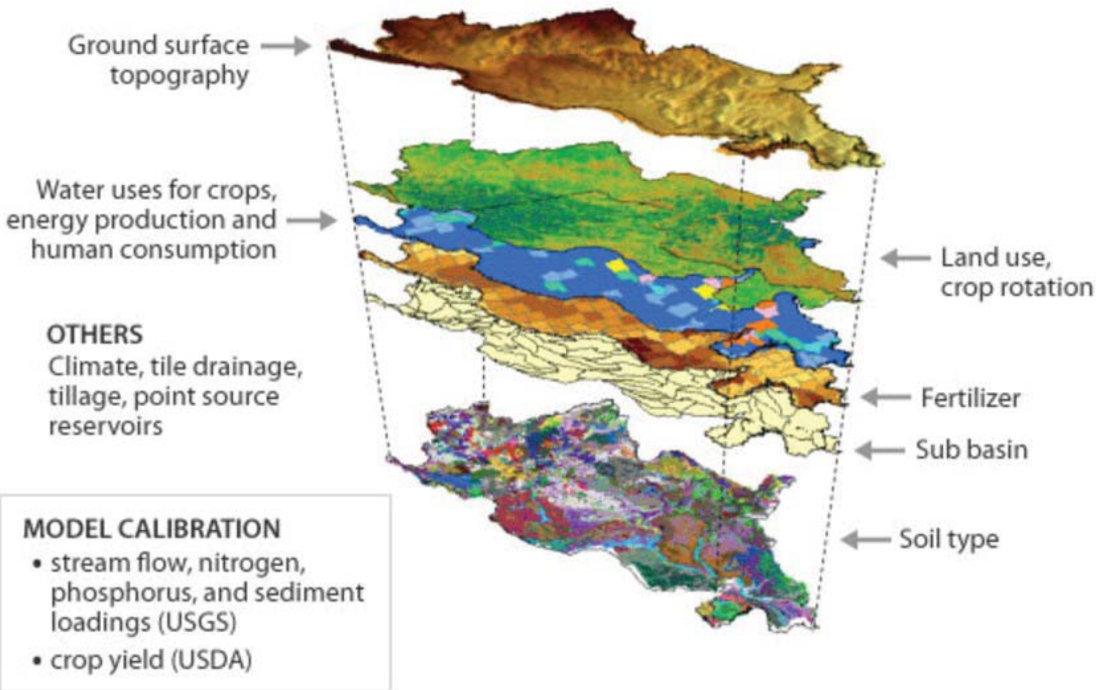

Figure 2.3 Conceptual layout of the ArcSWAT model setup

One of the most important drivers is the meteorological data, which has been vastly improved in this model over recent years. ArcSWAT has options to use measured solar radiation, wind speed, relative humidity and evaporation data. Daily rainfall and temperature data may be generated if unavailable or missing for the simulation period and there are no limitations to the number of rainfall and temperature gauges that can be used in the simulation (Neitsch *et al*., 1999).

2.5.1.1 Empirical models

Empirical models provide a simplistic, homogeneous representation of the environment, relying on empirically derived fits of observed data (Merritt *et al*., 2003; Devi *et al*., 2015), and generally run on minimal, coarsely measured inputs (Merritt *et al*., 2003; Aksoy and Kavass, 2005). Empirical models are used to relate the input and output variables using transformation functions, and as such they do not consider the features, processes or the governing physical principles of processes involved in hydrological systems (Legesse *et al*., 2003; Devi *et al*., 2015).

2.5.1.2 Conceptual models

Conceptual models describe the hydrological processes of a number of interconnected components representing the physical elements of a catchment (Merritt *et al*., 2003; Devi *et al*., 2015). Conceptual models can be considered as semi-empirical as they rely on observed field data. However, they also rely on calibration to assess model parameters (Devi *et al*., 2015). For the calibration of conceptual models, large amounts of meteorological and hydrological data are required (Devi *et al*., 2015). Examples of conceptual models include the Hydrologiska Byrans Vattenavdelning (HBV) model (Bergström, 1992; Devi *et al*., 2015) and the TOPography based hydrological MODEL (TOPMODEL) (Beven *et al*., 1995; Beven, 1997).

2.5.1.3 Physically-based models

Physically-based models are used to describe the ideal mathematical representation of the real world (Devi *et al*., 2015). They include the principles of physical processes that are measurable and are functions of both time and space (Legesse *et al*., 2003). Physically-based models quantify outputs based on a large number of physically-based input parameters. Unlike conceptual models, physically-based models do not require extensive data for calibration (Merritt *et al*., 2003; Devi *et al*., 2015; Ma *et al*., 2016). Physically-based models can overcome many problems of empirical and conceptual models due to their physical interpretation and increased complexity at which hydrological processes are considered (Merritt *et al*., 2003). Physically-based models can be more precise, provided that there is sufficient available input data, as they aim to reduce the bias between the modelled processes and observations made (Devi *et al*., 2015). An example of a physically based model is the MIKE SHE model (Graham and Butts, 2005).

2.5.1.4 Comparing lumped and distributed hydrological models

Differences in spatial consideration in modelling distinguish lumped from distributed hydrological models (Merritt *et al.*, 2003; Aksoy and Kavass, 2005; Devi *et al*., 2015). Lumped models consider an entire area as a single unit, thereby disregarding spatial variability in the components and the natural heterogeneous nature of the system (Aksoy and Kavass, 2005; Moradkhani and Sorooshian, 2009). Distributed models, on the other hand, explicitly represent spatial variability of hydrological components, such as: topography, LULC, soil, precipitation and ET, and system heterogeneity (Legesse *et al*., 2003; Merritt *et al*., 2003; Moradkhani and Sorooshian, 2008). Hence in the selection of a model there are trade-offs to consider in terms of data availability, time constraints and computing capabilities.

In the range of hydrological models, models differ in their consideration of spatial scale and physics considerations, for example the *Kinematic Runoff and Erosion* (KINEROS) model, the *Institute of Hydrology Distributed* (IHDM) model and the MIKE SHE model are all physically-based fully distributed models while the SWAT and the *Precipitation Runoff Modelling System* (PRMS) are physically-based semi-distributed models and the *North American Mesoscale Forecast System* (NAM) is a conceptual lumped model (Isik *et al*., 2013). Over time the different modelling categories have evolved from the initial creation of simplistic empirical approaches, to lumped parameter models, to spatially distributed models (DeFries and Eshleman, 2004).

With ever increasing consequences of human impacts, it is becoming increasingly important to account for change, interactions and feedback mechanisms at play in hydrological systems (Ma *et al*., 2016). Thus, there is a shift toward distributed hydrological modelling due to both social need and technological advancements in computing (Ma *et al*., 2016). Physically-based, distributed models have important applications in interpreting and predicting the effects of LUCC and climate variability as they are able to relate model parameters directly to physically observable land surface characteristics (Legesse *et al*., 2003). Although there is a shift toward distributed hydrological modelling over lumped models, there are concerns with regards to these complex distributed models. One of the main sources of uncertainty and concern surrounds the estimation of the excessive parameters within distributed models, as due to the large amount of input requirements not all parameters can be known and some will need to be estimated causing a degree of uncertainty in the model (Moradkhani and Sorooshian, 2008; Ma *et al*., 2016).

2.5.2 Hydrological models

In general, hydrological models are the popular tools for investigating hydrological processes and assisting in water management (Devi *et al*., 2015). However, there will always be a degree of uncertainty in model predictions as all models employed are abstractions, simplifications and interpretations of reality and not reality themselves (Ma *et al*., 2016). Some examples of hydrological models are described in this section.

2.5.2.1 The Soil and Water Assessment Tool (SWAT) model

The SWAT model is a physically-based, continuous daily time step model developed to simulate long-term impacts of land and water management and agricultural practices (Govender and Everson, 2005). The physical processes simulated in a catchment by the SWAT model can be grouped into upland and channel processes (Govender and Everson, 2005). The model components include: climate, surface runoff, ET, crop growth, irrigation, and nutrient and pesticide inputs (Arheimer and Olsson, 2003).

The model can simulate a catchment in both a lumped or distributed approach, by automatically delineating the catchment either into sub-catchments or grid cells based on a digital elevation model (DEM; Govender and Everson, 2005). By delineating into sub-catchments, the model is based on semi-distribution. During this process, a catchment is first sub-divided into sub-catchments according to the terrain and river channels, and then into multiple hydrological response units (HRUs) based on the soil and LULC types within the sub-catchments (Devi *et al*., 2015). An HRU is a fundamental homogeneous spatial unit upon which SWAT simulates the water balance (Xu *et al*., 2009). The use of sub-catchments in a simulation is useful in differentiating between the impacts of various land uses and soils on the hydrology of a catchment (Govender and Everson, 2005).

SWAT is a valuable model due to its availability and user-friendliness (Xu *et al*., 2009). SWAT has been developed with an ArcView GIS interface (Easton *et al*., 2010), allowing for improved spatial analysis and visualization together with increased model flexibility (Govender and Everson, 2005). ArcGIS provides a platform to incorporate soil input maps, DEMs and LULC maps required in a SWAT model (Easton *et al*., 2010). SWAT is computationally capable of modelling small and large sub-catchments or catchments within reasonable times (Govender and Everson, 2005).

Soil erosion involves the detachment, transport and deposition of soil particles (including plant nutrients and organic matter) by water or wind. The process may be natural or accelerated by human interference in the environment (Tolosa, 2015). The amount of sediment actually leaving a site or catchment is a function of the erosional and depositional processes occurring above the discharge outlet. Sustainable land management and water resources security are threatened by soil erosion and sediment-related problems. In response to such threats, there is an urgent need to estimate soil loss and identify problematic areas for improved catchment-based erosion control and sediment management strategies (Tolosa, 2015). However, soil erosion, transportation and deposition are high variable spatially and temporally, and are expensive to monitor accurately resulting in limitations for calibration.

Erosion and sediment yield in SWAT are estimated for each HRU with the Modified Universal Soil Loss Equation (MUSLE) and Bagnold's equation to route the sediment loads (Winchell *et al*., 2010). It uses the amount of runoff to simulate erosion and sediment yield. The hydrology module supplies estimates of runoff volume and peak runoff rate, which, with the sub-basin area, are used to calculate the runoff erosive energy variable (Tolosa, 2015). The crop management factor is recalculated every day that runoff occurs. It is a function of above ground biomass, residue on the soil surface, and the minimum crop factor for the plant. Surface runoff is calculated using Equations 2.1 and 2.2 and is then used to calculate sediment yield (Equation 2.3).

$$Q_{surf} = \frac{(P - I_a)^2}{(P - I_a + S)}$$	*(Eqn. 2.1)*

$$S = 254(\frac{100}{CN} - 1)$$	*(Eqn. 2.2)*

$$Sediment\ Yield = 11.8 \times (Q_{surf} \times q_{peak} \times A_{hru})^{0.56} \times K \times C \times P \times LS \times CFR$$	*(Eqn. 2.3)*

where

Q_{surf} = Surface runoff volume
q_{peak} = Peak runoff rate ($m^3.s^{-1}$)
A_{hru} = Area of the Hydrological Response Unit
K = USLE soil erodibility factor
C = USLE cover & management factor
P = USLE support practice factor
LS = USLE topographic factor
CFRG = Coarse fragment factor

Soil texture is an important component affecting soil erodibility. Output from the SWAT model can determine the texture of the load per day, which is usually composed of high silt levels and some clay. To a lesser extent, soil structure and permeability impact upon this component. This is particularly important for areas such as dirt roads, where compaction is high. The C factor (cover and management) reduces the soil loss estimate based on the effectiveness of vegetation and mulch to prevent detachment and transport of soil particles. Due to its strong sediment yield component, SWAT could be used to extrapolate sediment distribution throughout the catchment, identify vulnerable areas and promote best management practices.

2.5.2.2 The Systeme Hydrologique European (MIKE SHE) model

MIKE SHE is a physically-based distributed hydrological model developed to integrate the simulation of both surface water and groundwater flow and transport processes in a fully coupled modelling environment (Hughes and Liu, 2008). MIKE SHE is globally recognized and has been implemented in numerous water related research projects at a range of spatial scales from 1 km² to 1000 km² (Bathurst, 1986; Wicks and Bathurst, 1996; Christiaens and Feyen, 2001; Hughes and Liu, 2008; Zhang *et al*., 2008; Ma *et al*., 2016; Sonnenborg *et al*., 2017). MIKE SHE modelling software covers all the major processes of the hydrological cycle (Figure 2.4) and the interactions between the processes: precipitation, ET, overland flow (OL), unsaturated flow, saturated flow and channel flow (Graham and Butts, 2005) and is capable of simulating water quality (Butts *et al*., 2005).

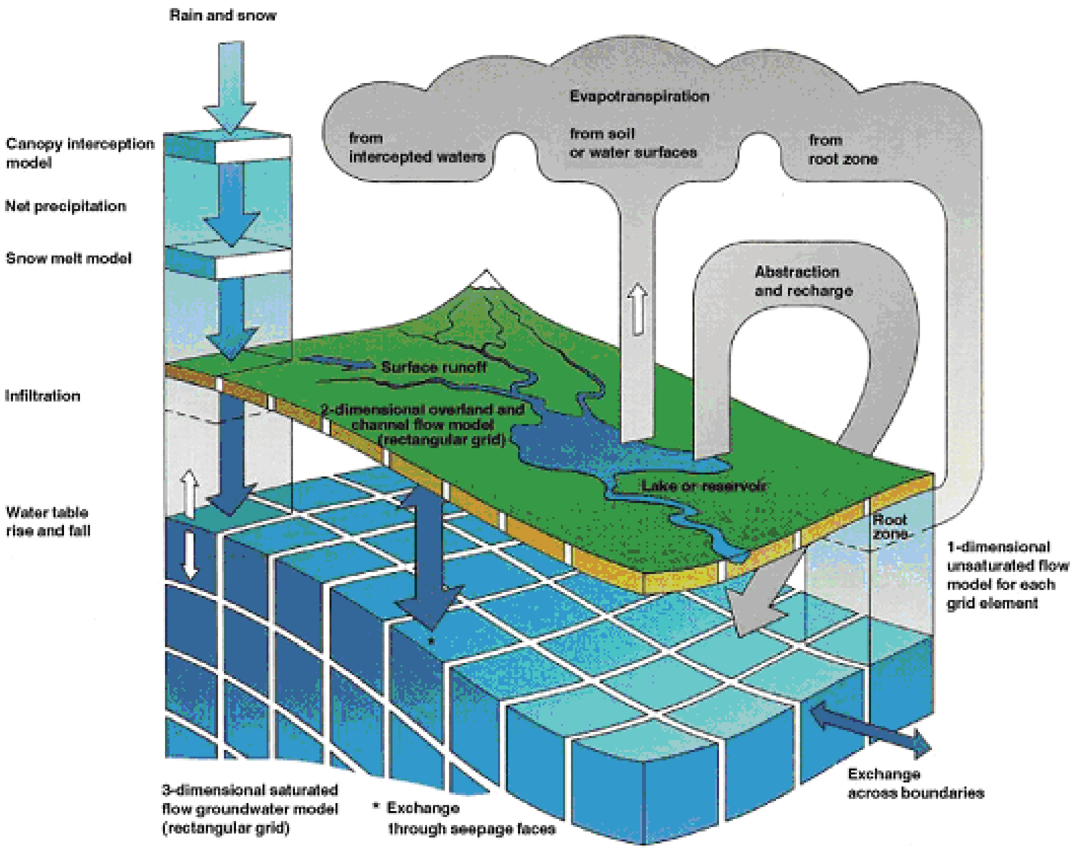

Figure 2.4 Hydrological processes simulated by MIKE SHE (Graham and Butts, 2005)

MIKE SHE software is flexible to user preferences and data availability enabling the user to select from a number of different modelling options when modelling different processes and allowing for flexibility in spatial and temporal analysis (Graham and Butts, 2005). Temporally, the model allows the user to define the simulation and run time of each process enabling different processes to run at different time intervals or speeds, simulating more realistic representations of hydrological processes and the hydrological cycle (Graham and Butt, 2005; DHI Software, 2012). For example, movement of groundwater in the SZ is slower than the movement of water in the unsaturated or OL regions (DHI Software, 2012).

Not all hydrological processes can be calculated directly in MIKE SHE and are calculated through additional software that is then linked to the MIKE SHE framework, such as channel flow. MIKE SHE uses MIKE 11 to simulate channel flow (Graham and Butts, 2005), which allows for the modelling of complex channel networks, lakes and reservoirs and river structures for example gates, sluices and weirs (Graham and Butts, 2005). Separate software is used to allow for a more accurate representation of the river structures and their processes of operation (Butts *et al*., 2005).

Many studies have employed MIKE SHE modelling, such as Zhang *et al*. (2008), who used MIKE SHE to quantify the response in hydrology with changes in LULC and climate for the Loess Plateau in Northwestern China. Through calibration and validation, the study found that the model could capture the dominant runoff process of the small watershed and that the model was useful for understanding the rainfall-runoff mechanisms (Zhang *et al*., 2008). However, more measured data with higher temporal resolution are needed to further test the model for regional applications (Zhang *et al*., 2008). Another study by Im *et al*. (2009) considered the impact a change from non-urban to urban land use, in the Gyeongecheon watershed, South Korea, would have on catchment hydrology. The study successfully showed that between 1980 and 1990 there was a 10% increase in runoff, followed by a further 15% increase between 1990 and 2000 (Im *et al.*, 2009). Results further showed that over the studied years (1980 – 2000) ET declined by 18 mm (Im *et al.*, 2009). This study supported previous views on urbanization increasing surface runoff and decreasing ET (Im *et al.*, 2009).

2.5.2.3 The Hydrologiska Byrans Vattenavdelning (HBV) model

The HBV model is a semi-distributed conceptual model (Bergström, 1992). It was designed to consider what were deemed by Bergström (1992) as the most significant components of the runoff generating processes, and thus the HBV model avoided complexities by only focusing on certain hydrological components. The HBV model, divides the modelled catchment area into sub-catchments or primary hydrological units that are then further classified based on elevation and land use (Lindström *et al*., 1997). The HBV model consists of three main components: snow accumulation and snowmelt, soil moisture and river routing (Bergström, 1992).

The HBV model is primarily used in Scandinavian countries, but has been globally applied under a range of varying conditions such as in Zimbabwe, India and Colombia (Lindström *et al*., 1997). Originally the HBV model was developed at the Swedish Meteorological and Hydrological Institute (SMHI) for runoff simulation and hydrological forecasting (Bergström, 1992), however the scope of applications has increased with the model undergoing multiple revisions since inception (Lindstrom *et al*., 1997). However, even with revisions, the model philosophy has remained the same, which is that the model complexity and data demand must not be in conflict with the operational requirements (Bergström, 1992). Today many versions of the HBV model exist and new codes are constantly being developed by different research groups (Scheepers *et al*., 2018).

2.5.2.4 TOPMODEL (a TOPography based hydrological MODEL)

TOPMODEL provides a user-friendly model structure that makes use of digital terrain model (DTM) data to model runoff (Beven, 1997). TOPMODEL differs to the previous hydrological models discussed in that it does not comprise of a single model structure that is generally applicable, but rather comprises a set of conceptual tools that can be used to simulate hydrological processes (Beven *et al*., 1995). The two main factors considered by TOPMODEL in modelling hydrology are catchment topography and soil transmissivity (Beven, 1997). The main aim of the model is to spatially determine the water table depth of the modelled area (Devi *et al*., 2015) and thereby TOPMODEL is capable of capturing the dynamics of surface or subsurface areas (Beven *et al*., 1995). Due to advancements in RS and GIS, topographic data are more readily available and at higher resolutions, making the TOPMODEL popular and widely implemented (Devi *et al*., 2015).

2.5.2.5 The Variable Infiltration Capacity (VIC) model

The Variable Infiltration Capacity (VIC) model is a semi-distributed macroscale hydrological model that represents surface and subsurface hydrologic processes on spatially distributed grid cells (Demaria *et al*., 2007; Devi *et al*., 2015). The VIC model uses energy and water balance equations (Demaria *et al*., 2007; Gao *et al*., 2009) and has been extensively used in studies on water resources management, land-atmosphere interactions, and climate change. (Xu and Singh, 2004**)**. The key characteristics of the VIC model are the representation of heterogeneous vegetation, multiple soil layers with individual I_{UZ} measures, and non-linear base flow (Gao *et al*., 2009). The VIC model consists of three layers; the top layer allows quick soil evaporation (E_s), the middle layer represents the dynamic response of soil to rainfall events and the lower layer is used to characterise behaviour of soil moisture (Devi *et al*., 2015). The VIC model is useful at considering the dynamic nature of surface and ground water interactions and at modelling the ground water table (Devi *et al*., 2015).

2.5.2.6 The Agricultural Policy/Environmental eXtender (APEX) model

The Agricultural Policy/Environmental eXtender (APEX) model differs from the hydrological models discussed previously. It is a flexible and dynamic model capable of simulating a wide range of management practices, cropping systems, and other land use across a broad range of agricultural landscapes (Gassman *et al*., 2009; Wang *et al*., 2012). The model was developed for the evaluation of land management strategies by considering sustainability, erosion, water supply and water quality, soil quality, plant competition, weather conditions and pests (Williams *et al*., 2015). The APEX model is an advancement on its predecessor, the Erosion/Productivity Impact Calculator (EPIC) model (Wang *et al*., 2012), as APEX can be used at a range of spatial scales and soil types (Williams *et al*., 2015). APEX functions on a daily time step and can perform long term continuous simulations or can be used for simulating the impacts of different short-term management practices (Gassman *et al*., 2009).

2.5.3 Water balance

In hydrological research, and for water management, knowledge of the amount of water and change in water storage in a system is critical. Thus, tools for such application are of importance, such as the water balance equation which is the central equation used in studying hydrological processes (Hendriks, 2010). Overall, hydrological models account for, or allow for, the calculation of a water balance as part of the simulation run (Singh *et al*., 2017). The water balance provides a framework for studying the hydrological behaviour of an area and for identifying changes in the hydrological components as a result of hydrological processes (Hendriks, 2010). The components considered in the water balance equation, can be extensive or they can be an amalgamation to simplify the process (Harlow, 2018). Ultimately the water balance concept is used to determine whether all water inflows into the system are equal, or balance out, the water outflows. Water balance calculations incorporate both reservoirs and fluxes (DHI software, 2012). The water balance method was first used by Thornthwaite and Mather (1957) (Equation 2.4). Since its introduction the equation has undergone alterations and revisions to improve performance and refine parameters (Harlow, 2018), however the simplistic notion originally developed by Thornthwaite and Mather (1957) still holds true (Zhang *et al*., 1999). For water management purposes, the water balance is an important tool for estimating water management effects such as those related to LUCC and climate change (Hendriks, 2010).

$$P = ET + Q + R + \Delta S \qquad \textit{(Eqn. 2.4)}$$

$$P = ET + Q + R + \Delta S$$

Where *P* is precipitation, *ET* is evapotranspiration, *Q* is surface runoff (streamflow), *R* is groundwater recharge and Δ*S* is the change in soil water storage.

2.5.3.1 Precipitation (P)

Precipitation is the largest water inflow into an area and comprises all atmospheric water entering the system inclusive of both liquid (rainfall) and solid (snow or hail) water particles (Hendriks, 2010). Precipitation is both spatially and temporally variable (Pohl *et al*., 2017). In hydrological modelling and water balance calculations rainfall and snow are dominant precipitation measures (Bergström, 1992; DHI software, 2012). Less conventional precipitation measures, including fog and other horizontal precipitation, are not commonly measured with conventional rain gauge instruments, and are often not included in hydrological modelling and water balance calculations (Scholl *et al*., 2010).

2.5.3.2 Total evaporation (ET)

Evaporation is the change of water in a liquid or solid state into water vapour and involves the movement of water into the atmosphere (Hendriks, 2010). Transpiration (E_t) accounts for the movement of water within a plant and the conversion of and/or loss of water in the form of water vapour through the stomata in plant leaves (Hasenmueller and Criss, 2013). Total evaporation (often referred to as evapotranspiration - ET) is the combination of evaporation from soil, evaporation from intercepted storage, E_t, and evaporation from surface ponded water (Savenije 2004; Hendriks, 2010). Excluding precipitation, ET is typically the largest component of many ecosystem water balances (Zhang *et al*., 2008). Globally, approximately 57% of all precipitation on land evaporates or transpires and in warm, dry climates this value increases up to approximately 96% (Hendriks, 2010). ET thus constitutes an important component of the hydrological cycle and water balance (Hasenmueller and Criss, 2013). There exist different types of ET: potential, actual (ET_A) and reference (ET_{Ref}; Hendriks, 2010). Potential evapotranspiration is the maximum ET rate (mm.day^{-1}) that can occur, whilst ET_A is the amount (mm.day^{-1}) that occurs under the existing environmental conditions of an area (Hendriks, 2010). The ET_{Ref} is the potential ET rate (mm.day^{-1}) of an idealized grass crop that serves as a reference value for other crops (Hendriks, 2010; Zotarelli *et al*., 2015).

ET is difficult to directly measure and the issues that surround calculation accuracy are generally related to the calculation techniques used (Zotarelli *et al*., 2015). Generally, conventional methods of lumping ET measures (all evaporation and E_t are lumped together) tend to underestimate ET. Eveopration from interception (E_i) and this is a concern given that E_i is a considerable proportion of total ET (Savenije, 2004). For example, Calder (1990) explored E_i, in upland forest catchments in Britain, and found that E_i amounts to 35% in areas receiving 1000 mm of rainfall per annum and up to between 40 and 50% in areas receiving between 500 and 600 mm of rainfall per annum. A further concern with the estimation of ET is spatial heterogeneity. ET is spatially affected by land cover (vegetation type), soil hydraulic properties and subsurface storage of moisture (Zhang *et al*., 1999). Within plant communities, the type, structure, abundance and geographic location of the vegetation can have significant impacts on the rate of ET (Zhang *et al*., 1999; van Dijk and Keenan, 2008).

2.5.3.3 Surface runoff and streamflow (Q)

Surface runoff and streamflow originate when the capacity for the land surface to store water is overcome, this occurs once I_{UZ}, evaporation and interception have all taken place (Hendriks, 2010). Water will flow as OL or surface runoff once both CI capacity and surface storage capacity have been reached (Hendriks, 2010). Surface runoff will generally show good correlation with annual rainfall, particularly in areas with winter dominant rainfall (Zhang *et al*., 1999). When surface runoff makes its way into streams, rivers or other terrestrial water bodies it becomes known as streamflow (Hendriks, 2010). Streamflow is an important aspect of the water balance and the water cycle as streams are a major source of freshwater for humans, animals, plants and the natural ecosystem (Oyebode, 2014). Thus, prediction of streamflow, both in the short- and, long-term, are critically important forming the basis upon which water managers, consumers, policy makers and other stakeholders put in place plans and adaptive strategies for the allocation and control of water resources (Oyebode, 2014).

2.5.3.4 Recharge (R)

Recharge is the amount of infiltrated water that leaves the bottom of the soil zone and becomes part of the saturated, groundwater, zone (Zhang *et al*., 1999; Harlow, 2018). The calculation of recharge is dependent on many physical factors including: LULC, climate, geology, snowmelt and soil type (Jyrkama and Sykes, 2007; Harlow, 2018), all of which impact on the determination of recharge rates and thus recharge rates are highly variable, ranging from less than 10 mm to multiple meters per year (Harlow, 2018). Determination of GR is important for developing and monitoring groundwater management strategies and for determining the impacts of climate change and urbanization on groundwater aquifers (Jyrkama and Sykes, 2007). This is particularly important in areas where the underlying aquifers are vulnerable to abstraction, contamination or exploitation (Jyrkama and Sykes, 2007).

2.5.3.5 Change in soil water storage (ΔS)

A significant percentage of precipitation infiltrates to become stored soil water (Hendriks, 2010). The soil water storage is the total amount of water stored in the soil within the rooting zone of plants (Reichardt *et al*., 2013). Soil water, in the hydrological cycle, is dynamic, being either returned to the atmosphere by plant E_t and evaporation or moving into lower levels to become groundwater (through recharge) (Saxton and Rawls, 2006). Understanding the characteristics of the soil properties is necessary to determining soil water storage and the change thereof. This is emphasised by Yates *et al.* (1989), who explain that an understanding of the basic soil hydraulic properties (particularly unsaturated hydraulic conductivity) is essential in accurately determining, flow, water movement and water storage potential.

2.6 Conclusion

Soil erosion is the process of detachment and transportation of soil materials by wind or water. The loss of fertile topsoil on-site decreases soil productivity and reduces crop yields over time. It affects water catchments through sedimentation and eutrophication of waterways. The dominant agent causing erosion in South Africa is water (Le Roux *et al*., 2008). South African soils are generally fragile; they have low organic matter and are susceptible to high rates of erosion (Van Zyl *et al*., 1996). The rate of soil erosion worldwide and in South Africa are likely to increase given the increasing pressure on the land and extreme events exacerbated by caused by global climate change (Van Oost *et al*., 2000).

The degree of soil erosion ranges from splash erosion to gully formation. The factors which influence the rate at which soil erosion occurs are wind and rainfall intensity, soil erodibility, topography, vegetation cover, soil management practises and conservation measures. It estimated that approximately 5 to 7 million hectares of productive topsoil are lost annually through erosion.

Soil erosion models have been modified and applied to regional scales for scenario analysis and to make objective comparisons to guide research and soil conservation efforts in South Africa. Water scare countries, such as South Africa, are becoming increasingly threatened by pollution and sedimentation of water bodies. Soil erosion impacts negatively on the natural water storage capacity of catchments areas, service of man-made reservoirs and dams, quality of surface water. Sediment represents a carrier of nutrients, trace and heavy metals, micro-pollutants and pathogens. It is becoming increasing accepted that erosion control should be linked to both soil (on-site erosion) and water (off-site sedimentation) conservation initiatives. Erosion is a natural process which cannot be stopped. It can, however, be minimized to an acceptable rate. Thus, understanding the processes of soil erosion is crucial as field data collected can aid in calibrating and verifying models and be able to minimise the impact of controlling factors on the environment. This study is inclusive of field data in the aim to populate and verify models. Models currently are increasingly being utilised which further helps in quantifying soil erosion processes and predicting different scenarios which will aid in achieving objectives set (Morgan, 2009). Models are continuously being improved and modified to minimise uncertainties in soil erosion conservation efforts.

3: SITE SELECTION

To determine the suitability of a study area, certain criteria need to be met. Sites were assessed based on their suitability (presence and severity of erosion), historical monitoring, proximity from resources and students, and safety. In addition, the type of land-use and prevailing climate was an important consideration. It was then determined whether these sites would be able to meet the study objectives.

3.1 Land-use

A high portion of KwaZulu-Natal's land is under communal land tenure. Fifty-eight percent of KwaZulu-Natal's land is used for stock farming, with crops account for a further 17% of the land use. The primary crops being sugarcane, subtropical fruit, maize and potatoes. Eight percent of the province is used for commercial forestry and only 3% for conservation (Hoffman and Ashwell, 2001). Over time there has been a decline in land used for grazing and crops and an increase in forestry and conservation. Communal areas are significantly more degraded then commercial farming areas, evident in steep, sloping parts of the escarpment. Gully and sheet erosion affect croplands, grazing lands, commercial forestry and settlement areas. Community regions are most affected by land degradation evident in widespread erosion and degraded grazing land. The amount of soil degradation in some commercial croplands of KwaZulu-Natal are decreasing due to minimum tillage and applying agricultural legislation. However, many communal areas suffer from a lack of funds, education and have insufficient access to land, factors which have culminated in overstocking and poor cultivation practices which has led to high levels of soils erosion. Figure 3.1 (Ezemvelo KZN wildlife, 2011) illustrates the diversity of land uses in KwaZulu-Natal.

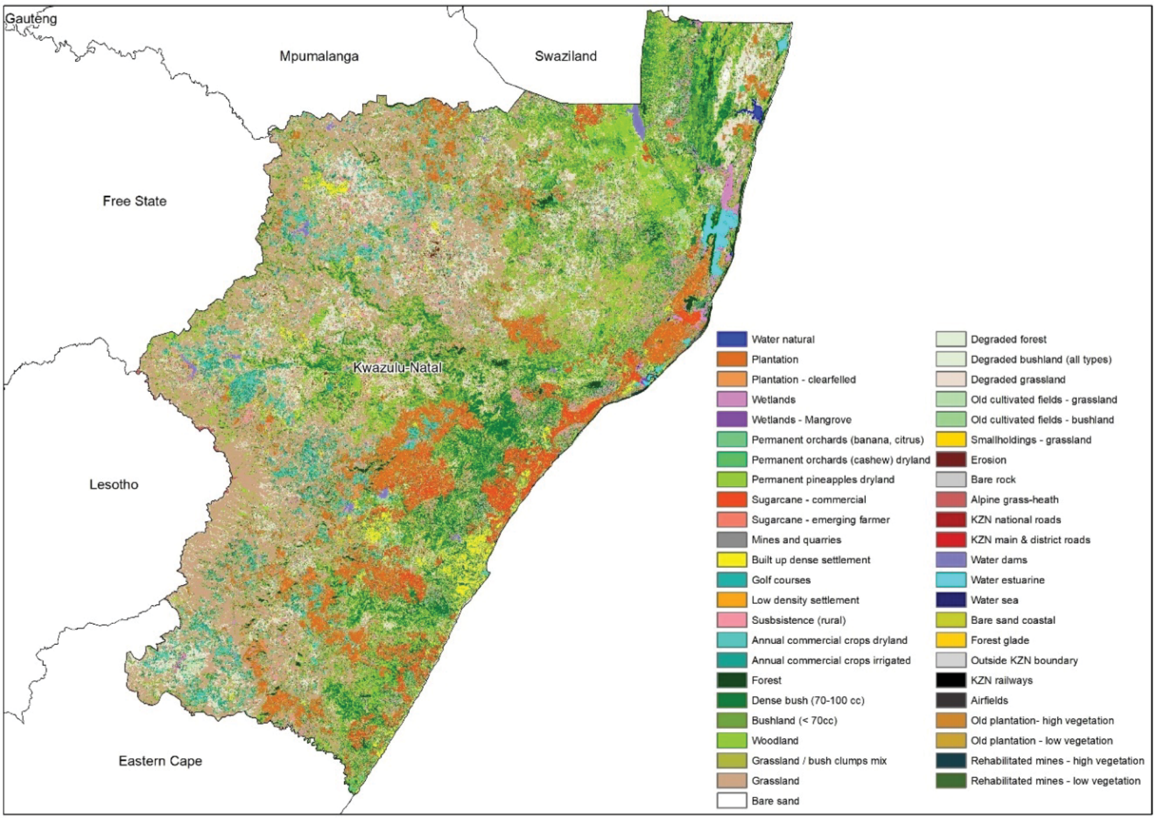

Figure 3.1 Land uses in KwaZulu-Natal (Ezemvelo KZN Wildlife, 2011)

A. mearnsii (hereafter referred to by its common name of 'black wattle') is a fast growing, nitrogen fixing tree which is often used in commercial agroforestry (Moyo *et al*., 2009). In the mid-nineteenth century the species was imported to South Africa from Australia where it originates from where is has been widely planted (De Wit *et al*., 2001). Currently the species supports a small but very valuable industry, for building materials, charcoal, and firewood for rural people, commercial forestry and associated industries for example tanning products (De Wit *et al*., 2001: Moyo *et al*., 2009). Black wattle thrives in areas that exceed 500 mm annually. There is currently over 130 000 hectares of black wattle commercial forests in South Africa, these are specifically located in the provinces of KwaZulu-Natal, Mpumalanga, and previously the Eastern Cape which have subsequently been abandoned. According to Moyo *et al*., (2009) riparian ecosystems are highly threatened by *A. mearnsii* due to their nutrient availability and their ability to disperse. According to the South African Plant Invaders Atlas Datasheet, tall trees are one of the most common invaders of riparian areas, with *A. mearnsii* being the most recorded invader and is one of the top ten most invasive species in South Africa, with an estimated 2.5 million hectares being invaded (Holmes *et al*., 2008, Moyo *et al*., 2009). *A. mearnsii* is said to have negative impacts upon the functionality of riparian ecosystems and further impacts on biodiversity and water resources (De Wit *et al*., 2001). A conflict of interest therefore exists, where there is the damaging invasive effect on one hand which gives rise to future costs to society, and a commercial value on the other that provides economic value – a true paradox species.

Commercial forestry has destructive impacts that are often unavoidable and allows invader species to encroach into areas zoned for water production and conservation (De Wit *et al*., 2001). Black wattle is one of a number of invasive species in South Africa that is considered to have increased river bank erosion as it is less well adapted to flash floods than native plants (Macdonald and Richardson, 1986).

Soil erosion in South Africa is most prevalent along the eastern side of the country (Figure 3.2), with KwaZulu-Natal having the second highest provincial soil degradation. Erosion risk classes are the highest in Eastern Cape, KwaZulu-Natal and Limpopo (Figure 3.2) and the risk of potential erosion is again high in KwaZulu-Natal (Figure 3.3). There is some correlation between the higher rainfall, slope and runoff distribution throughout South Africa (Figure 3.4) and the higher erosion risk areas. However, this is drastically enhanced by land management practices. Given the higher potential for erosion in KwaZulu-Natal and a history of poor land management, this province is a practical location to pursue soil erosion measurements.

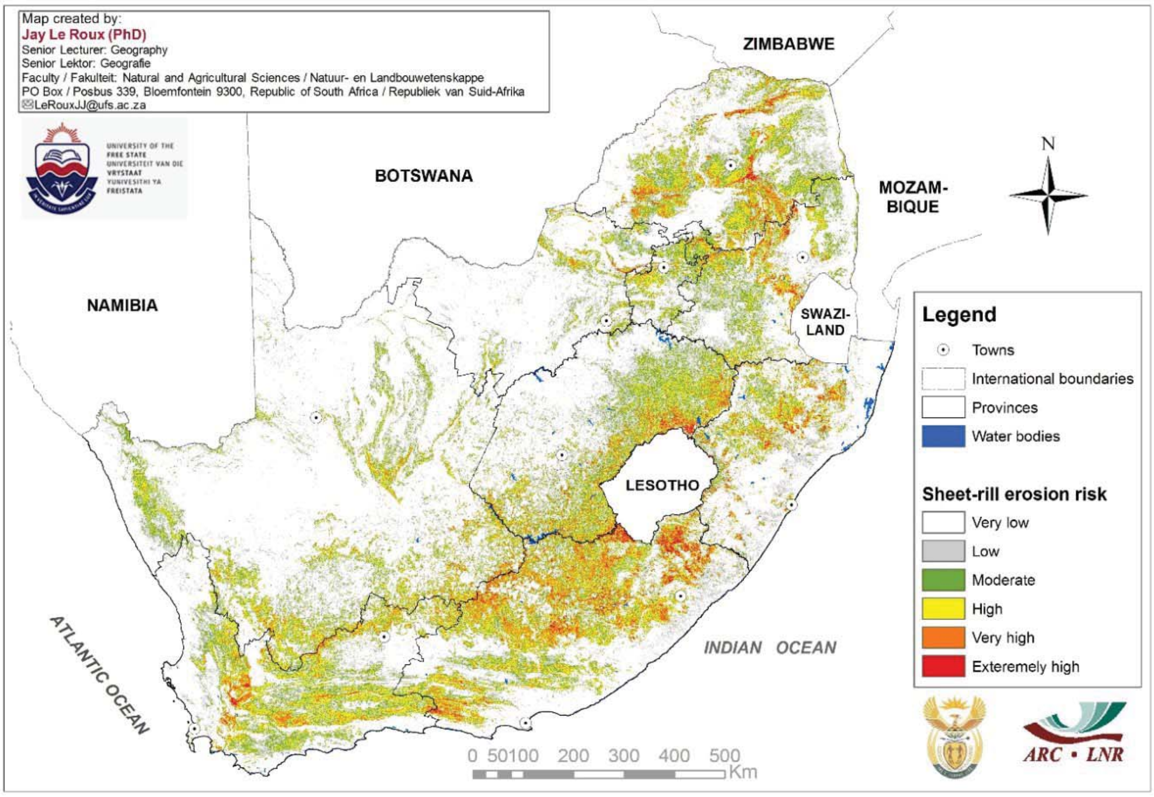

Figure 3.2 Sheet-rill erosion risk map of South Africa (Le Roux, et al., 2008)

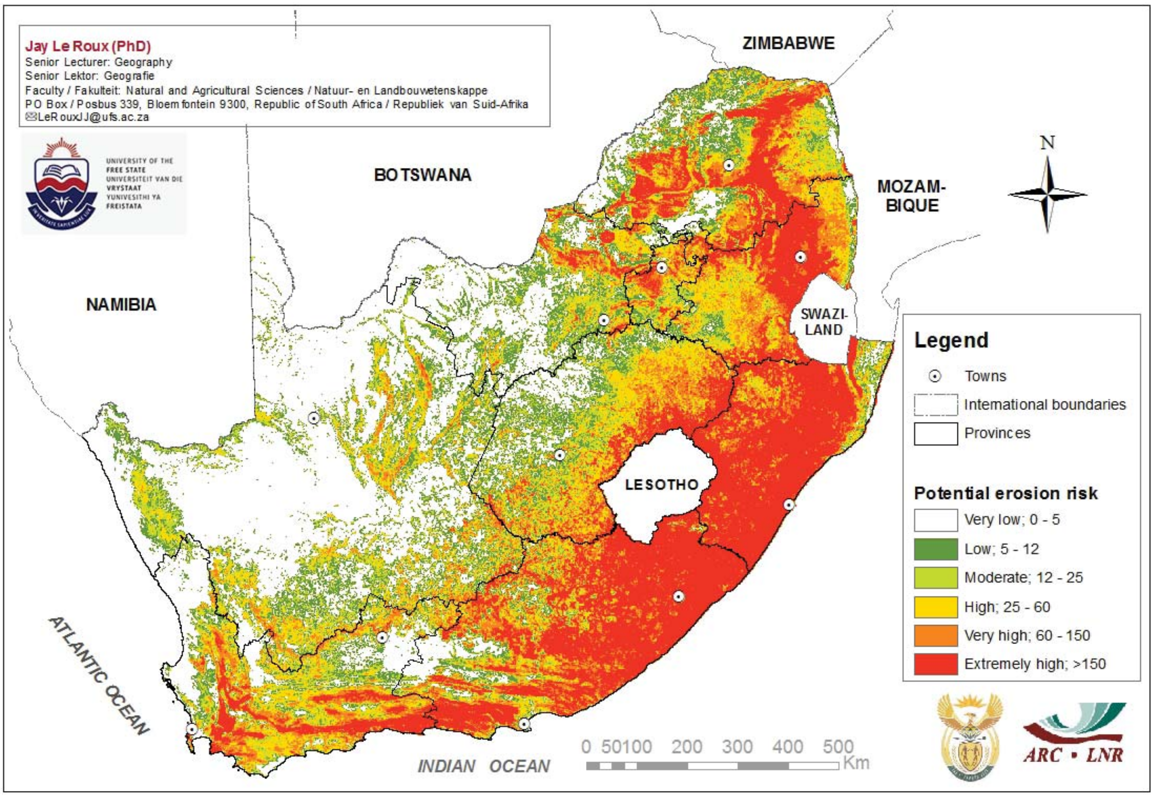

Figure 3.3 Potential soil erosion risk of South Africa (Le Roux, et al., 2008)

3.2 Climate

The climate in KwaZulu-Natal is conducive to erosion, with a relatively high mean annual precipitation and air temperature. The mean annual precipitation (MAP) varies between 255 and 1923 mm (Figure 3.4) with most rains falling in the summer months (October to March), although there are occasional winter showers. The national average MAP is approximately 450 mm per year. The peak rainfall months are December to February in the inland areas and November to March along the coast of the province. The prevailing weather patterns are predominantly orographic, where warm moist air moves in over the continent from the Indian Ocean, rises up the escarpment, cools down and creates rainfall. Rain shadows occur in the interior valley basins of the major rivers where the annual rainfall can drop to below 700 mm. Due to the high amount of precipitation, high volumes of runoff are experienced which leads to increased erosion (Figure 3.4). These climatic conditions make KwaZulu-Natal an ideal province to investigate soil erosion as the conditions are ideal for soil erosion.

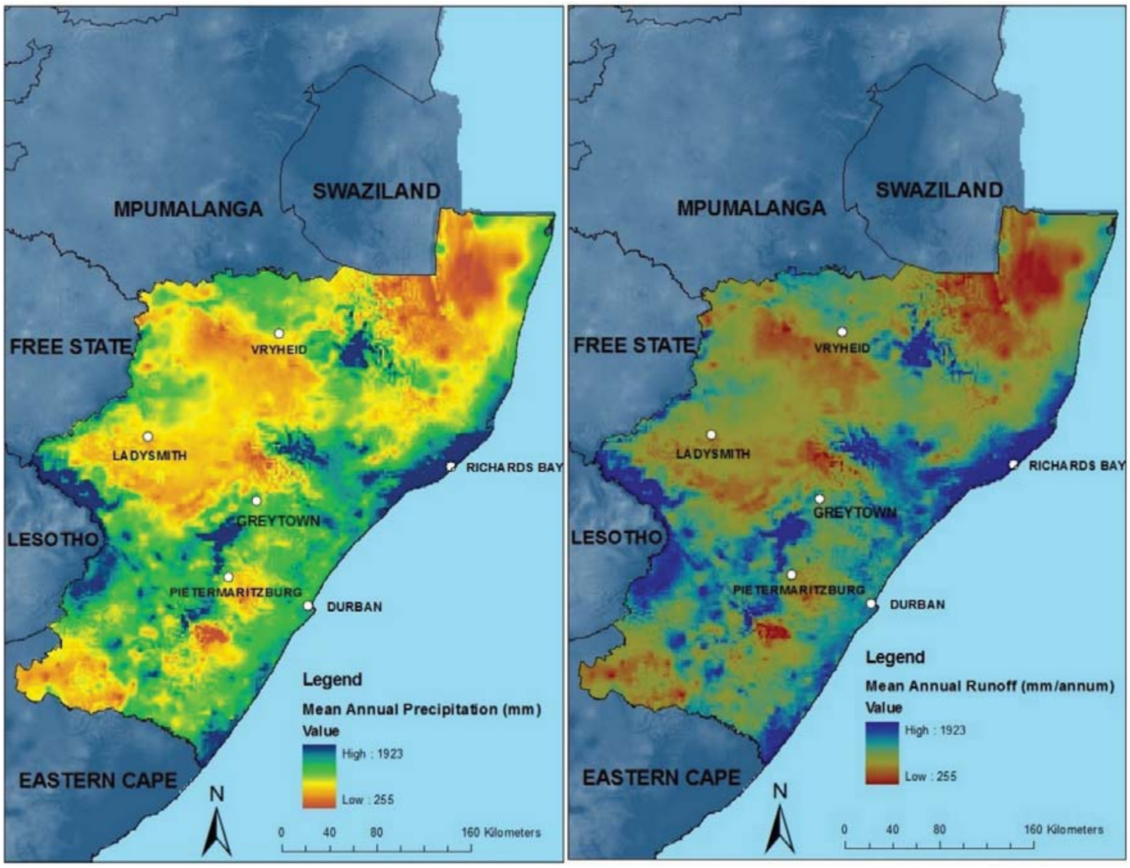

Figure 3.4 Mean annual precipitation and mean annual runoff distribution in KwaZulu-Natal

3.3 Final Selection

Through the selection criteria, three suitable sites were chosen. One of these catchments is funded by the DEA (Okhombe), the second by Working for Water and WRC (Two Streams). An additional site, Fountainhill Estate, was selected due to an ongoing research relationship with UKZN and ideal landuse treatments within the farm area. Okhombe is located within a rural sourveld area in northern Drakensberg. Two streams located in a catchment dominated by commercial forestry and sugarcane, between New Hanover and Greytown. Fountainhill Estate is a private farm with natural grassland, pastures and maize, within the eastern extent of the uMgeni catchment (Wartburg). The techniques used within each site are described further in section 5.

Erosion and sediment yield are variable across and between catchments. However, for practical reasons, measurement has to be limited to research catchments that can be used for model development and application beyond the research catchments. Formulating recommendations and guidelines for model application of erosion and sediment yield for application at areas outside the research catchments is an outcome that will be beneficial to numerous applications including risk assessment and design, amongst others.

The primary catchment area for this study was the Two Streams catchment situated near Seven Oaks, 20km outside Greytown. The Bioregion for the area is ‘midlands mistbelt grassland’, and is characterized by an undulating rolling landscapes, a large proportion of which is arable. It is dominated by forb-rich, tall, sour *Themeda triandra* grasslands of which only a few patches remain due to invasion of native *Aristida junciformis.* The soil formations are apedal and plinthic and are derived mainly from the Ecca Group with dolerite dykes and sills. The rainfall occurs predominatly in summer with an annual rainfall that ranges from 659 to 1139 mm.

A number of study sites have been established across the catchment area, with some sites and research infrastructure being well established during the course of previous research projects. For example, a weir was constructed in 1999, an Automatic Weather Station (AWS) was setup in 2006 and boreholes were drilled in 2001 and 2007. This current project thus benefited extensively from these established sites and they have been refurbished and maintained during the course of this project. However, to fulfil the specific objectives of this project a number of new sites and monitoring strategies were implemented.

This catchment’s location is a one-hour drive from the University of KwaZulu-Natal, Pietermaritzburg campus, making it accessible for data to be collected regularly. The land cover consists primarily of commercial timber and sugar cane thus being ideal to investigate the different land-uses and compare the formation of soil erosion between the two. An added advantage was the established relationship with MONDI the owners of the plantations and who agreed to operate within the requirements of the project by conforming to different management plans in terms of the harvesting, clearing up, planting and burning. Different strategies and management regimes have been applied to different locations of the catchment.

4: THE STUDY AREAS AND ESTABLISHED SITES

4.1 Two Streams

The bioregion for the area is 'midlands mistbelt grassland', and is characterised by an undulating rolling landscapes, with a large proportion of the land being arable (Clulow *et al.*, 2011). It is dominated by forb-rich, tall, sour *Themeda triandra* grasslands of which only a few patches remain due to invasion of native *Aristida junciformis.* The soil formations are apedal and plinthic and are derived from the Ecca Group with dolerite dykes and sills. The land cover consists primarily of communal land in the inland areas, commercial timber in the upper reaches of the Mvoti catchment and dryland and irrigated sugar cane along the coastal strip. Summer thunderstorms or cold fronts cause most of the rain with an annual rainfall ranging from 659 to 1139 mm (Clulow *et al.*, 2011). Mist can be heavy and frequent and might add significantly to precipitation. Moderate frosts, droughts, hail and berg winds are common and the average number of heavy frost days per annum range from 31 to 60 days for inland areas.
The soils are underlain by well weathered sandstone saprolite generally to a depth of 4-5 meters. The Inanda profile is situated in a lower midslope position with a slope of approximately 4%. The Magwa profile is situated on a slope of 0.25% at the footslope just above the valley bottom, where the Katspruit soil is located. There is a high humus content in the A horizons. This is attributed to the hydrophobic nature of the A horizons in this catchment. In most cases water repellence in soils can be attributed to coatings on the soil particles of hydrophobic substances of organic origin, especially under wattle plantations. A soil map for the area can be retrieved from (Le Roux *et al.,* 2015).

Two Streams is a thirty-four hectare catchment which has had a number of study sites established across the catchment (Figure 4.1). Over the last fifteen years the catchment has been intensively instrumented and the hydrology of the catchment monitored. Some sites have been well established during the course of previous research projects. For example, a weir was constructed in 1999, an Automatic Weather Station (AWS) was setup in 2006 and boreholes were drilled in 2001 and 2007. This current project benefited significantly from the established sites which were refurbished and maintained during the course of the project. However, to fulfil the specific objectives of this project a number of new sites and monitoring strategies were implemented.

Following a previous clear felling of the catchment in 2005 there was a single rainfall event of nearly 90 mm observed (Clulow *et al.*, 2011) which caused widespread erosion across the exposed areas and sedimentation of the weir and riparian areas. The hypothesis contributing factors were the intensity of the rainfall, the large areas of bare soil, water repellent soils, slope and lack of management strategies to reduce runoff. In 2010, widespread burning in the catchment during winter for firebreaks and burning of slash piles caused severe damage to the soil due to the heat of the fires. For six months following these burns, severe erosion and sedimentation was observed in the catchment (Clulow *et al.*, 2011). The monitoring and research from this site were to establish results prior to harvesting and the intention is for more research to continue post-harvest to analyse the land use change and management.

There is over 3 million hectares of commercial forestry in South Africa with consequences of on-going erosion and sedimentation which contributes to the sedimentation of rivers and dams in South Africa and significantly reduces the nutrient and carbon stock within the soils. This project used runoff plots or varying size, in different locations of the Two Streams catchment before clear-felling to determine the sediment loads of slopes in an afforested catchment. Mondi are the owners of the plantations and operated within the requirements of the project by conforming to different management plans (determined in consultation with Mondi) in terms of the harvesting, clearing up, planting and burning. Different strategies and management regimes were applied in different locations of the catchment.

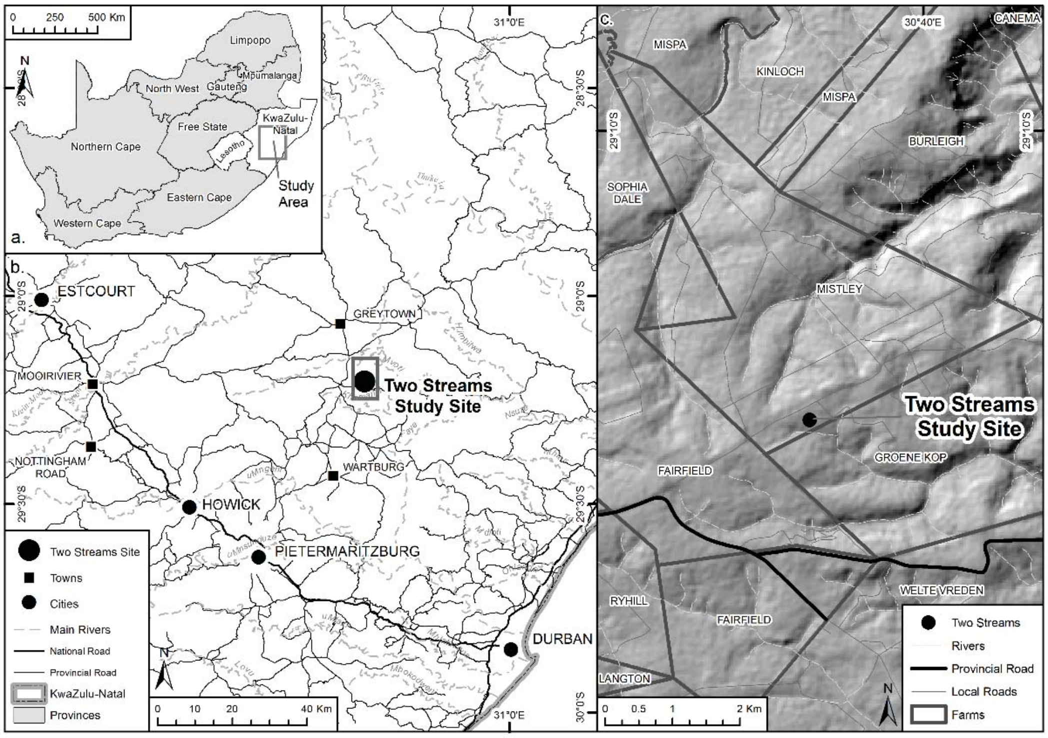

Figure 4.1 Location of the Two Streams research catchment

4.2 Fountainhill Estate

Fountainhill Estate is an established private commercial farm (Kort Kranz Kloof) and nature reserve, adjacent to the town of Wartburg (Figure 4.2). The property comprises of approximately 2 200 ha, of which approximately 780 ha is dedicated to commercial cropping (sugar cane & avocados) and the balance to conservation of the biodiversity of the uMgeni catchment. The area is a mix of Valley Thicket Biome and Natal Central Bushveld Savanna Biome (Low and Rebelo, 1996). Over the year's degradation of the land and its resources has occurred through erosion and over-grazing. This was particularly the case with the farm Georgenau, which had been managed by German Lutheran missionaries. Land rehabilitation was conducted during the period of 1969-1979. There is an ongoing relationship between Fountainhill Estate, the Institute of Natural Resources (INR) and the University of KwaZulu-Natal.

The Fountainhill Estate is at latitude 29.45260 S and longitude 30.54617 E at approximately 890 m above sea level. The catchment is within Quaternary Catchment (QC) U20G of the uMgeni catchment. Four runoff sites were installed at the site and are currently being monitored under four different landuse types (Figure 4.3).

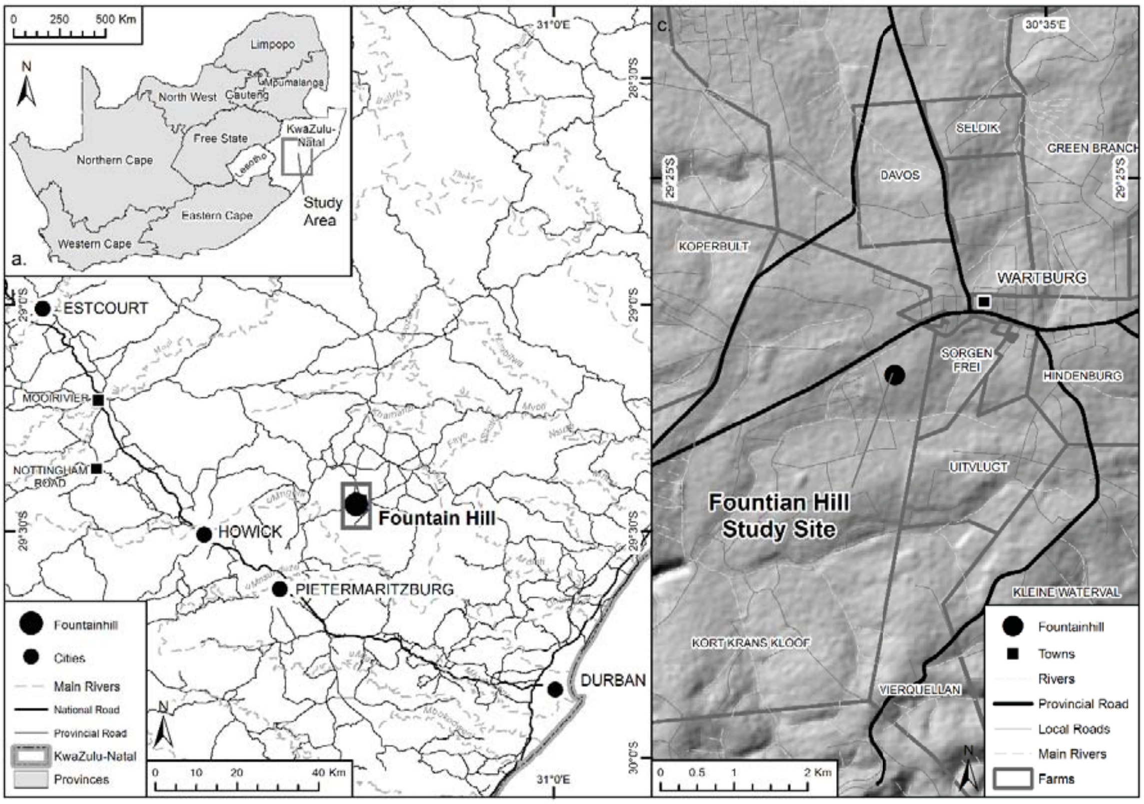

Figure 4.2 Location of Fountainhill Estate research farm

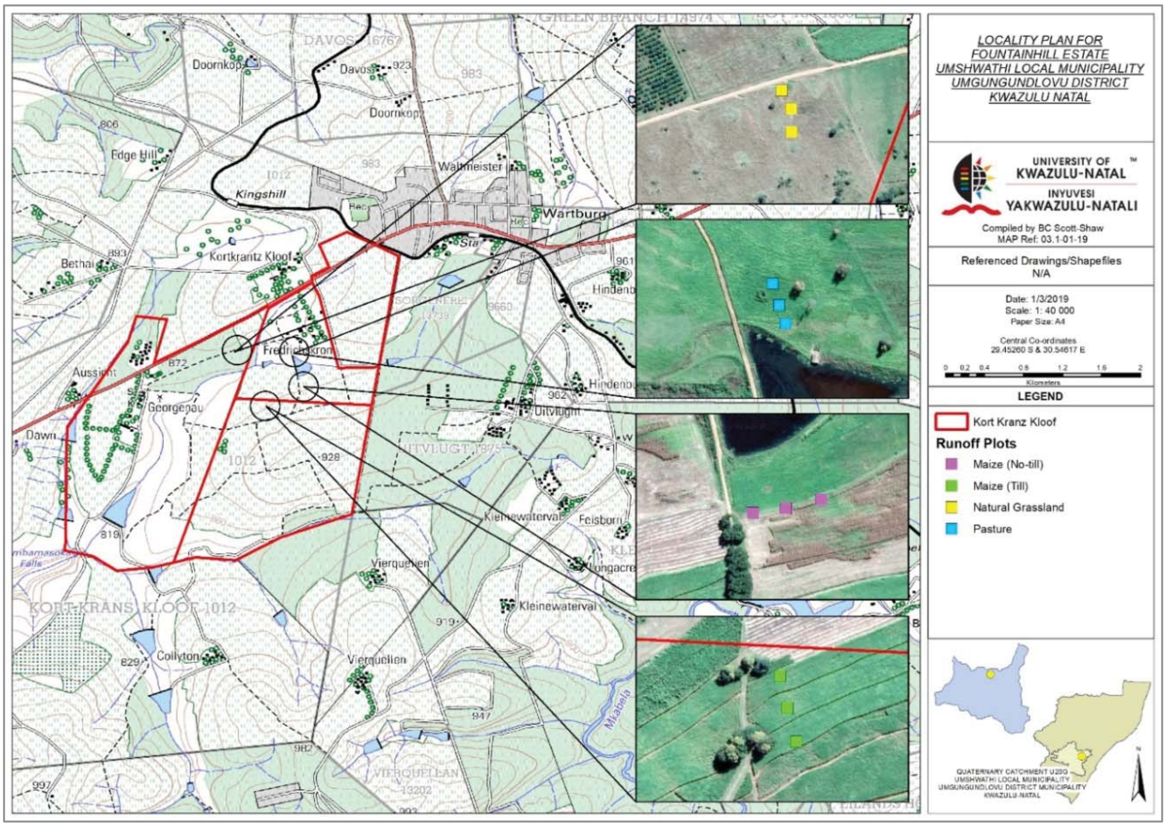

Figure 4.3 Location of Fountainhill Estate and the ongoing runoff plots

4.3 Okhombe Community, Natal Drakensberg

The study area covers part of the catchment of Okhombe (28°42° S; 29°50° E), located in the Upper Thukela catchment area in the province of KwaZulu-Natal, South Africa (Figure 4.4). The climate is sub-tropical, humid and with a summer rainfall (October–March) (Schulze, 1995). At Bergville, located 10 km to the east of the study site, the mean annual precipitation is 684 mm per annum, potential evaporation 1600 mm annum^{-1} and a mean annual temperature of 13 °C (Schulze, 1997). The dominant geology consists of rock types of Triassic and Permian age, belonging to the Beaufort Group (Verster, 1998). The plateau consists of sandstone of the Tarkastad formation whereas the lower area consists of sandstone, mudstone and shales of the Adelaide formation. In the lower reaches, dolerite is present. The Okhombe valley is located between 1000 and 1500 m amsl and rainfall is between 800–1000 mm annum^{-1}.

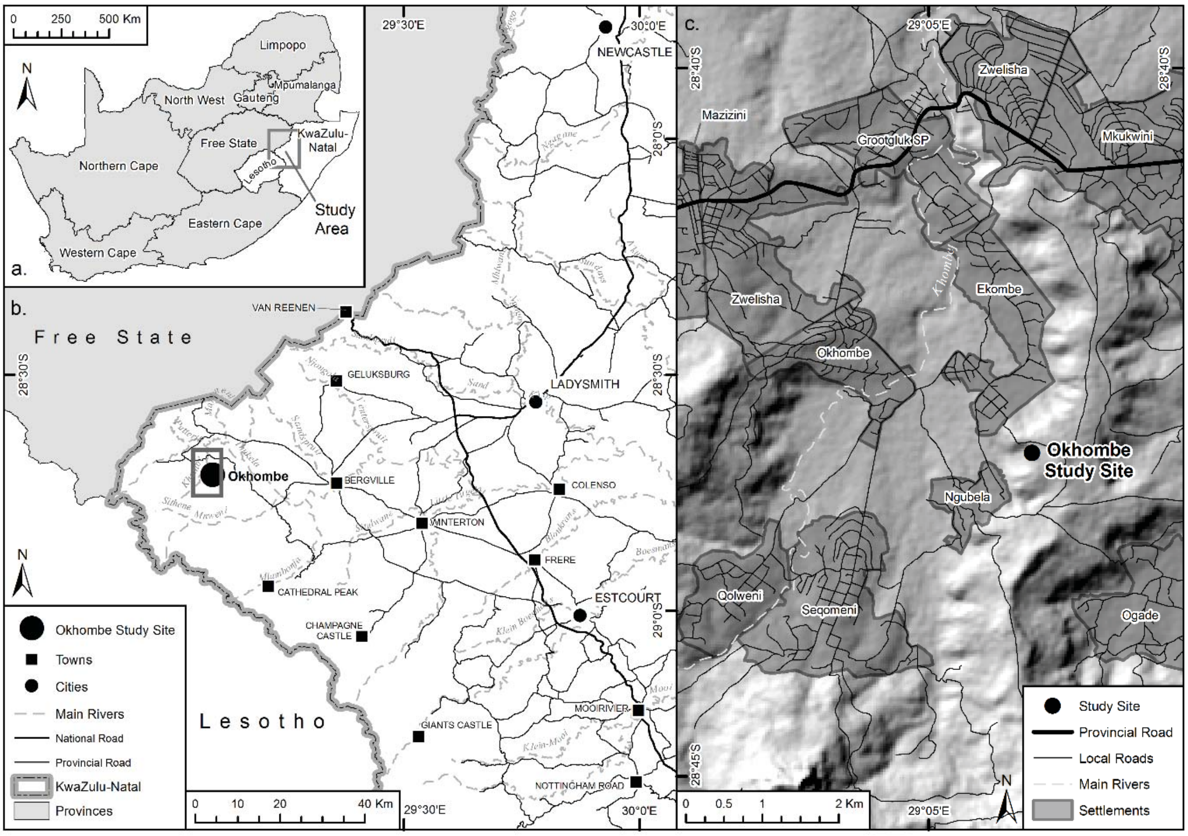

Figure 4.4 Location of the Okhombe catchment in South Africa and one of the potential study sites within the catchment

Soils developed from sandstones and dolerites are Acrisols and Inanda soil form (Soil Classification Working Group, 1991). Within hillslopes, deep Acrisols (∼2 m) characterize footslopes and bottomlands. Bottomlands exhibit features of waterlogging such as a surface dark grey (2.5YR4/1) A horizon, enriched in organic matter and the presence of redoximorphic features (Soil Survey, 1999) from the soil surface to 2 m depth. These soils show a massive structure. Horizons are compact (1.4 < BD < 1.6), except the A horizon with a BD of 0.8. At the footslope position, the soils are well drained. The humiferous A horizon is dark reddish brown (5YR 3/3), blocky and friable. The Bw horizon, from 0.4 to 0.9 m is dark reddish brown (2.5YR3/4), massive and clayey. A sandy saprolite is reached at about 1.7 m. The midslope position exhibits a similar soil profile but much shorter, the Bw being found between 0.3 and 0.6 m and the saprolite from 0.9 m. The soils at the terrace (T) and the shoulder (SD) developed from dolerites. Both soil profiles show a dark reddish brown (5YR 3/3) A horizon with a clear fine angular blocky structure. The Bw is red (2.5YR 4/6) and is 0.9 m thick (0.5–1.4 m) at T and 1.25 m thick (0.45–1.7 m) at SD. A sandy red (10R4/8) saprolite was reached below followed by a brownish yellow (10YR 6/8) at about 2 m deep. The situation T differs from the SD by a high proportion of blocks from the A horizon to the saprolite. Finally, the SD situation shows a 0.1 m brown (7.5YR 4/4) friable humiferous horizon with a substructure fine angular blocky. The Bw horizon found from 0.5 to 1.4 m is yellowish red (5YR5/7), friable and massive. It exhibits a sharp limit with a cohesive saprolite of sandstones.

The Okhombe catchment was re-planned for agricultural production in the early 1960s (Von Maltitz, 1998). Mountain slopes and plateaus were designated as communal grazing land, the people were forcibly removed to one of six closer settlements (sub-wards) at the foot of the slopes and lower areas adjacent to rivers were designated for cropping. Grazing camps, surrounded by fences, were designed for the communal grazing areas to accommodate different types of cattle in different parts of the camp. Currently, these grazing camps are being re-established but there has been a long period where there has been no control of the movement of cattle. Furthermore, the lack of security and herders and theft have led to the situation that most cattle are kept near the homestead and are daily moved up and down the slopes. This, combined with the highly acidic low productive soils, rapidly leads to overgrazing with decreasing proportion of soil surface coverage by the vegetation and associated increase of bare soils. The Okhombe community, consisting of about 4000 inhabitants, relies heavily on the surrounding natural resources for its daily living.

4.4 Conclusion

Three sites were used during this study, all well-established sites in which previous Water Research Commission projects have occurred and in which an existing research infrastructure exists. Two Streams was used for commercial plantation and crop (sugarcane), whilst Fountain Hill estate had subsistence agriculture (till and non-till maize) and grasslands (natural and pasture) set-up, and Okhombe valley was the site chosen for investigating cattle path surface and gulley erosion.

5: METHODS

A detailed overview of the experimental design for each site is provided in this section. Detail on site specific catchment and erosion monitoring at Two Streams, Okhombe and Fountain Hill Estate has allowed for comprehensive findings that address objectives 1 and 2. Subsequently, the implementation of two sediment yield models (using site observations) allowed for the research to be extrapolated into a catchment management tool. The modelling component addresses objective 3. To meet the aforementioned objectives, the following land uses were considered at each site:

- Commercial plantations;
- Commercial sugarcane;
- Grasslands (natural and pastures); and
- Subsistence agriculture (till and non-till).

5.1 Experimental Design

To meet the requirements of the objectives at Two Streams and Fountainhill Estate, three scales of spatial analysis were implemented. These were:

a) Micro-plots (nine 1 m^2 runoff plots were installed at three different hillslope positions).
b) Runoff plots (nine 10 m^2 runoff plots were installed at three different hillslope positions).
c) 34 ha catchment (An ISCO sampler was installed, from which flow height is recorded by a data logger. An automatic water sampler was located at the outlet of the catchment).

The installation of plots and microplots at different hillslope positions, and in conjunction with a data-logger for runoff and rainfall, accounted for the spatial and temporal variations of overland flow in the catchment. The frequency of site visits depended on the frequency and intensity of the rainfall events. High frequency and high intensity rainfall events required regular visits to the research catchment to collect rainfall and ensure that the equipment was maintained.

5.1.1 Meteorological station

Two long-term automatic weather stations (AWS) are located within the Two Streams research catchment. One monitors a flat uniform grassland area to meet the requirements for FAO 56 reference evaporation calculations. The second AWS is located above the *Acacia mearnsii* canopy to provide a measure of the gross rainfall for the catchment.

At each runoff plot additional rainfall data was obtained through the use of manual rain-gauges which are located next to at all the plots (Figure 5.1). Rainfall data may vary spatially within the catchment and the amount of rainfall data may vary from rain-gauge to rain-gauge. The rain gauges were installed 2 m above the ground within the *Acacia mearnsii* stand and sugar cane fields to represent the amount of rainfall that reaches the surface (throughfall).

Figure 5.1 Manual rain gauge to measure the amount of rainfall hitting the ground

5.1.2 Microplots (1 × 1 m)

Nine 1 m × 1 m overland flow microplots were installed within each land use type. The microplots were installed at three topographical or landscape positions with varying degrees of steepness (Figure 5.2). The metal borders surrounding the micro-plots were inserted at a depth of 0.1 m in the soil. The microplots were installed parallel to the slope direction. This allowed for any overland flow that was generated to be directed down the slope and into the gutter of the micro-plot. The gutter is designed to channel and concentrate water into the bottom of the gutter. The gutter feeds into the outlet of the micro-plot. This outlet was connected to a pipe, which feeds into a bucket to capture the water that is generated by the overland flow. After each site visit, total overland flow volume (R) from each microplot replicate was measured with a measuring cylinder, allowing for a 500 ml sample of the water from the overland flow to be taken. In addition, soil trapped in the gutters was collected.

Figure 5.2 Example of a microplot at Two Streams

5.1.3 Standard Runoff Plots (5 × 2 m)

Nine 5 × 2 m² runoff plots were installed adjacent to the microplots, with three replicates per slope position (Figure 5.3). The metal borders surrounding both the microplots and runoff plots were inserted in the soil to a depth of 0.1 m. All plots were installed parallel to the slope direction. This allowed for any overland flow that was generated to be directed down the slope and into the gutter of the plot. The gutters of all the plots had rain shields to prevent direct rainfall into the gutter which would compromise the results of the study. The gutter was designed to channel and concentrate water into the bottom of the gutter. The gutter feeds into the outlet of the plot. This outlet was then connected to a pipe which feeds into a JOJO tank which stored the overland flow water (Figure 5.4). A bucket was placed within the tanks, making it easier to measure the volume of small rainfall events (Figure 5.4).

Figure 5.3 Standard plot (5 × 2 m) installed at Two Streams

After each site visit, total overland flow volume (R) from each plot replicate was measured manually using a measuring cylinder. If the water overflowed into the JOJO tank the volume was measured by using πr^2 where the dimensions of the JOJO tank were known, calculating the depth of the water and a 500 ml sample of the water for extrapolation. Soil trapped in the gutters was also collected.

Figure 5.4 JOJO tank gathers the sample (left) and fills the bucket below the runoff plot (right)

At three of the plots representing each landuse type and landscape position (described further in section 5.1.7 and chapter 6), the outlets of the plots were connected to a pipe which fed first into a tipping bucket system before being collected in the bucket inside the JOJO tank. At the three locations, the tipping bucket mechanism were connected to a HOBO event-logger (Pendant logger). The tipping bucket mechanism were designed to measure 2 litres for the 5 m × 2 m runoff plots. In addition, the specific time at which the tip occurred, was logged (Figure 5.5). This ensured that the exact temporal response of each individual microplot location (in terms of overland flow) was measured after the onset of a rainfall event. The intensity of the overland flow was calculated.

Figure 5.5 Tipping bucket connected to a hobo logger to measure amount of runoff

5.1.4 Catchment Monitoring

To study catchment scale processes, an ISCO sampler was installed at the gauging weir outlet to allow for the integration of the total sedimentation load from the catchment. A existing V-notch weir (13-year record of streamflow) was located at the catchment outlet (representing approximately 50 ha). The logger was coupled to an ISCO 6712 and 3700 series automatic sampler. The height of flow at the catchment outlet was logged by a datalogger and converted to runoff using a site-specific rating curve derived for the site. Catchment water quality (nutrients and sediments) during both baseflow and stormflow events were measured by collecting samples at the appropriate locations on the hydrograph curve.

Figure 5.6 Compound V-notch weir located at Two Streams

5.1.5 Water quality analysis at each scale

Water samples were collected at the different spatial scales and used to assess water quality of the runoff. Water samples were collected manually (from runoff collecting buckets at the micro-plots and plots). The water quality constituents are the Nitrates-Nitrogen ($NO^{3-}N$), Total phosphorus (P), Dissolved Organic Carbon (DOC) and Particulate Organic Carbon (POC). POC was defined as the fraction of carbon which had been bonded onto soil particles and then subsequently eroded, POC included any organic matter which had been eroded. DOC was defined as the fraction of carbon which has been dissolved into solution by rainfall and soil water. Water samples were collected in the field by taking 500 ml samples and stored in a cooler box on-site. Once back at the laboratory, samples were stored in a fridge, which was kept at a constant temperature of 4 °C until completion of analysis.

5.1.5.1 Sediment analysis

Water samples were filtered using Ø 47 mm filter paper, the filtered sample was dried at 110°C for 24 hours. Samples were placed in a furnace at 550 °C for 2 hours to burn off the organic matter. This was then multiplied by the volume of water (l) to determine the sediment concentration (g/l). The sediment yields for each nested scale were calculated by multiplying the sediment concentration (gl^{-1}) by the runoff flux per unit area (l/m^2).

5.1.5.2 Nitrates (NO^{3-}) and total phosphorus measurements

NO^{3-} and P concentration in water samples were obtained, using an AQUALYTIC spectrophotometer AL800. The absorbances of the water samples were read, using an AQUALYTIC spectrophotometer AL800 and converted to concentrations (given as mg/l but converted to g/l), using frequently calibrated standard curves. The accuracy of all nutrient analyses was within 10 % of the actual concentrations. Concentrations were converted to yields (in g/m^2) by multiplying the concentrations by the runoff flux per unit area (l/m^2).

5.1.5.3 Dissolved organic carbon

Dissolved organic Carbon (DOC) was determined using a Shimadzu TOC- 5000 analyser with an ASI-5000 autosampler and Balston 78-30 high purity total organic carbon (TOC) gas generator. In this technique, the organic solutes were converted to CO^2 and the CO^2 produced was measured as DOC (in g/l). Concentrations were converted to yields (in g/m^2) by multiplying the concentrations by the runoff flux per unit area (l/m^2).

5.1.5.4 Particulate carbon and nitrogen

Sediments were dried at 105 °C for 24 hours. The sediments were weighed to determine the sediment concentration in runoff and subsequently to compute sediment losses. Sediment samples from these aliquots were dried and stored for further analyses of total soil organic carbon and nitrogen. C and N were estimated, using a LECO CNS-2000 Dumas dry matter combustion analyser. The output from this analysis Particulate organic carbon (POC) and particulate organic nitrogen (PON) was given as a percentage of total soil analysed. This percentage was then used to calculate the yields of POC and PON in (g/m^2) by multiplying the sediment yield (in g/m^2) by the percentage of POC and PON.

5.1.5.5 Water repellency

Water repellence was measured at each of the runoff plots and the micro-plots during the sampling period. This was done by adding a drop of deionised water (approximately 6 mm diameter) from a height of 1.5 cm on to the surface of the soil. Indications of water repellency occurred if the drop adopted a spherical shape on the soil surface. The length of time the drop remained on the surface was taken as the index of water repellence. This procedure was repeated three times at each microplot and runoff plot to improve the reliability of the measurements.

5.1.6 Rainfall simulation

A workshop demonstrating the use of a rainfall simulator and on-site experimentation was implemented to inform community members of the severity and impact of land use management on soil erosion and cattle access paths. The rainfall simulations were used as a demonstration tool in a workshop to demonstrate the primary driving factors of land degradation.

Rainfall simulation trials were carried out on cattle access paths, rehabilitated paths and what is described as ‘natural’ grassland, all within the same micro-catchment and on comparable slopes. The methods for the rainfall simulation was very specific with importance placed on calibration, for consistency and protocol to accurately record erosion rates for specific rainfall intensities and allow for comparability between simulations, trials and sites (Podwojewski *et al*, 2010).

Two separate calibrations were carried out; one with the plot level to the ground to determine consistent flow rates and a second with the plot at the angle of the slope to determine flow rates on varying slope angles as evident on the access paths. This was undertaken to accurately determine the rate of ‘artificial’ rainfall being applied to the slope as there are many factors that can influence the rainfall rate. The plot was calibrated at the horizontal to the correct rainfall rate to replicate a particular rainfall rate on the slope. The two rainfall intensities used for the simulations was 30 mm/h and 60 mm/h, described by Nel and Summer (2007) as the average and extreme values for rainfall in the area. The second calibration was to correct for the slope and as less rainfall would fall on the plot, due to the reduction in surface area, which needed to be accounted for when determining the infiltration rates and runoff rates.

The simulations were run for 10 minutes to wet the soil and then stopped for 10 minutes to create an air gap between the infiltrating water and the soil surface (Podwojewski *et al.*, 2010). During the 10 minute break a 100% runoff plot was placed over the 1 m^2 runoff plots to determine the exact intensity of the rain simulation. The simulator was run for 1 minute and all runoff collected to determine the intensity over time. After the 10 minute break, the simulation was started and ran for 20 minutes. After the first 20 minute simulation the simulator was stopped and the intensity rechecked on the 100% runoff plot placed over the 1 m^2 runoff plot. Twenty-four hours later the simulator was re-run at a higher intensity following the same procedure as the first simulation. The simulations were run on cattle access paths, natural grassland and rehabilitated access paths with the intention of understanding erosion rates and identifying the effectiveness of community implemented rehabilitation measures on the landscape. In conjunction with the scientific research that took place, community involvement was of paramount importance as the community members had been involved in land degradation mitigation and prevention through the various programmes implemented in the area.

Figure 5.7 Community meeting in progress demonstrating use of the rainfall simulator

5.1.7 Catchment monitoring summary

A summary of each technique used within this research project, the measurement area and recording period, the theoretical basis, the respective sites and landuse have been provided in Table 5.1. Further detail on the specific slope positions and tree or crop species is provided in chapter 6.

Table 5.1 List of measurement and monitoring techniques used within the three research sites

Method	Measurement area, distance or height	Averaging period	Description/theoretical basis/comment	Sites implemented		Representative Landuse
AWS & Reference evaporation	Point measurement (2 m above short grass) of solar irradiance, air temperature, wind speed, water vapour pressure.	Hourly/daily	Penman-Monteith method for reference evaporation estimation (FAO 56), and use of a crop factor (Allen *et al.*, 2006) for short grass (0.1 m tall) and tall crops (0.5 m tall)	Two Stream	✓	NG
				Fountainhill Estate	✓	NG
				Okhombe		N/A
Microplots	1 m^2	Event driven	Strategic topographical or landscape positions, installed parallel to the slope direction allowing for any overland flow to be captured and measured.	Two Stream	✓	SC & CP
				Fountainhill Estate	✓	M, NG & P
				Okhombe		N/A
Standard Plots	10 m^2	Event driven	Strategic topographical or landscape positions, installed parallel to the slope direction allowing for any overland flow to be captured and measured.	Two Stream	✓	SC & CP
				Fountainhill Estate	✓	M, NG & P
				Okhombe		N/A
ISCO 6712 and 3700 series	Catchment size (e.g. 73.3 ha at Two Streams	Hourly/daily	Integrates sediment load from the catchment. During both stormflow and base flow events, catchment water quality is measured by collecting samples at appropriate points on the hydrograph curve.	Two Stream	✓	SC & CP
				Fountainhill Estate		N/A
				Okhombe		N/A
Rainfall Simulation	1 m^2	≥ 10 minutes	Used in conjunction with micro-plots. A known rate of 'artificial' rainfall is applied to the surface. Calibrated intensities are used to derive a relationship between intensity and sediment runoff.	Two Stream		N/A
				Fountainhill Estate		N/A
				Okhombe	✓	NG
Water Quality Analysis	Strategic point measurements	As required	Manually collected from the micro-plots and plots. Constituents are the Nitrates-Nitrogen ($NO^{3-}N$), Total phosphorus (P), Dissolved Organic Carbon (DOC) and Particulate Organic Carbon (POC).	Two Stream	✓	SC & CP
				Fountainhill Estate		N/A
				Okhombe		N/A
Soil Analysis	Strategic point measurements	Once off	Taken for analysis at Cedara soil analytical laboratory, inclusive of soil texture, total carbon and nitrogen and soil fertility.	Two Stream	✓	SC & CP
				Fountainhill Estate	✓	M, NG & P
				Okhombe		N/A

**Note: Landuse classes are SC (sugarcane), CP (commercial plantations), M (maize), NG (natural grassland) and P (pasture).*

5.2 Erosion and Sediment Yield Modelling using MIKE SHE

This chapter details the methods employed to set-up, calibrate and validate the MIKE SHE current scenario model that simulated an approximate ten-year period from 14 February 2007 to 02 October 2016, and to set-up the MIKE SHE future scenario model that simulated from 14 February 2019 to 02 October 2028. Furthermore, this chapter details the analysis methods employed for both MIKE SHE scenarios. Due to the complexity of the MIKE SHE model and the detailed process taken in setting up the models (both current and future), this chapter provides a meticulous description of the set-up process. Furthermore, this chapter details the inputs of the MIKE SHE model, and in some cases these inputs were generated, and thus technically are results. These results were included in the methods chapter for ease of understanding of the process followed, as the MIKE SHE set-up comprises a number of interlinked sequential steps where one step is directly affected by the previous step. As such the methods chapter deals with the set-up and some of the input results generated, while the results chapters deal more with the modelled output results. In addition to the inclusion of input results, model screenshots (termed screen displays) of certain input parameters were also included for ease of understanding through visualization. The level of detail included has been done to exemplify the magnitude of inputs required and to show the researchers understanding and how she went about addressing all the input needs of the model. This study centres around the set-up of the MIKE SHE model and thus the detail in this section is important in illustrating what the set-up entailed and the work effort expended.

The MIKE SHE model set-up for the Two Streams study site incorporated the results of past research undertaken on-site (Clulow *et al.*, 2011; Kuenene 2013; Everson *et al.*, 2014). To-date, most research conducted on-site has been focused on the larger of the two sub-catchments (Clulow *et al.*, 2011; Kuenene 2013; Everson *et al.*, 2014) and as such, the MIKE SHE modelling study was restricted to the larger sub-catchment (Figure 5.8).

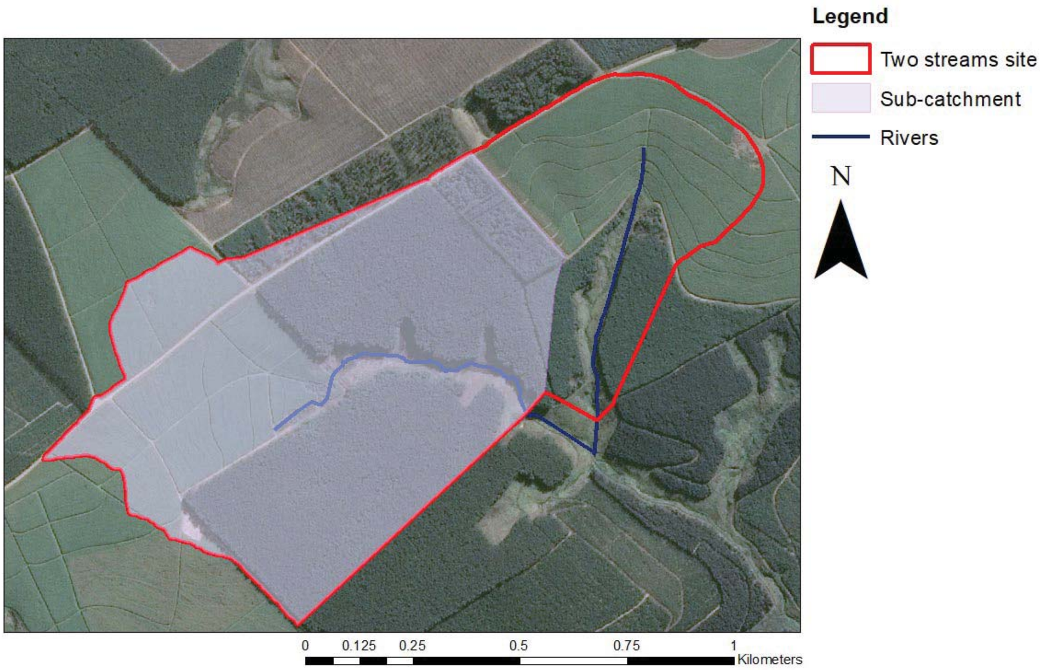

Figure 5.8 The Two Streams sub-catchment.

All data inputs for the MIKE SHE model were set to the same projected coordinate system - WGS 1984 UTM 36S to ensure spatial alignment of the datasets. All time series and spatial data inputs were either generated in, or converted to, MIKE SHE file formats (Table 5.2). Spatial datasets were all input in a MIKE SHE grid file format (Table 5.2) as opposed to the more conventional shapefile format and set to the same grid size, ensuring an exact fit of all grid cells. The grid file (raster) format enables easier modelling due to the regular structure of the grid (Hörmann and Floater, 2006). Thus, all shapefile data generated in ArcGIS software were first converted into a MIKE SHE grid series file (.dfs2) prior to being input into the MIKE SHE model.

Table 5.2 MIKE SHE file formats

Data record types	File format
Time series files	.dfs0
Profile series files	.dfs1
Grid series files	.dfs2/.dfs3
ET Vegetation Properties file	.etv
UZ Soil Properties file	.uzs

To convert a shapefile into a grid series file (.dfs2) the shapefile was first converted into an .ASCII file format. This conversion was completed in ArcGIS 10.3 using the *Conversion tool – From Raster to ASCII*, and then the grid series file was imported into MIKE SHE and converted into a .dfs2 file. To do so, the *MIKE Zero toolbox* was activated in MIKE SHE and the *Grd2Mike* tool was used. All other inputs that were required in specific file formats (e.g. time series files), were manually inputted directly into the MIKE SHE model (Table 5.3).

Table 5.3 The file formats used for the different data inputs (derived from external sources) as required by the MIKE SHE simulation modules

Simulated modules	Data inputs required	External sources of data	MIKE SHE file format used
Topography	DEM	• University of KwaZulu-Natal	.dfs2
Climate	Precipitation ET_{Ref}	• Food and Agriculture Organisation (FAO) AWS • Two Streams mast AWS • South African Weather Services (SAWS) AWS (refer to Table 4.3 for the locations of the AWS's)	.dfs0
Land use	Land cover map Vegetation properties	• University of KwaZulu-Natal • Clulow *et al*. (2011) • Burger (1999) and Dye *et al*. (2008)	.dfs2 .etv
OL	Manning number	• Morgan (2005)	.dfs2
UZ	Soil profile definitions Soil properties	• Kuenene (2013)	.dfs2 .uzs
SZ	Initial potential head	• University of KwaZulu-Natal • Clulow *et al.* (2011)	.dfs2

The MIKE SHE modelling software has three tabs in which the user works: the set-up tab; the processing tab; and the results tab. The set-up tab was used to input all data to run a MIKE SHE model, the processing tab was used to view all the data processed by MIKE SHE once the set-up was completed, and the results tab housed the results generated by the model that were compared to observed results from the sub-catchment. Data from both the processing tab and the results tab stored information for model calibration and validation used once the model set-up and run were completed. Two MIKE SHE model scenarios were set-up and run. The one scenario described the current scenario of the Two Streams sub-catchment and the second described the future scenario of the sub-catchment (with a change in vegetation from *Acacia mearnsii* to *Eucalyptus dunnii*). The MIKE SHE model set-up of both scenarios and model calibration and validation methodology are discussed below (Sections 4.3 to 4.5).

5.2.1 Model set-up

The MIKE SHE model set-up was complex, with a number of model modules and processes requiring a multitude of input data. The MIKE SHE model set-up was managed using a data tree, which assisted in managing the complexity of the modelling environment by displaying all modules included in the model: *display, simulation specification, model domain and grid, topography, climate, land use, rivers and lakes, overland flow, unsaturated flow, saturated groundwater flow* and *storing of results*. Where necessary, these modules and their inputs have been described in the paragraphs to follow.

5.2.1.1 Simulation specification module

The *simulation specification module* specified which components of the hydrological cycle to model and, where applicable, specified the methods used to model certain components. Once the components were selected, they were displayed in the set-up MIKE SHE data tree as modules. Under the *simulation specification module* other factors: the *simulation title* and *simulation period*, and the *time step controls*, were also defined.

The *simulation period* extended from the 14th of February 2007 to the 2nd of October 2016; this period was used as it corresponded to the length of the rainfall record available. The default settings for the MIKE SHE *time step controls* were used (Figure 5.9).

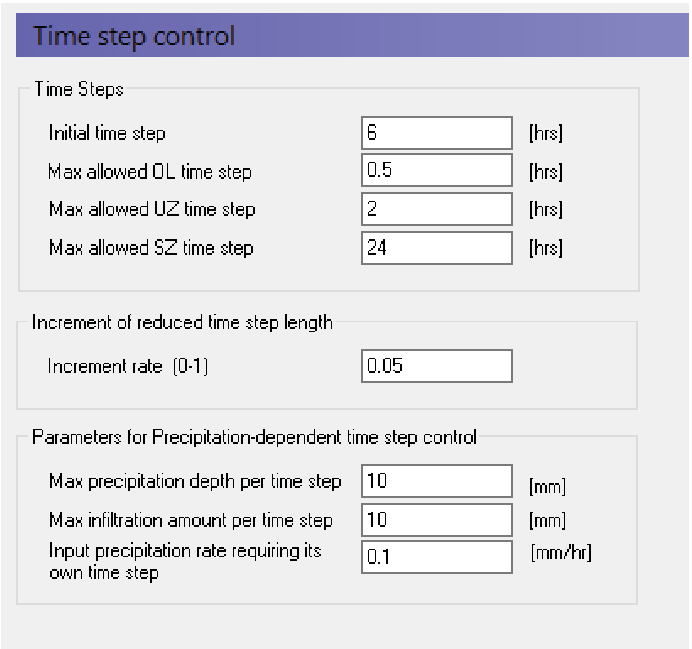

Figure 5.9 Screen display of the default time step control settings used for the MIKE SHE current scenario set-up

5.2.1.2 Model domain and grid module

The *model domain and grid module* (Figure 5.10) defined the model area of the research. For this study, the model area was defined by the larger sub-catchment boundary of the site – the boundary used was taken from previous research undertaken at the Two Streams site (Everson *et al*., 2006; Clulow *et al*., 2011; Everson *et al*., 2014). However, on visual inspection of the boundary it appeared to have very straight edges, not typical of a hydrologically defined boundary. Thus, as opposed to using the boundary provided, a new hydrologically defined sub-catchment was delineated using Arc-Hydro in ArcGIS 10.3. Arc-Hydro is used to define drainage patterns for catchments through a set of sequential steps. To delineate catchment or sub-catchment boundaries, the Arc-Hydro software was reliant on the input of a DEM. The DEM input was provided by the Discipline of Geography, University of KwaZulu-Natal (Pietermaritzburg Campus). Once input, the DEM underwent a sequence of processing steps to produce a delineated sub-catchment. Once delineated the sub-catchment boundary (Figure 5.10) was input into MIKE SHE as a .dfs2 file and used to define the model domain and grid size – the file had a cell size of 25 m^2.

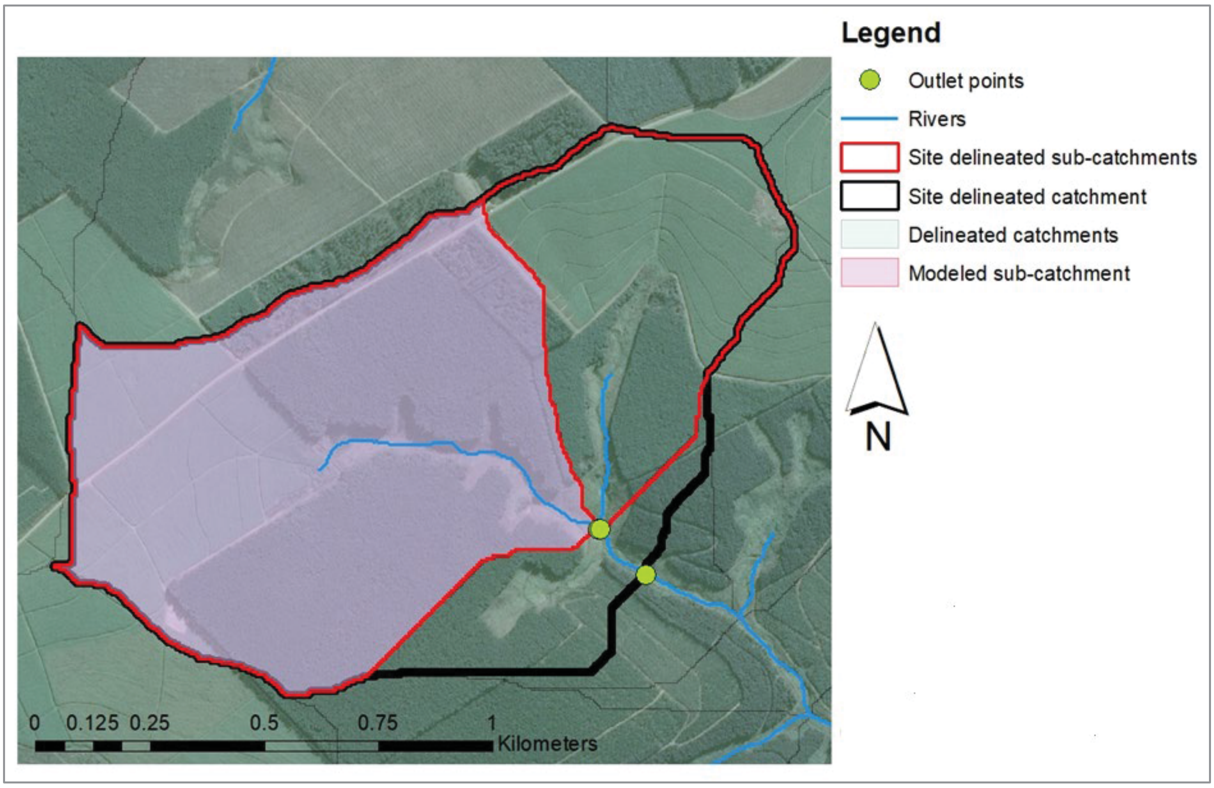

Figure 5.10 The Two Streams catchment boundary and sub-catchment (study site) boundaries delineated through Arc-Hydro tools in ArcGIS 10.3 software.

5.2.1.3 Topography module

Within MIKE SHE, topography was defined from a DEM. The DEM for the Two Streams site was derived by the Cartographic Unit, Discipline of Geography at the University of KwaZulu-Natal (Pietermaritzburg Campus) from 5 m and 10 m contours and spot heights (Figure 5.11). The DEM had a resolution of 5 m and was input into MIKE SHE as a .dfs2 file.

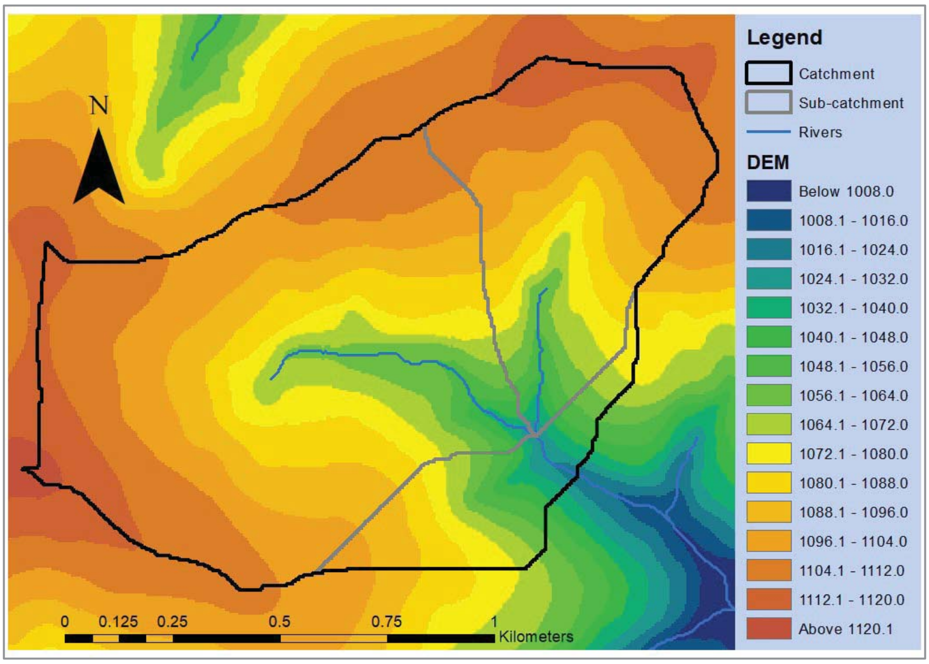

Figure 5.11 5 m Digital Elevation Model (DEM) showing the Two Streams site topography, based on 5 m and 10 m contours and spot heights

5.2.1.4 Climate module

All weather data inputs were input under the *climate module*. The *climate module* comprised three sub-modules: *precipitation rate*, *reference evapotranspiration* and *snow melt*. No measure of snow melt had been taken on-site and, due to the infrequency of snowfall in the area, was deemed unnecessary. Thus, the only sub-modules considered for this research were: *precipitation rate* and *reference evapotranspiration*. All climatic data were taken from three AWSs (Table 5.4).

Table 5.4 Coordinates of the locations of the Automatic Weather Station's (AWSs) used in this research.

AWSs	Coordinates	Approximate distance from the Two Stream site
FAO AWS	29°11'47.9''S; 30°39'58.8''E	1km
Mast AWS	29°12'19.2''S; 30°39'1.3''E	Located on-site
SAWS AWS	29°4'58.8''S; 30°36'10.8''E	15km

Two Campbell Scientific AWSs collect standard atmospheric data at or near to the Two Streams study site. The one station was a FAO registered AWS that had been set-up in a short grassland area, approximately 1km outside of the Two Streams site (Table 5.4). The FAO AWS record extended from the 14th of February 2007 to the 2nd of October 2016. The second AWS at Two Streams was attached to the top of a 24 m lattice mast in the black wattle (*Acacia mearnsii*) stand (Table 5.4). Originally, the Mast AWS was set-up to provide data for energy balance calculations, to determine ET (Clulow *et al*., 2011; Everson *et al*., 2014). The mast AWS record extended from 23rd March 2011 to 2nd October 2016. The FAO AWS was considered as the primary AWS record due to the record length and close proximity to the Two Streams site. Gaps in the FAO AWS record were patched using the mast AWS record. Where gaps in the record could not be filled using the mast AWS, the SAWS data for Greytown were used. The SAWS station was located approximately 15km from the Two Streams site and had a record extending from 14th February 2007 to 2nd October 2016 (Table 5.4).

5.2.1.5 Precipitation rate

In MIKE SHE, precipitation refers to the measured rainfall falling into the defined project domain (DHI software, 2012). In the *precipitation rate* sub-module both the spatial and temporal distribution of rainfall were considered. Daily rainfall data (mm) were input as a time series file (.dfs0) for the period 14 February 2007 to 2 October 2016 (3519 days) and the rainfall was deemed spatially uniform across the sub-catchment (due to the lack of availability of multiple measures of within-catchment rainfall data). Out of the 3519 days modelled, the FAO AWS rainfall record accounted for 2587 days (approximately 73.5%), the mast AWS 812 days (approximately 23.1%), of which 526 days had experienced rainfall and the SAWS record 120 days (approximately 3.4 %), of which 43 days experienced rainfall.

Prior to patching, the AWS records were correlated to determine whether the datasets showed a good linear correlation and thus could be used for patching gaps. The correlation between the FAO AWS record and the mast AWS record were assessed using a scatter plot (Figure 5.12) and a Pearson's correlation coefficient (r) and found to have an extremely significant ($P < 1 \times 10^{-4}$), very strong, positive, linear correlation, r = 0.94. This was deemed sufficient to patch the FAO AWS record.

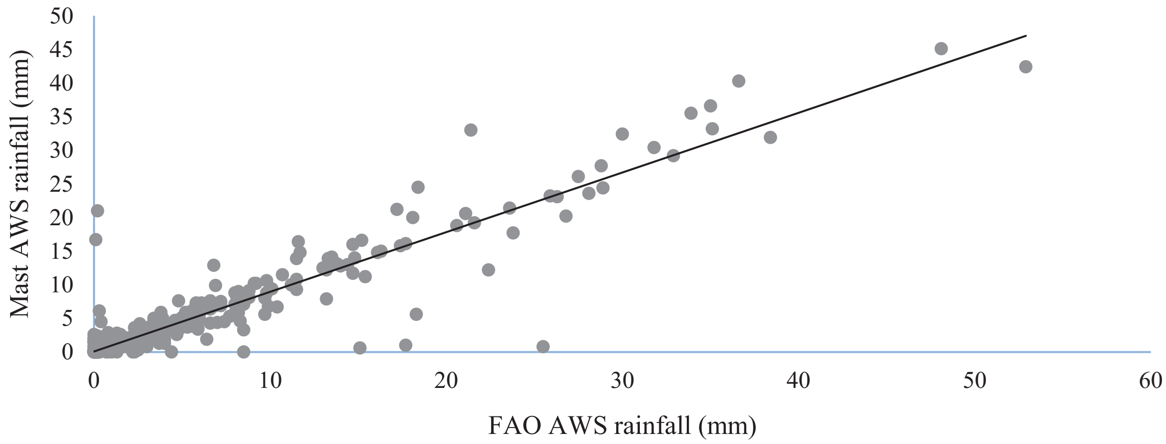

Figure 5.12 Correlation between the FAO Automatic Weather Station (AWS) daily rainfall (mm) record and the mast Automatic Weather Station (AWS) daily rainfall (mm) record

The SAWS AWS rainfall record was correlated to the combined AWS record and was found to have an extremely significant ($P < 1 \times 10^{-4}$), positive, linear correlation, r =0.67 (Figure 5.13). This was deemed sufficient to patch the rainfall record.

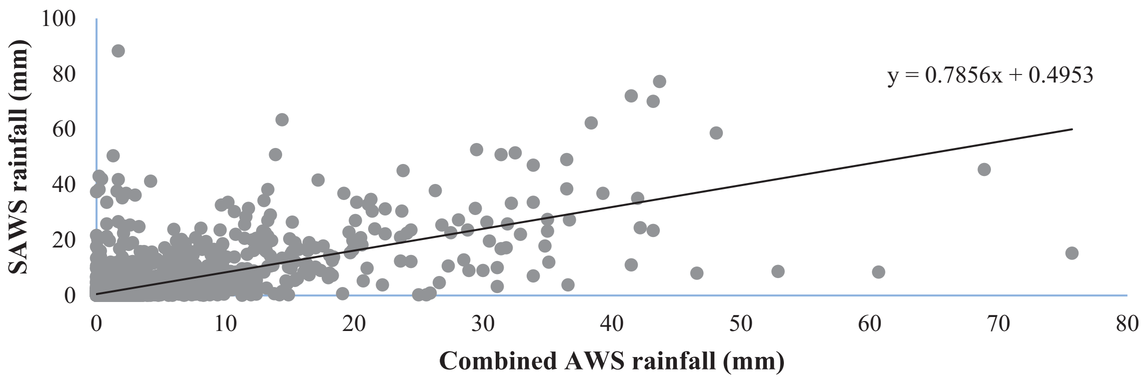

Figure 5.13 Correlation between the combined Automatic Weather Station (AWS) daily rainfall (mm) record for the Two Streams site and the South African Weather Services' Greytown weather stations daily rainfall (mm) record

5.2.1.6 *Reference evapotranspiration*

ET_{Ref}, in MIKE SHE, refers to the rate of ET from a reference surface that has an unlimited amount of water (DHI software, 2012). To calculate the ET_{Ref} for the Two Streams sub-catchment the FAO Penman-Monteith method (Allen *et al*., 1998), recommended for use in MIKE SHE (DHI software, 2012), was used (Equation 5.1). It is an internationally recognized method and popular for many reasons, including the relatively low data requirements (Allen *et al*., 1998). The Penman-Monteith equation is reliant on easily acquired weather station data: solar radiation, air temperature, air humidity and wind speed (Zotarelli *et al*., 2015). The calculation of ET_{Ref} using the FAO Penman-Monteith equation, described in Zotarelli *et al*. (2015), was an exhaustive process.

$$\mathrm{ET_0} = \frac{0.408\Delta(\mathrm{R_n} - \mathrm{G}) + \gamma\frac{900}{\mathrm{T} + 273}\mathrm{u_2}(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma(1 + 0.34\mathrm{u_2})} \quad \textit{(Eqn. 5.1)}$$

Where:

$\mathrm{ET_0}$ = the ET_{Ref} (mm.day^{-1}); $\mathrm{R_n}$ = the net radiation at the crop surface (W.m^{-2}); G = the soil heat flux density (unitless); T = the mean daily air temperature at 2 m height (°C); $\mathrm{u_2}$ = the wind speed at 2 m height (m.sec^{-1}); $\mathrm{e_s}$ = the saturation vapour pressure (kPa); $\mathrm{e_a}$ = the actual vapour pressure (kPa); Δ = the slope vapour pressure curve (kPa); and γ = the psychrometric constant (kPa ºC^{-1}; Allen *et al*., 1998).

5.2.1.7 *Land use module*

The *land use module* was used to define the properties of the land surface and the distribution of vegetation within the Two Streams sub-catchment. The *land use module*, in MIKE SHE, has a *vegetation* sub-module, under which the spatial distribution of vegetation was defined. The land cover map input (as a .dfs2 file) was provided by the Discipline of Geography, University of KwaZulu-Natal (Pietermaritzburg Campus) and was defined using the Ezemvelo KwaZulu-Natal Wildlife (EKZNW) LULC shapefile for the area (Figure 5.14).

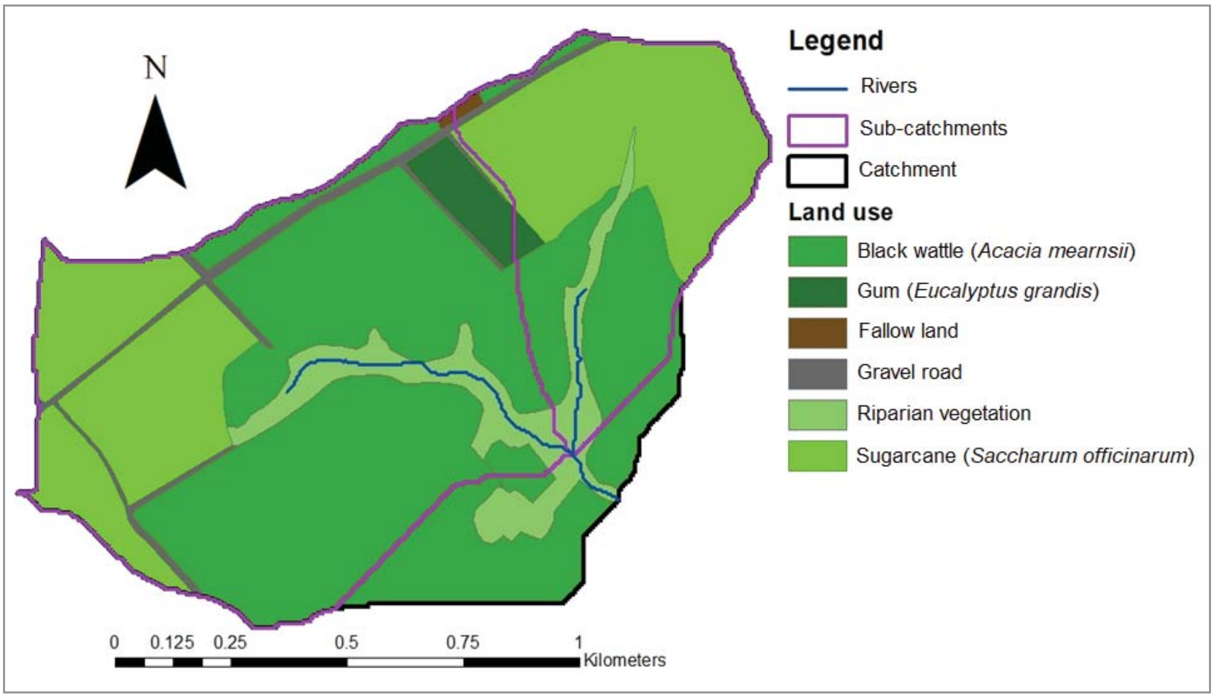

Figure 5.14 LULC map of the Two Streams catchment and sub-catchments, generated using the Ezemvelo KwaZulu-Natal Wildlife (EKZNW) LULC shapefile for the area

Once the vegetation .dfs2 file was input into MIKE SHE, the vegetation properties for each vegetation class were defined. For this study, three vegetation classes were considered: black wattle (*Acacia mearnsii*), sugarcane (*Saccharum officinarum*) and riparian vegetation. For the black wattle and sugarcane, *vegetation property files* (.etv) were created, as more data were available for these vegetation types than were available on the riparian vegetation. To generate *vegetation property files,* data on Leaf Area Index (LAI), RD and the crop coefficient (K_c) were required (DHI software, 2012).

LAI is included in the model as it provides a characteristic value for a specific plant type providing an indication of seasonality and plant stress (DHI software, 2012). LAI is defined by Graham and Butts (2005) as being the one-sided area of green leaves per area of ground surface. The LAI of vegetation depends on species composition, development stage and seasonality (Jonckheere *et al*., 2004). In MIKE SHE, the LAI assigned to a vegetation class is based on the average leaf area per grid cell within the model (DHI Software, 2012). RD provides an indication of the depth at which water can be extracted from the UZ and, in the case of deep rooting systems, from the SZ (Graham and Butts, 2005; DHI software, 2012). The K_c value is used in the calculation of ET_A and it provides a ratio for observed ET_A to ET_{Ref} (Zotarelli *et al*., 2015). To generate the *vegetation property files* for the black wattle and sugarcane, the stages of development of both species were defined and for each stage the LAI, RD and K_c values were specified.

For the black wattle (*Acacia mearnsii*), LAI values had been measured on-site from August 2006 to October 2013 using a LAI-2000 Plant Canopy Analyzer. The LAI-2000 allows for easy estimation of LAI whereby light readings are taken both below and above the canopy and transmittances are computed at five angles (LAI-2000 Plant Canopy Analyzer). Within the LAI-2000 a control unit records the light readings and calculates LAI from the transmittances (LAI-2000 Plant Canopy Analyzer). The LAI data were input in the *vegetation property file* for the specific days recorded. RD was input as a constant figure of 10 m throughout the study period. RD had not been determined on-site, however, Everson *et al*., (2014), whilst conducting other studies on soil moisture content, identified *Acacia mearnsii* tree roots extending to depths deeper than 8 m. Thus, a depth of 10 m was assumed for the RD. The K_c values for black wattle were taken from the Compoveg database from the ACRU Agrohydrological Modelling System, user manual version 3.00 (Smithers and Schulze, 1995). The black wattle *vegetation property file* comprised 2431 days of varied LAI and K_c value readings and a constant RD.

For the sugarcane (*Saccharum officinarum*), the LAI was determined from Dye *et al*., (2008) in the Seven Oaks region. Based on this study an average LAI value of 3.57 was identified. The *vegetation property file* was used to incorporate harvesting times of the sugarcane crop. According to the farmer who currently owns the sugarcane crop, crops are harvested approximately every 22 months. The last harvest took place at the beginning of October 2017 (Table 5.5). Based on the data provided by the sugarcane farmer, all harvest dates over the study period were calculated. At each harvest time the LAI was assumed to be 0, sugarcane crops generally take four months to reach maturity (Blackburn, 1984). Thus, four months after harvest LAI was recorded as 3.57. This pattern was continued throughout the study period. The RD of the sugarcane was set as 1 m based on information from the sugarcane farmer. The RD was verified in the literature (Dye *et al*., 2008). A constant K_c coefficient value of 0.96 was used for sugarcane, as recommended by Smithers and Schulze (1995).

Table 5.5 Sugarcane harvest periods that fall within the study period considered.

Harvest month	Ratoon*
April 2008	5th
February 2010	6th
December 2011	1st
October 2013	2nd
August 2015	3rd
October 2017	4th

*Ratoon refers to a new shoot or sprout growing from the base of a crop plant (i.e. sugarcane), referring to the start of the new growing season. Sugarcane crops are not reseeded after they are cut down; they grow in ratoon cycles, until the crop quality declines at which point they are reseeded. Sugarcane normally grows for six ratoon cycles (Cabral *et al*., 2012).

The riparian vegetation was treated differently from the black wattle and sugarcane, as less information was available on this vegetation class. As opposed to using a *vegetation property file*, constant values for LAI and RD were inputted. The riparian area comprised of a mixture of vegetation types. To determine the LAI of the riparian vegetation, remote sensing was used. LAI values were derived from Normalized Difference Vegetation Index (NDVI) calculations undertaken on satellite imagery (discussed below).

The Normalized Difference Vegetation Index (NDVI) is a popular vegetation index incorporating the regions of the electromagnetic spectrum showing the highest absorption and highest reflectance of chlorophyll, making it a useful index for vegetation assessment over a wide range of conditions (Bulcock and Jewitt, 2010). The NDVI does not consider topography, making it easier to calculate as no prior knowledge of the ground conditions is required. The NDVI is a ratio of shortwave infrared and red reflectance (Bulcock and Jewitt, 2010; Equation 5.2).

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{red}}{\mathrm{NIR} + \mathrm{red}} \qquad \textit{(Eqn. 5.2)}$$

Where:

Red = the red band (± 600nm to 700nm); and NIR (Near Infrared) = the NIR band (± 750nm to 900nm). The part of the spectrum included in the red and NIR bands will depend on the satellite considered.

For this study, SPOT satellite images were used (Table 5.6). These images were acquired from the South African National Space Agency (SANSA).

Table 5.6 Information on the SPOT satellite imagery acquired from the South African National Space Agency (SANSA)

Date	Satellite used	Band wavelength (nm)	Resolution (m)	Cloud cover (%)
01/02/2007	SPOT 5	Red = 610 – 680; NIR = 780 – 890	10	0
17/07/2007	SPOT 5	Red = 610 – 680; NIR = 780 – 890	10	0
19/01/2011	SPOT 4	Red = 610 – 680; NIR = 780 – 890	20	0
31/07/2012	SPOT 5	Red = 610 – 680; NIR = 780 – 890	10	0
04/10/2015	SPOT 5	Red = 610 – 680; NIR = 780 – 890	10	0

NDVI values were calculated (using 50 random points taken in the riparian zone), for all of the acquired images, and LAI values were derived based on each NDVI value. To calculate the LAI from the NDVI values, an equation to relate LAI and NDVI needed to be used. An equation relating a similar vegetation index, the *Soil-adjusted Vegetation Index* (SAVI), to LAI was found (Equations 5.3 and 5.4) (Bulcock and Jewitt, 2010).

$$\mathrm{LAI} = \frac{-\ln(\mathrm{SAVI} + 0.371)}{0.48} \qquad \textit{(Eqn. 5.3)}$$

$$\mathrm{SAVI} = \frac{(1 + \mathrm{L})(\mathrm{NIR} - \mathrm{red})}{\mathrm{NIR} + \mathrm{red} + \mathrm{L}} \qquad \textit{(Eqn. 5.4)}$$

Within the SAVI equation L = 0 in densely vegetated areas; L = 0.5 in sparsely vegetated areas; and L = 1 in areas with no vegetation (Elvidge and Chen, 1995). Based on field observations, the majority of the sub-catchment was densely vegetated, and as such an 'L' value of zero was used. With L = 0 the SAVI equation (Equation 5.4) becomes the NDVI equation (Equation 5.2). Thus, the relationship between LAI and the SAVI (Equation 5.3) was deemed sufficient to derive LAI values for each random point considered. Based on the above process a constant LAI value of 2.01 was calculated. However, there was concern regarding this value due to the resolution of the satellite imagery (Table 5.6), bringing into question the reliability of the LAI data. To determine the validity of the above LAI value obtained, ground measures of LAI were taken.

5.2.1.8 Field validation and ground truthing

Three fieldtrips to the Two Streams site were undertaken. The first fieldtrip took place from the 24th of April 2016 to the 30th of April 2016. This fieldtrip was undertaken to gather data on past research undertaken on-site and to become acquainted with the study site. The second fieldtrip was undertaken from the 16th of October 2016 to the 21st of October 2016. This fieldtrip involved the gathering of information on past research undertaken on-site and to better understand data previously acquired. The third fieldtrip was undertaken from the 18th of October 2017 to the 21st of October 2017. During this fieldtrip, LAI was measured at 20 locations within the riparian vegetation class using a LAI-2200 Plant Canopy Analyzer (Figure 4.10) to determine the average LAI of the riparian vegetation class and to ground truth the average LAI measure derived from satellite imagery.

The LAI-2200 is an upgraded version of the LAI-2000 previously used on-site (making their outputs comparable), to determine LAI of the black wattle stand (Clulow *et al*., 2011). The LAI-2200 calculates LAI and other canopy attributes from light measurements made with a 'fish-eye' optical sensor (148° field-of-view; LAI-2200 Plant Canopy Analyser). Measurements made above and below the canopy are used to calculate canopy light interception at five zenith angles, from which LAI is computed using a model of radiative transfer in vegetative canopies (LAI-2200 Plant Canopy Analyser). To operate the LAI-2200 a LAI-2250 optical sensor (wand) is connected to a LAI-2270 control unit (console). The LAI-2270 control unit is used to configure the instrument, to store the recorded data and to compute results and the LAI-2250 optical sensor is used to collect the data (LAI-2200 Plant Canopy Analyser).

Figure 5.15 LAI-2200 Plant Canopy Analyzer used to measure the average Leaf Area Index (LAI) for the riparian vegetation

The optical sensor contains high precision optical components, including lenses, optical filters and light sensors and is very sensitive to light (LAI-2200 Plant Canopy Analyser). The LAI-2250 should ideally be used during times of minimal, uniform light which is not always practically possible, as was the case in the ground truthing fieldtrip visit (LAI-2200 Plant Canopy Analyser). To account for this limitation, view caps are supplied with the LAI-2250 optical sensor (Figure 5.16) to limit the field of view and block out unwanted light (LAI-2200 Plant Canopy Analyser). For this study the 90˚ cap was used to limit both the impact of the operator of the instrument and the sun (Figure 5.16).

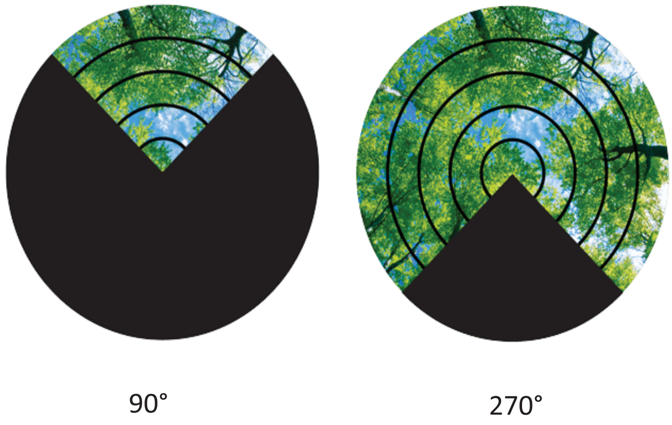

Figure 5.16 Example of view caps used by the LAI-2250 optical sensor (LAI-2200 Plant Canopy Analyser)

When LAI was measured, using the LAI-2200, the coordinates of the location of the measurement were recorded. Once fieldwork was completed and the average LAI from the 20 samples was obtained it was compared to the LAI measured from the SPOT imagery. A LAI value was obtained and input into MIKE SHE for the riparian vegetation. In addition, a constant RD of 1 m was used for the riparian vegetation class.

5.2.2 Overland flow module

In MIKE SHE the *overland flow module* models the interactions between the LULC in the sub-catchment and the properties of the water flowing overland and integrates these OL properties to the *rivers and lakes model* by modelling the interactions between river flow and OL (DHI software, 2012). There are two possible methods for calculating OL in MIKE SHE: the *finite difference method* which uses diffusive wave approximation of the Saint Venant equations, or the *semi-distributed method* which uses a semi-distributed approach based on Manning's equation (DHI software, 2012). The *finite difference method* calculates a more detailed OL and is more suited to small scale study sites, whilst the *semi-distributed method* is of a coarser resolution and more suited to larger regional scale study sites (DHI software, 2012). The Two Streams study site occupies a small area (79.16 ha) and thus the *finite difference method* was used. The *finite difference method* was selected for under the *simulation specification module* and the following items were required for the calculation of OL under the *overland flow module*: Manning number, detention storage and initial water depth.

The Manning number refers to the Manning's m number which is equivalent to the Stickler roughness coefficient and the inverse of the more conventional Manning's n number (Morgan, 2005). Manning's n is the sum of roughness generated by the soil particles, surface micro-topography and vegetation, all acting independently of each other (Morgan, 2005). Manning's n values characteristically range between 0.01 for smooth channels and 0.10 for densely vegetated channels. For Manning's m values this corresponds to values between 100 and 10 respectively. If a Manning's m value of zero (0) is used for a particular cell, then the OL becomes inactive within that cell (DHI software, 2012). For the Two Streams site a different Manning's m value was used for each vegetation class (i.e. black wattle, sugarcane and riparian vegetation). The resistance to OL by the black wattle plantation was determined to be high with a Manning m value of 10, the sugarcane was estimated to have a Manning's m value of 40 based on values recommended in Morgan (2005) for similar crops and the riparian vegetation was provided a Manning's m value of 20 determined by the basal coverage relative to the other land covers considered and based on a recommended value in Morgan (2005) for dense bunch grasses.

Detention storage, in MIKE SHE, is used to limit the amount of water that can flow over the ground surface by accounting for ponded water on the surface (DHI software, 2012). The detention storage is a threshold value that must be overcome for OL to take place (DHI software, 2012). The detention storage value used for this study was 2 mm uniformly across the study site; this value was a default MIKE SHE setting and considered sufficient given that this has never been investigated on-site. In MIKE SHE, the initial water depth is the depth of water present on the ground surface at the start of the simulation (DHI software, 2012). The initial water depth is usually zero (i.e. no water present on the surface), but can be given a higher value if the area has experienced a significant amount of rainfall i.e. if there has been a flood or if the site is situated in a wetland or lake area where there is a natural 'film' of water constantly present (DHI software, 2012). For this study, the initial water depth was set at 0 mm.

5.2.3 Rivers and lakes module

MIKE SHE software is incapable of modelling the streamflow or water level of terrestrial water bodies and relies on external software extensions to do so (i.e. MIKE 11; Figure 5.17). MIKE SHE links to MIKE 11 software, which is used to model the one-dimensional flow in a river, in this case the river in the Two Streams sub-catchment. However, to generate the input requirements for MIKE 11, MIKE Hydro software (Figure 5.17), which is a graphical user interface framework used for water resources related applications, was used (DHI software, 2012). Thus, MIKE Hydro generated the MIKE 11 files which are linked to the MIKE SHE *rivers and lakes module* to model streamflow (Figure 5.17).

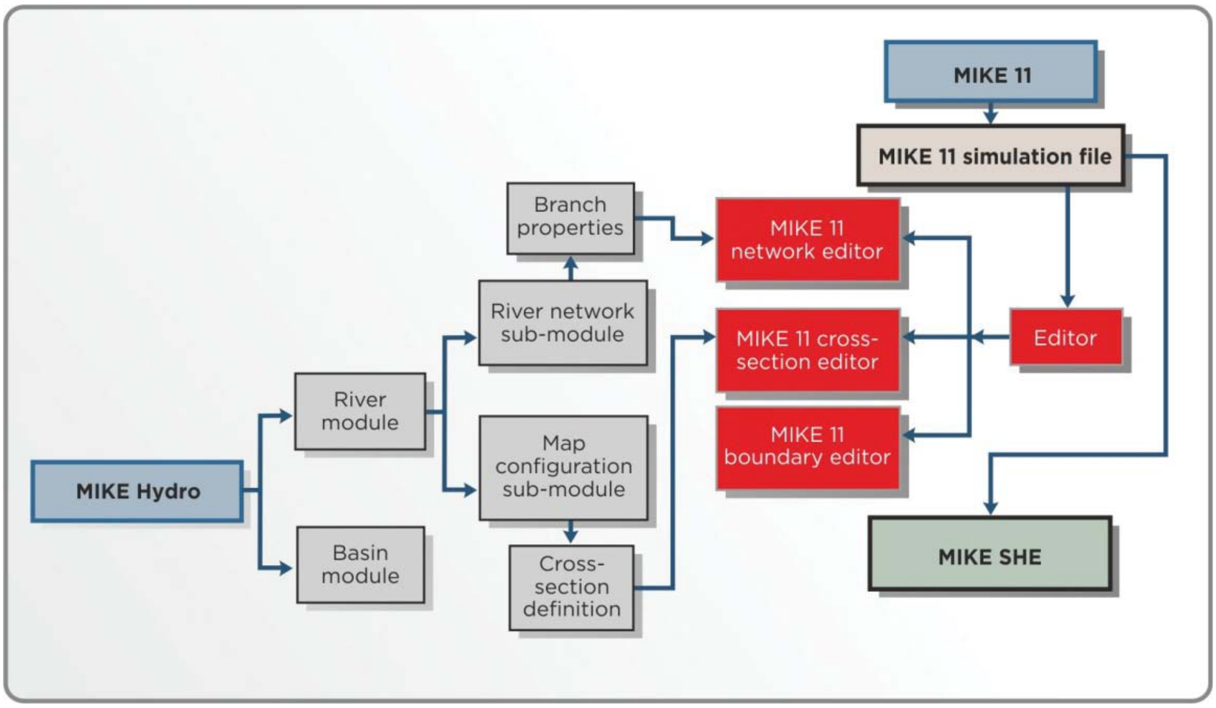

Figure 5.17 Flow chart showing the link between MIKE Hydro, MIKE 11 and MIKE SHE software

5.2.3.1 *Generating MIKE 11 inputs in MIKE Hydro*

The *river module* in MIKE Hydro was used to generate the MIKE 11 inputs required. In the *river module*, two sub-modules were considered: *river network* and *map configuration*. The *river network* sub-module is used as the basis for all river applications and was used to input information on river branches. One river (stream) branch was considered for this study and was generated in Arc-Hydro before being inputted into the *river network* sub-module. Branch properties were defined for the inputted river branch (Table 5.7).

Table 5.7 Branch properties of the Two Streams stream

Branch Property	Model setting used
Branch name	Two streams stream
Topo ID	Stream 1
Start chainage	0 m
End chainage	748.93 m
Flow direction	Positive
Branch type	Regular

The *map configurations* sub-module was used to define the river cross-sections. Under the *map configurations* sub-module the DEM for the site was input and the option to *use DEM for cross-section digitization* was selected. To generate the cross-sections the *auto generate cross-section* option under the tools tab was selected, the input requirements included the cross-section interval and cross-section width, an interval of 200 m and a width of 100 m were input and the cross-sections were generated (Figure 5.18).

Following the generation of the river network and river cross-sections all data were exported as MIKE 11 files (Figure 5.17), which all together, made up the *MIKE 11 simulation file,* and were then inputted into the MIKE SHE *rivers and lakes module* (Figure 5.17). The MIKE SHE *rivers and lakes module* is used to direct the MIKE SHE software to the *MIKE 11 simulation file* (for more information on the MIKE 11 and MIKE SHE *rivers and lakes module* set-up.

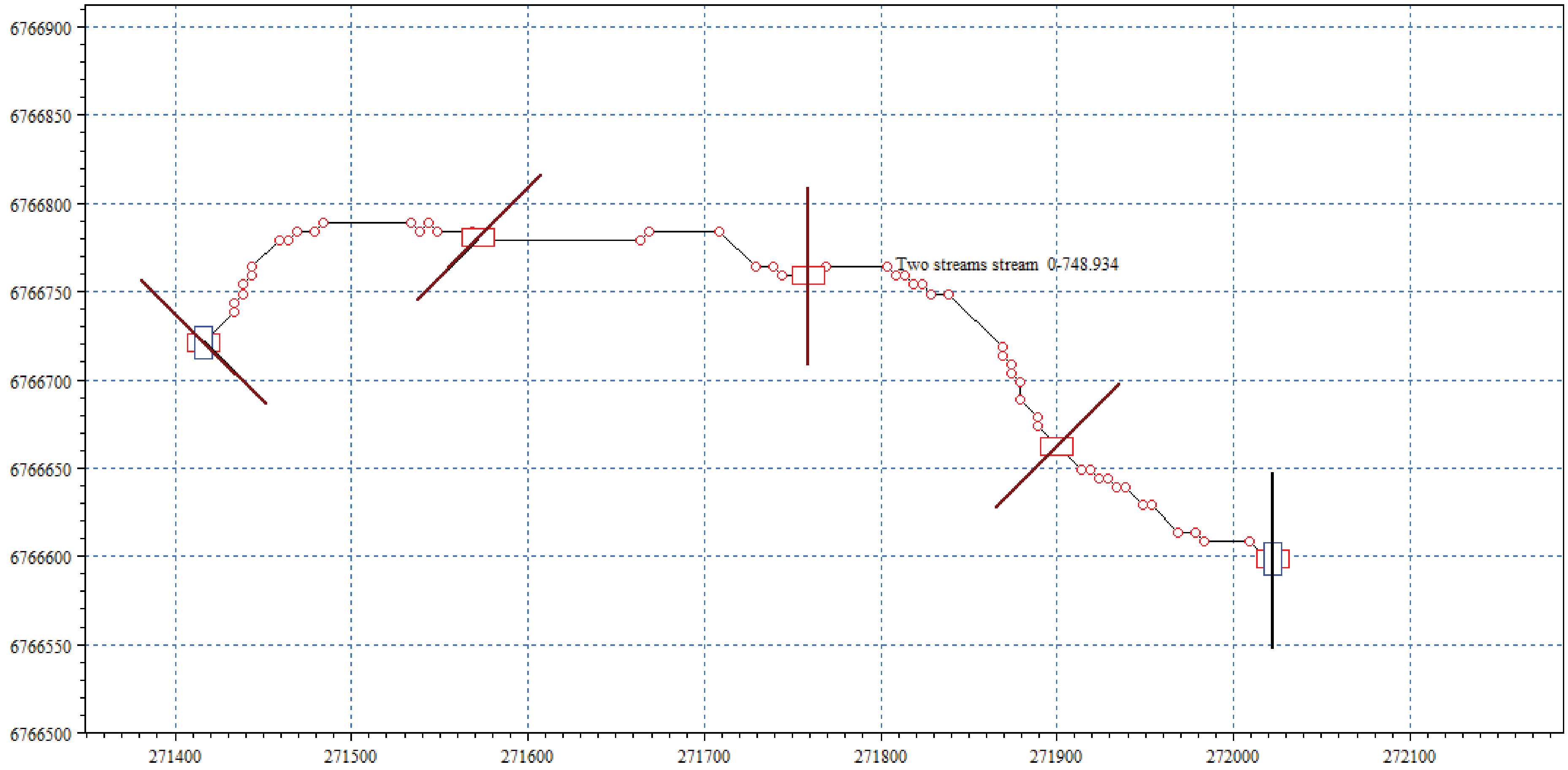

Figure 5.18 Model screen display showing of the locations of cross-sections generated along the length of the Two Streams stream. The stream is mapped on a geo-reference grid (m). The red boxes indicate were cross-sections were generated and the black lines perpendicular to the stream indicate the length and angle the cross-sections were captured at. The blue boxes indicate the start and end chainage points of the river

5.2.4 Unsaturated flow module

The *unsaturated flow module* in MIKE SHE considers the vertical movement of soil water. The UZ in the hydrological cycle is normally heterogeneous, experiencing dynamic, cyclic changes in soil water when water is added to the system through rainfall, removed through ET, and when water moves through the UZ to the SZ to form GR (DHI software, 2012).

Prior to working in the *unsaturated flow module*, the method used to calculate vertical flow was selected under the simulation specification module. There were three options to select from: the full *Richards equation*, a simplified *gravity flow* procedure and a simple *two-layer water balance method*. The full *Richards equation* is the most thorough method when dealing with dynamic unsaturated flow. The simple *two-layer water balance method* is the most simplified method and is more suitable when the water table is shallow and when GR is primarily influenced by ET in the root zone (DHI software, 2012). For this study, the *Richards equation* method was chosen as there was sufficient hydraulic data available. Data used for the *unsaturated flow module* were taken from Kuenene (2013).

Under the *unsaturated flow module* there were certain selections that were made prior to the input of UZ characteristics. The selections included: the *calculation column classification type* (allowing for computational time to be decreased for larger study sites), *macropore flow* (allowing for the inclusion of macropores), and the *initial conditions* (the conditions of soil pressure and water content for the start of the simulation; DHI software, 2012). The study site area is small (79.16ha), therefore the *calculate in all grid points* option was chosen for the *calculation column classification type*. The *none* option was chosen for the *macropore flow* on-site, as the presence of macropores on-site is unknown. The *equilibrium pressure profile* option was chosen for the *initial conditions* as the initial conditions at the start of the simulation were not known and this option overcomes this constraint (Figure 5.19).

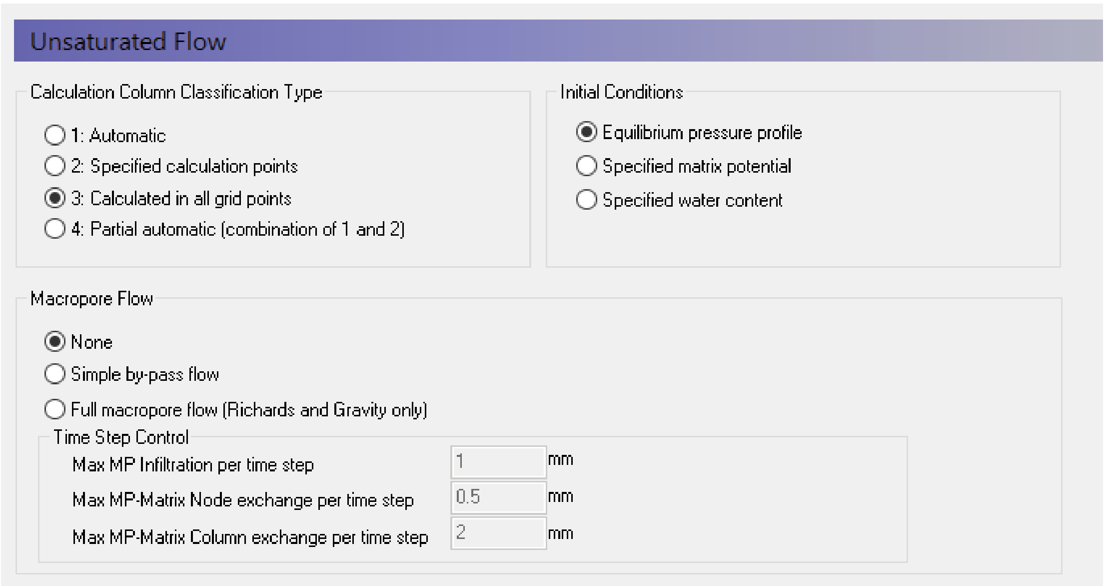

Figure 5.19 Available selection options in the unsaturated zone and the options selected for this study

5.2.4.1 Soil profile definitions

Kuenene (2013) studied the hydropedological characteristics of the Two Streams sub-catchment and identified seven soil forms, namely: Kranskop (*Kp* 1100), Inanda (*Ia* 1100), Magwa (*Ma* 1200), Katspruit (*Ka* 1000), Oakleaf (*Oa* 1220/1210), Clovelly (*Cv* 2100) and Griffin (*Gf* 1100; Figure 5.20).

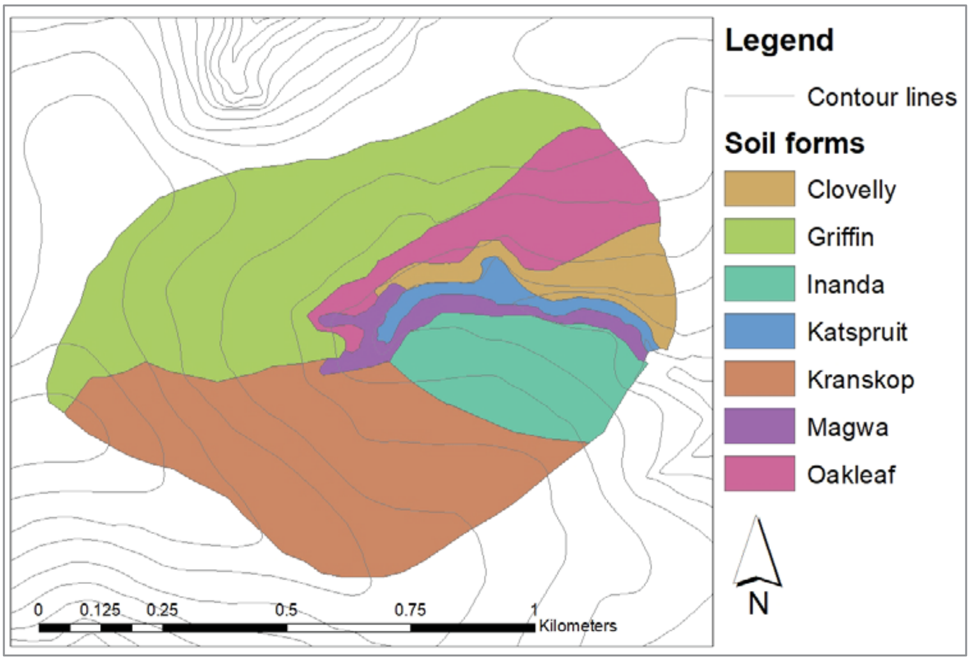

Figure 5.20 Soil map showing the soil forms of the Two Streams sub-catchment (Kuenene, 2013)

The spatially distributed soil data for the Two Streams sub-catchment were input as a .dfs2 file under the soil definitions sub-module of the *unsaturated flow module*. Once input, various hydraulic characteristics were specified for each soil type, including: saturated moisture content (θ_s), residual moisture content (θ_r), and saturated hydraulic conductivity (Ks; Table 5.8).

Table 5.8 Soil hydraulic characteristics of the soil forms of the Two Streams sub-catchment (Kuenene, 2013)

Soil form	Soil horizon	Accumulated depth of horizon (mm)	Retention curve and Hydraulic conductivity					Bulk density ($Mg.m^{-3}$)
			θ_s ($cm^3.cm^{-3}$)	θ_r ($cm^3.cm^{-3}$)	α (cm^{-1})	n	K_s ($m.s^{-1}$)	
Kranskop *Kp 1100*	ah	400	0.60	0.01	0.02	1.24	1.97×10^{-5}	1.08
	ye	800	0.60	0.08	0.04	1.29	9.53×10^{-5}	1.19
	re	2500	0.54	0.11	0.05	1.34	1.03×10^{-4}	1.24
Inanda *Ia 1100*	ah	400	0.55	0.16	0.04	1.69	1.75×10^{-5}	1.33
	re	2000	0.52	0.21	0.03	1.69	6.39×10^{-5}	1.38
Magwa *Ma 1200*	ah	400	0.54	0.03	0.02	1.21	1.69×10^{-5}	1.06
	ye	1000	0.55	0.21	0.03	1.54	4.94×10^{-5}	1.31
	on	2000	0.54	0.16	0.02	1.45	4.72×10^{-6}	1.34
Katspruit *Ka 1000*	ot	1000	0.62	0.23	0.04	1.83	8.33×10^{-6}	0.95
	G	1200	0.54	0.14	0.05	1.62	1.47×10^{-5}	1.25
Oakleaf *Oa 1220/1210*	ot	400	0.575	0.16	0.025	1.58	5.94×10^{-5}	1.18
	ne	1750	0.535	0.15	0.06	1.63	7.94×10^{-5}	1.33
Clovelly *Cv 2100*	ot	400	0.57	0.15	0.04	1.53	1.83×10^{-5}	1.2
	ye	800	0.53	0.17	0.02	1.76	8.25×10^{-5}	1.25
Griffin *Gf 1100*	ot	400	0.58	0.17	0.04	1.77	2.44×10^{-5}	1.16
	ye	800	0.57	0.11	0.03	1.37	6.25×10^{-5}	1.31
	re	2500	0.54	0.08	0.06	1.26	5.81×10^{-5}	1.33

**θ_s is the saturated moisture content; θ_r is the residual moisture content; α is the inverse of the air entry value; n is the shape parameter; and Ks is the saturated hydraulic conductivity.*

Once inputted into the model, MIKE SHE uses the input values to generate soil water retention curves (SWRC) and hydraulic conductivity functions for each soil horizon. Within MIKE SHE the SWRCs were defined by the 1980 van Genuchten soil water retention curve function (DHI software, 2012; Equation 5.5).

SWRCs are used to describe the relationship between soil moisture suction (pf) and soil moisture content ($cm^3.cm^{-3}$; DHI software, 2012). The van Genuchten model is one of the most widely used empirical models for describing SWRCs as it is effective for a broad range of soils (Xiang-Wei *et al*., 2010). Within MIKE SHE the hydraulic conductivity function was defined by the Brooks and Corey for soil hydraulic conductivity (1964) model (Equation 5.6), where unsaturated hydraulic conductivity provides a measure of the rate at which water moves through the UZ (DHI software, 2012).

$$\theta(h) = \left[(\theta_s - \theta_r)\left(\frac{1}{1+(\alpha h)^n}\right)^m\right] + \theta_r$$	*(Eqn. 5.5)*

$$\mathrm{K}(\theta) = \mathrm{K}_{\mathrm{sat}}\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^N$$	*(Eqn. 5.6)*

Where:

$\theta(h)$ is the water retention curve ($cm^3.cm^{-3}$); h is the suction pressure of the water (cm); θ_s is the saturated water content ($cm^3.cm^{-3}$); θ_r is the residual water content ($cm^3.cm^{-3}$); α is is the inverse of the air entry value (cm^{-1}); and n and m are shape parameters of the van Genuchten relation (unitless); $\mathrm{K}_{\mathrm{sat}}$ is the saturated hydraulic conductivity (cm/day); and *N* is the Brooks and Corey shape parameter (DHI software, 2012).

5.2.5 *Saturated groundwater flow module*

The *saturated groundwater flow module*, in MIKE SHE was used to calculate the saturated subsurface flow and to input geological data. Under the simulation specification module there were two methods to select from for calculating saturated groundwater flow, the *finite difference method* and the *linear reservoir method*. The *finite difference method* allows for the consideration of three-dimensional flow in a heterogeneous aquifer with variations between unconfined and confined conditions (DHI software, 2012). The *linear reservoir method* provides an alternative to the physically based *finite difference method* and is a compromise between limitations on data availability, the complexity of hydrological response at the catchment scale, and the advantages of model simplicity (DHI software, 2012). For this model, the *finite difference method* was selected as it was done so in the *unsaturated flow module* and MIKE SHE requires the continuation of this physics based method. However, there were limited data available for the SZ of the Two Streams sub-catchment as research on-site has tended to focus on the surface and UZ (Everson *et al*., 2006; Clulow *et al*., 2011; Everson *et al*., 2014) and not the SZ.

5.2.5.1 Geological layers sub-module

The underlying geology of the Two Streams sub-catchment was identified as Natal Sandstone by the Council for Geosciences; based on a 1:100 000 geological map. To-date no geological study has been conducted within the Two Streams sub-catchment and thus the hydraulic characteristics of the geology had not been investigated. Various parameters needed to be defined for the geological layer under the *geological layers* sub-module including: *vertical hydraulic conductivity*, *horizontal hydraulic conductivity*, *specific yield* and *specific storage*. None of these parameters had been measured on-site and were all assumed to be uniform across the site (due to data limitations). Values for all of these parameters were taken from recent literature (Demlie and Titus, 2015) or default MIKE SHE values as recommended by the Danish Hydrological Institute (DHI) technical team. The *hydraulic conductivity* is a function of the texture of a material (i.e. soil, rock or vascular plant) and is related to the ease with which water can flow through the material (DHI software, 2012), the *hydraulic conductivity* was assigned a value of 3.20 x 10^{-5}m.s^{-1} (Demlie and Titus, 2015). *Specific yield* is the volume of water released per unit surface area of aquifer per unit decline in head (DHI software, 2012), the specific *yield* was given a value of 1.00 x 10^{-3}, default value. The *specific storage* (m^{-1}) is the volume of water released per volume of aquifer per unit decline in head (DHI software, 2012), the *specific storage* was given a value of 1.90 x $10^{-3}m^{-1}$ (Demlie and Titus, 2015).

5.2.5.2 Computational layers sub-module

Under the *computational layers* sub-module the following inputs were required for the Natal Sandstone geological layer: the *initial potential head, outer boundary conditions* and the *internal boundary conditions*. For this study, no *internal boundary conditions* were specified. The *initial potential head* is the starting head for the simulation and the initial 'guess' for steady-state simulations (DHI software, 2012). Data on the *initial potential head* were taken from the water table of the area which was defined using borehole data. There were three boreholes on-site (at the time of the start of the simulation), the data from these boreholes recorded during 2007 – the earliest date recorded to the start of the simulation was 11 October 2007 – were interpolated in ArcGIS 10.3 to produce a water table level for the site. The Inverse Distance Weighting (IDW) interpolation method was used. Once the water table was interpolated it was introduced into MIKE SHE as a .dfs2 file. Thereafter, the water table was subtracted from the topography .dfs2 file to determine elevation above sea level (Figure 5.21).

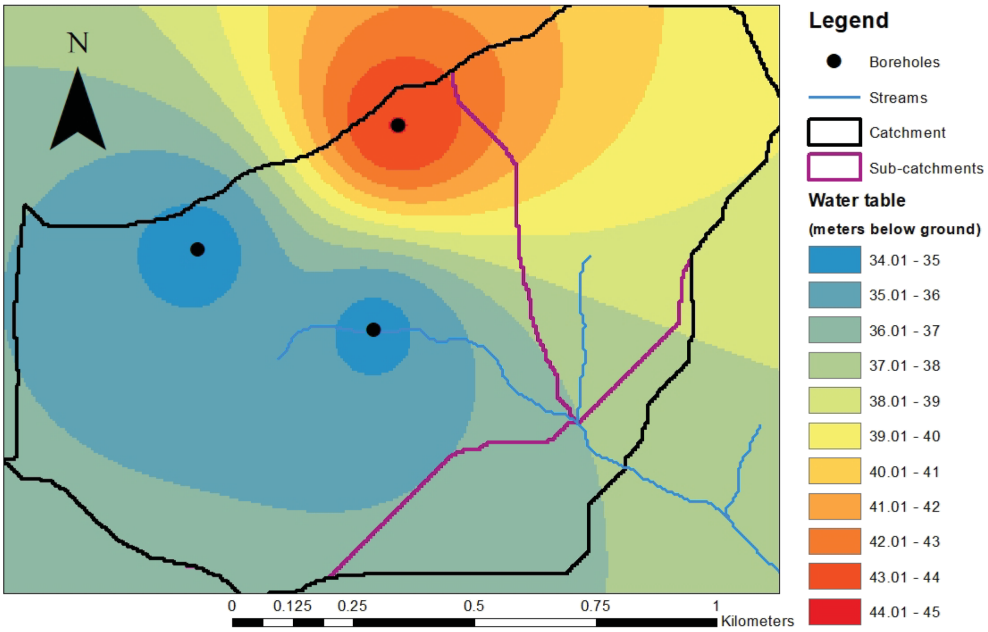

Figure 5.21 Initial water table depth of the Two Streams catchment and sub-catchments for the 11 October 2007 (the closest date to the start of the simulation – 14 February 2007)

The outer boundary conditions define the external boundaries of the SZ (DHI software, 2012). There are four possible boundary conditions from which to choose to describe the outer boundary conditions: fixed head, zero-flux, flux and gradient (DHI software, 2012). Fixed head – this option is selected when a head is introduced in the boundary (DHI software, 2012). The fixed head can be introduced as a fixed value (m) or as the initial value or it can be linearly interpolated from a time series file (i.e. .dfs0 or .dfs2; DHI software, 2012). Zero-flux - this option indicates a no-flow boundary and is the default option in MIKE SHE (DHI software, 2012). Flux – this option is used to define constant or time varying flux boundaries where a positive value indicates an inflow into the model (DHI software, 2012). A time varying flux boundary is specified as either a mean step-accumulated streamflow (e.g. $m3.s^{-1}$) or as a step-accumulated volume (e.g. m3; DHI software, 2012). Gradient – this option is used to describe a gradient (either constant or time varying) that exists between the outer boundary and the internal conditions of the model, where a positive gradient implies a flux into the model. A time varying gradient can either be specified as an instantaneous value or as a percentage (DHI software, 2012). For this study, the outer boundary was specified as having a zero-flux boundary. There were limited data available on the SZ of the site, thus no information was available to accurately specify the boundary conditions. However, as the sub-catchment boundary (which defines the extent of the study site) was hydrologically defined for the sub-catchment, a zero flux was assumed throughout.

5.3 Erosion and Sediment Yield Modelling using SWAT

A detailed overview of the methods has been provided in this section. These methods provide detail on the modification of model inputs for South African conditions.

5.3.1 Model Input Requirements

Catchment information has been collated for the Two Streams site and Quaternary Catchment (QC) U20A, which was used as a practical example for the modelling workshop held earlier in the year. This model is highly dependent on the resolution of the input data, in particular the Digital Elevation Model (DEM). A large amount of manipulation is required for modelling outside of the United States. Therefore, much of the time spent during this modelling exercise is translating data into suitable input data. An overview of the core input variables has been provided in Table 5.9.

Table 5.9 Summary of key SWAT input variables (after Arnold et al., 2012)

File name	Description
File.cio	*Watershed file that names catchment levels for output parameters*
.fig	*Watershed configuration file*
.pcp	*Precipitation input file (up to 300 stations)*
.tmp	*Temperature file with daily minimum and maximum temperatures*
Crop.dat	*Land cover/plant growth database file containing plant growth parameters*
.hru	*HRU level parameters*
.sol	*Soil input file*

5.3.1.1 Elevation & Topography

A digital elevation model (DEM) is used to configure the catchment by dividing it into a sub-basin or sub-catchments. The automatic watershed delineation tool, which is the first step of the model, allows for the creation and selection of outlet nodes and the determination of sub-catchment properties and river reach attributes. Depending on the resolution of the DEM used, either a manual or automatic setup can be chosen.

The 30 m Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global DEM was used at the starting point. The resolution of this DEM is 30 m by 30 m. However, this DEM does not provide accurate heights in areas of tall vegetation. Verified point and contour data was used to correct these errors and interpolate a higher resolution model. WGS 1984 UTM Zone 36S was used as the projection for this area (ArcSWAT requires all layers to be projected uniformly and UTM is the most commonly used projection for hydrological studies).

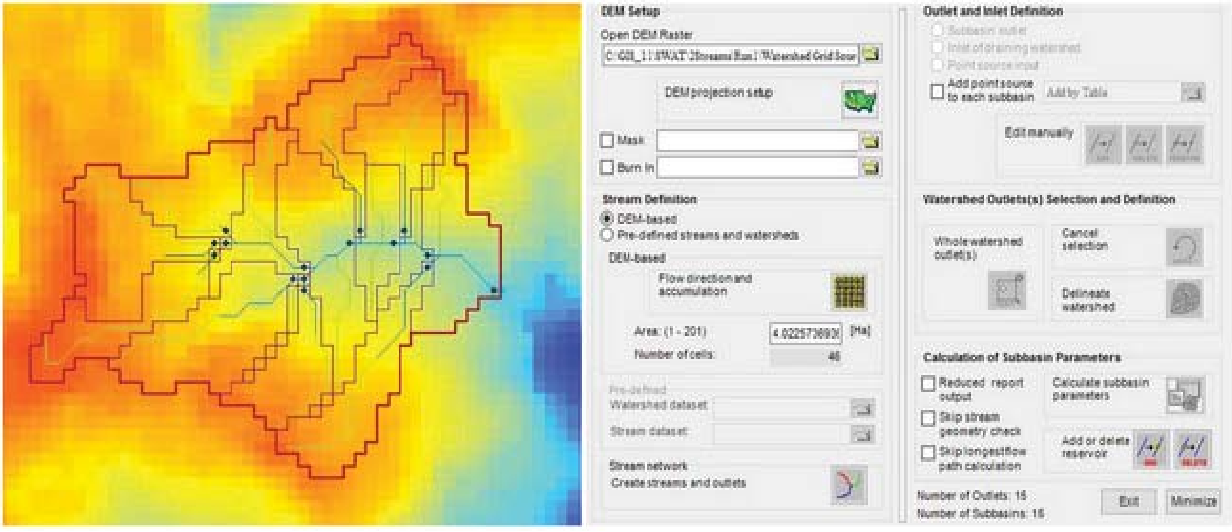

Figure 5.22 Watershed, sub-catchment and river reach delineation in ArcSWAT

5.3.1.2 Land Use

A combination of existing databases and user defined boundaries was used to create a new land use shapefile (Figure 5.23). Given the small catchment size, gravel roads were included in the land use set up. This is important as it is likely to contribute to sediment and nutrient wash at the site. The land use definition tool was used in ArcSWAT. This tool clips the land use to the catchment boundary and provides it with a code as determined by the user in GIS. A text file containing this code and the subsequent SWAT land code was compiled by the user. This text file is used to reclassify the land use layer to match attributes contained in the SWAT database.

An important addition to this component was land uses that are either different in South Africa or that do not exist in the SWAT database. In this case, new land uses can be added to the SWAT database. This can be done either through the Access database file or through the user interface. Table 5.10 provides a summary of some of the important land use input attributes and the additional land use attributes added to the SWAT database. The following changes have been made to the model database (further described in Table 5.10) to match South African condition:

- Eucalyptus and wattle have been modified to match South African species and hybrids grown in KwaZulu-Natal;
- New parameters for summer and winter pasture (although not extensive at the site) has been included;
- A new parameter for invaded wetlands with commercial species has been included; and
- A new parameter for cleared wetlands (natural grassland and sedge in this area has been included).

Table 5.10 Summary of modified land use input variables

Crop Name	Crop Code	Units	Modified Land Use						
			Wetlands-Invaded	Wetlands-Cleared	Pasture	Summer Pasture	Winter Pasture	*Eucalyptus grandis*	Wattle (*Acacia mearnsii)*
Crop Code	CPNM	N/A	WETF	WETN	PAST	SPAS	WPAS	EUCA	ACME
Radiation-use Efficiency	BIO_E	MJ/m2	15	47	35	35	30	15	15
Harvest Index	HVSTI	Frac	0.76	0.9	0.9	0.9	0.9	0.5	0.76
Maximum Potential LAI	BLAI	m2/m2	5	6	4	4	4	2.5	3.8
Fraction of Growing Season Leaf Decline	DLAI	m2/m2	0.99	0.7	0.99	0.99	0.8	0.99	0.99
Maximum Canopy Height	CHTMX	m	6	2.5	0.5	0.5	1.5	20	18
Maximum Root Depth	RDMX	m	3.5	2.2	2	2	2	3.5	3.5
Optimal Temperature for Plant Growth	T_OPT	C	30	25	25	25	15	20	25
Minimum Temperature for Plant Growth	T_BASE	C	10	12	12	12	0	0	0
Lower Harvest Index	WSYF	kg/ha	0.01	0.9	0.9	0.9	0.9	0.05	0.05
Minimum USLE C	USLE_C	Unitless	0.001	0.003	0.003	0.003	0.003	0.001	0.001
Maximum Stomatal Conductance	GSI	m s^{-1}	0.002	0.005	0.005	0.005	0.005	0.012	0.012
Vapour Pressure Deficit on Stomatal Conductance Curve	VPDFR	kPa	4	4	4	4	4	4	4
Fraction of Maximum Stomatal Conductance	FRGMAX	Frac	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Decline in Radiation-use Efficiency	WAVP	g/MJ/kPa	8	8.5	10	10	8	3	8
Elevated Co2 Efficiency	CO2HI	uL Co2/L	660	660	660	660	660	660	660
Biomass Energy Ratio	BIOEHI	Ratio	16	54	36	36	39	20	20
Minimum LAI During Dormancy	ALAI_MIN	m2/m2	0	0	0	0	0	0.75	0.75
Years Until Full Development	MAT_YRS	Years	30	0	0	0	0	10	12
Maximum Biomass	BMX_TREES	tons/ha	1000	0	0	0	0	800	1000
Management Schedule	OpSchedule	N/A	WETF	WETN	PAST	AGRR	AGRR	AGRR	AGRR

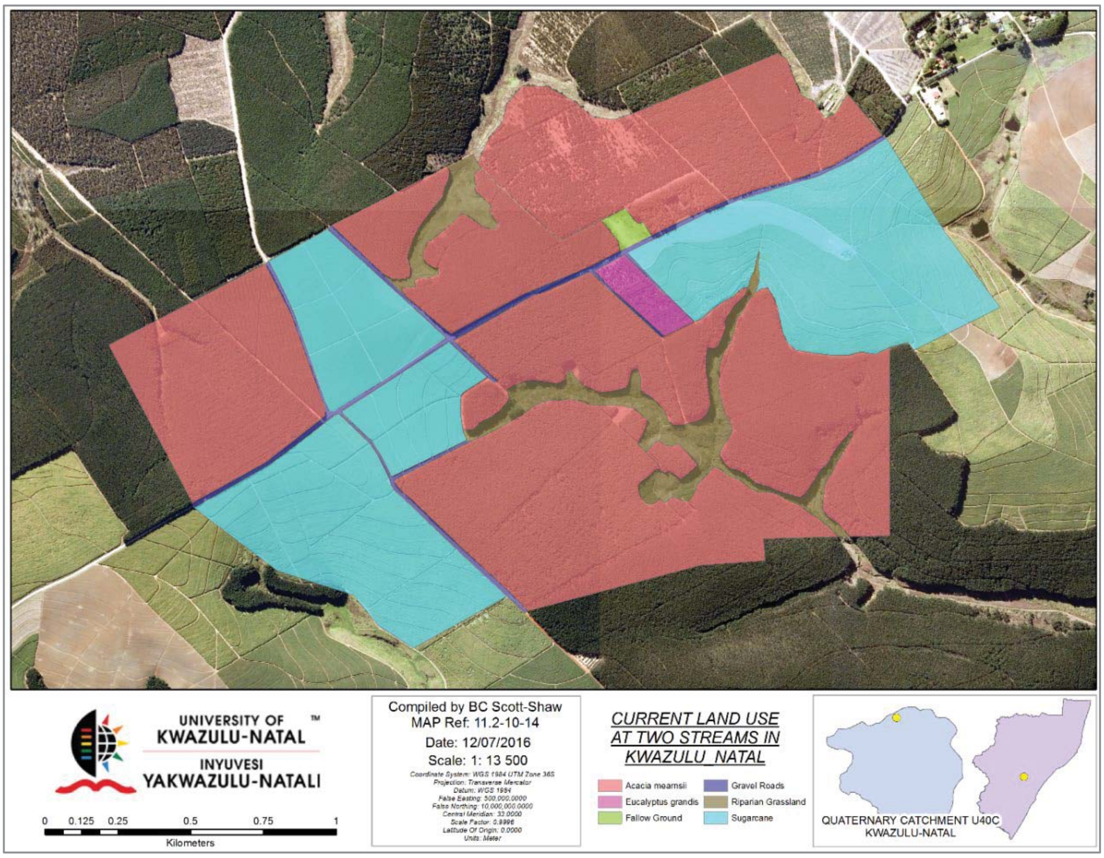

Figure 5.23 Land use classification as an input to ArcSWAT

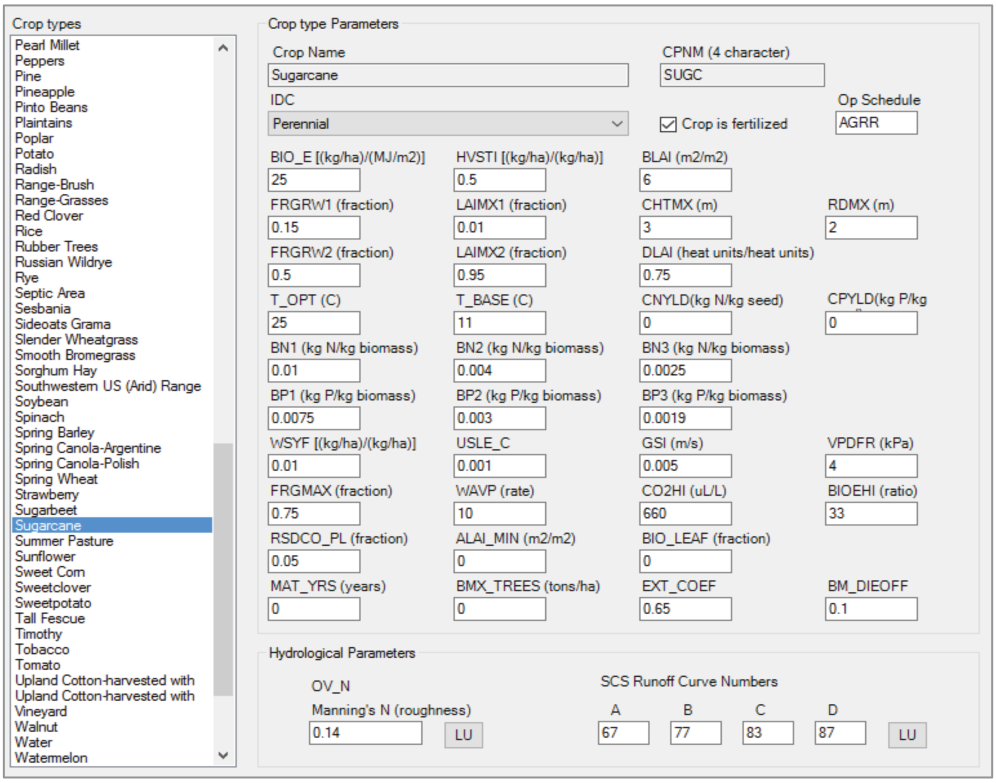

Figure 5.24 Modification of land use input variables

5.3.1.3 Soils

A soil survey was undertaken for WRC project K5/1748 and further described by Le Roux *et al*. (2015) - Hydrology of South African Soils and Hillslopes. The soil data was available as point form. The terrain of the land was used to extrapolate these points to a spatially explicit area. The structure, depth, number of layers, texture and chemical properties were used to construct a highly detailed soil layer with up to five variable soil layers in some areas.

The soils component is one of the more difficult definitions to translate outside of the United States. The database (Usersoils) was edited with each attribute for each representative polygon code. A text file was again used to code the data from the spatially explicit polygon (Figure 5.25) to match the code in the database. Soils data were checked using the GIS interface and modified if required.

Soil properties that influence runoff potential are those that impact the minimum rate of infiltration for a bare soil after prolonged wetting and when not frozen (Everson *et al*., 2006). These properties are depth to seasonally high-water table, saturated hydraulic conductivity, and depth to a very slowly permeable layer. Soil may be placed in one of four groups, A, B, C, and D, or three dual classes, A/D, B/D, and C/D. These are tabulated in Table 5.10.

Table 5.11 Soil hydrological group for ArcSWAT input

Group	Description
A	(Low runoff potential). The soils have a high infiltration rate even when thoroughly wetted. They chiefly consist of deep, well drained to excessively drained sands or gravels. They have a high rate of water transmission.
B	The soils have a moderate infiltration rate when thoroughly wetted. They chiefly are moderately deep to deep, moderately well-drained to well-drained soils that have moderately fine to moderately coarse textures. They have a moderate rate of water transmission.
C	The soils have a slow infiltration rate when thoroughly wetted. They chiefly have a layer that impedes downward movement of water or have moderately fine to fine texture. They have a slow rate of water transmission.
D	(High runoff potential). The soils have a very slow infiltration rate when thoroughly wetted. They chiefly consist of clay soils that have a high swelling potential, soils that have a permanent water table, soils that have a claypan or clay layer at or near the surface, and shallow +soils over nearly impervious material. They have a very slow rate of water transmission.

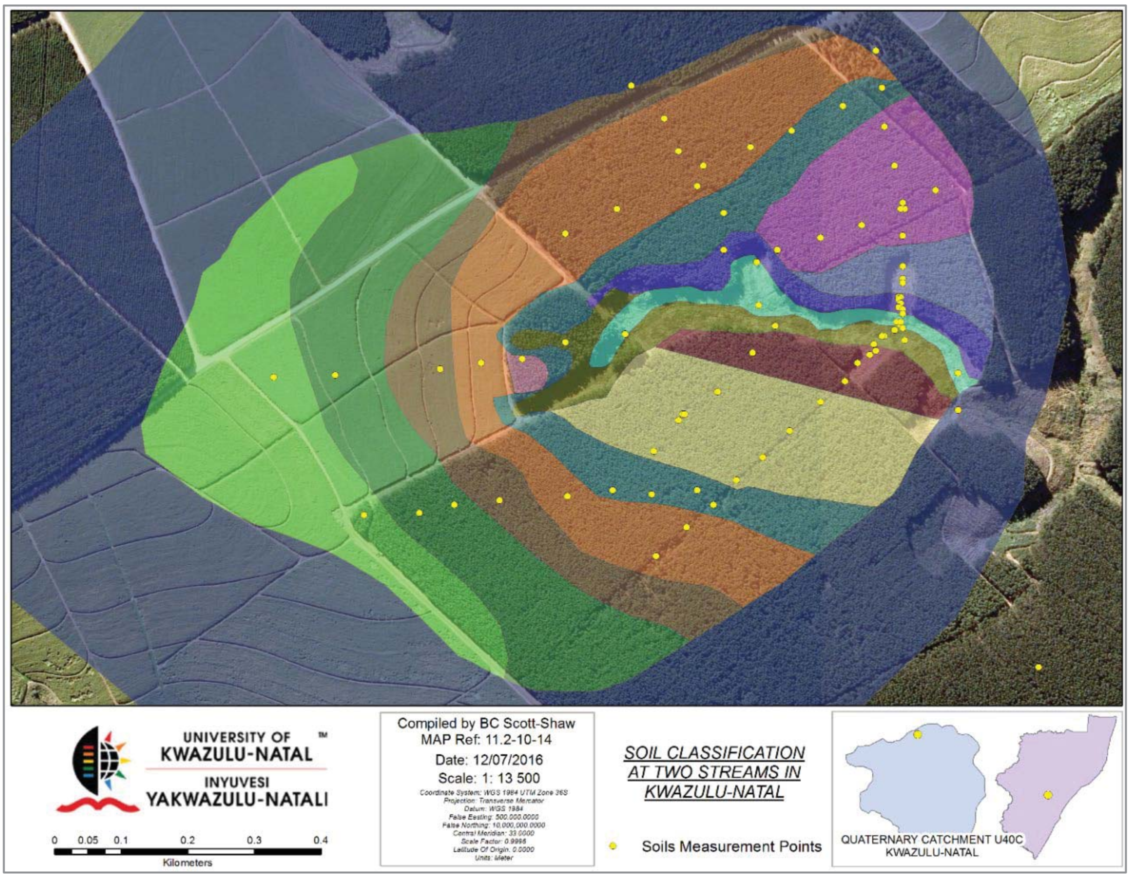

Figure 5.25 Soil characteristics for Two Streams

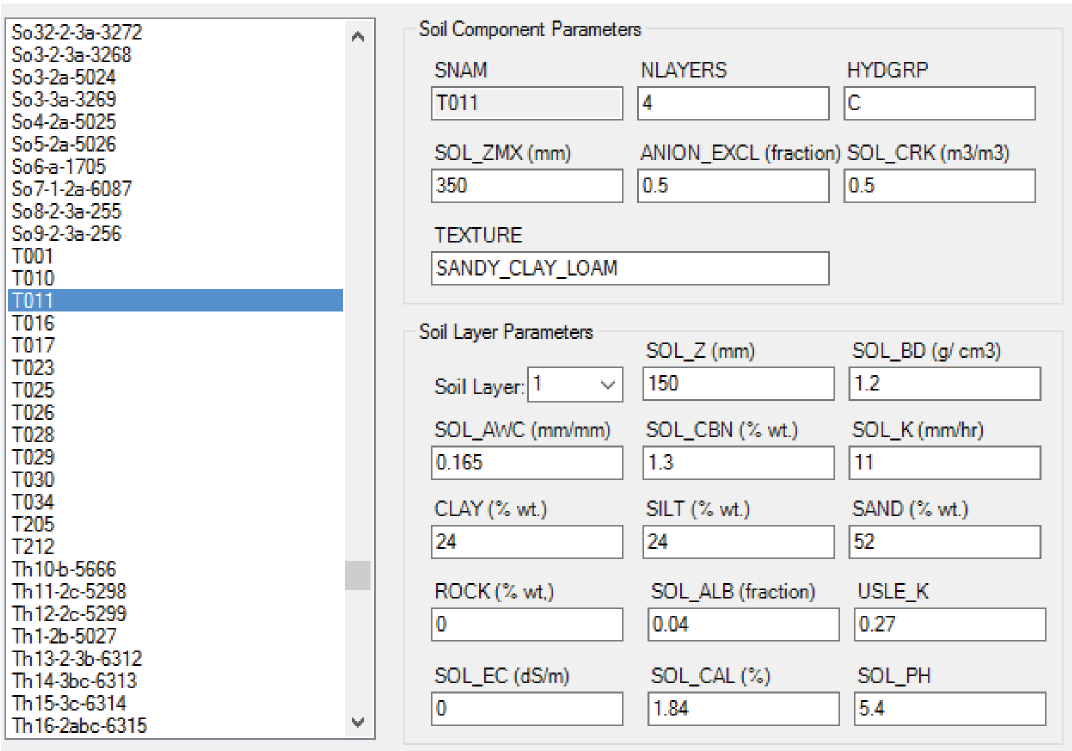

Figure 5.26 Modification of soil input variables

5.3.1.4 Slope

The slope definition uses the base DEM. This tool allows the user to define the slope classes. More slope classes would result in more HRUs. Once the user has chosen the slope classes, the layers are used to create the final HRUs. For this study, five slope classes were used. 189 HRUs were produced for the Two Streams catchment.

5.3.1.5 Climate

Weather Data Definitions were modified to allow for user defined data to be included. All the data was obtained from ongoing research at Two Streams. A table was created for each rainfall station including the Station ID, location and altitude. This was edited into the SWAT2012.mbd. Individual text files containing daily rainfall, temperature, solar radiation, relative humidity and wind speed were created that could be linked to the modified database.

The author is compiling a SWAT weather database for all of the catchments run previously and going forward. This will allow other models to use this data with ease (Figure 5.27).

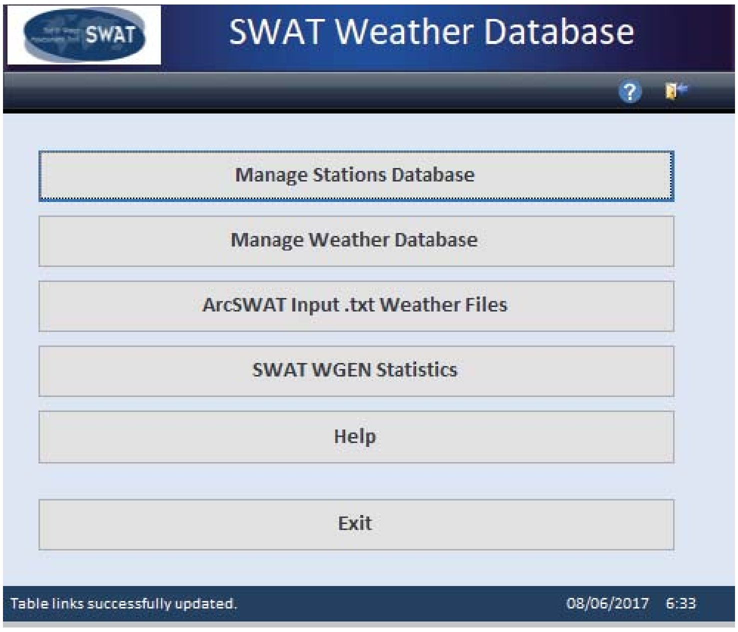

Figure 5.27 SWAT weather database interface

5.3.1.6 Management

Land management is crucial for hydrological simulations. The management operations were modified in ArcSWAT to specify the initial growing state and periods during harvest, fallow lands and planting – as the model is not South African in origin, we have had to modify to take account of local management practices (Figure 5.28). The management periods were obtained from previous research projects. Although the management practices have continued to the monitoring period, this previous management schedule was incorporated into the modelling component and extended with any information on the management available.

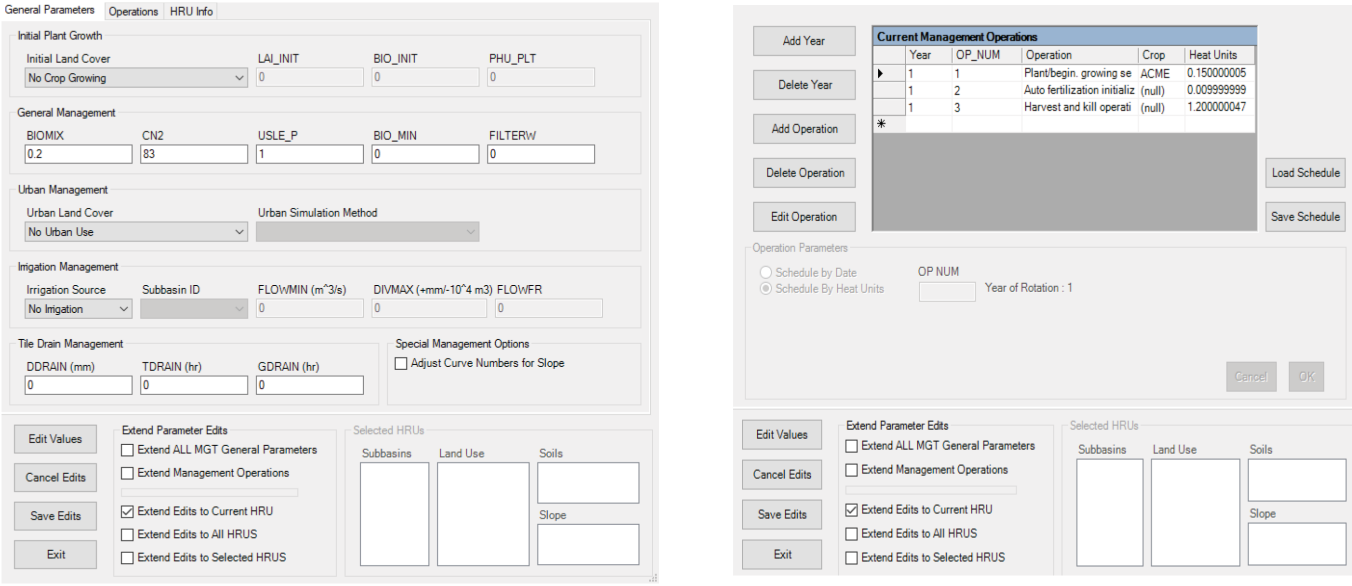

Figure 5.28 Modification of management input variables

The final output for the Two Streams catchment, with an area of 0.75 km^2, yielded 189 HRUs. The output for the greater Quaternary Catchment U40C is provided in Figure 5.29. This shows the high level of detail used in the model.

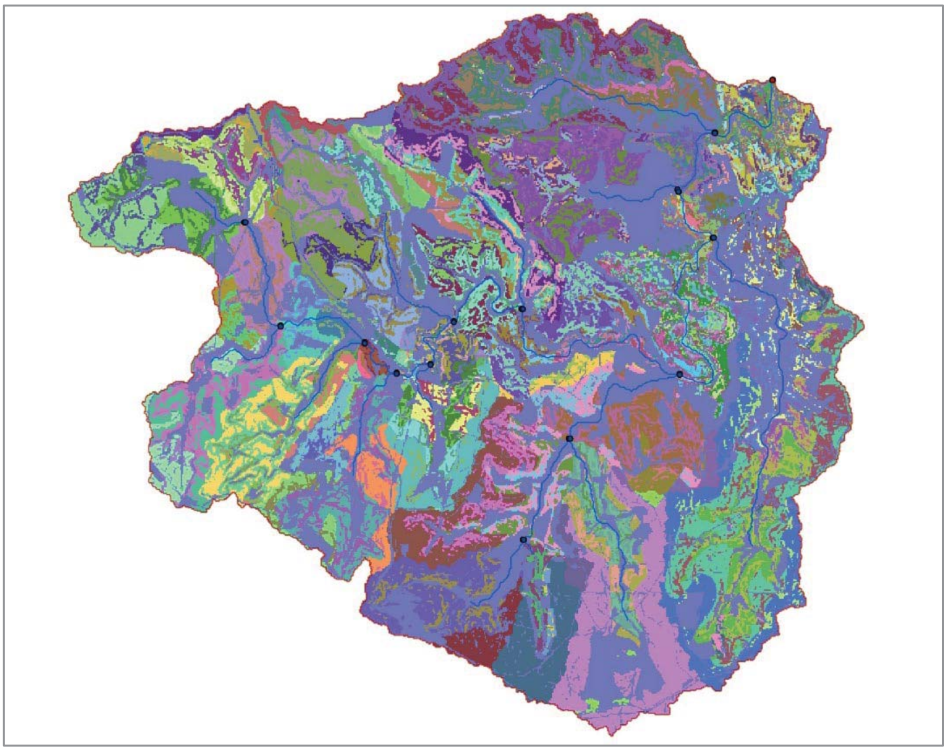

Figure 5.29 Final SWAT HRU output

5.3.2 *Sediment Yield*

Observed sediment yield data has been ongoing in the research site. Nine 1 m x 1 m runoff micro-plots were installed within the catchment with three replicates per slope position (Figure 5.30). An additional nine 5 m×2 m runoff plots were installed adjacent to the micro-plots with three replicates per slope position (Gillham, 2016). The gutter fed into the outlet of the micro-plot, connected to a pipe, which fed into a bucket to capture the water. After each site visit, total overland flow volume from each micro-plot replicate was measured with a measuring cylinder and a 500 ml representative sample of the water collected (Gillham, 2016). The sediment in the gutters was flushed down into the bucket with the sample water. Runoff plots are useful tools to evaluate interill erosion as they provide information on the impact that generated runoff flow has on sediment loss. (Chaplot and Le Bissonnais, 2003).

Figure 5.30 Runoff plots installed within the *Acacia mearnsii* stand at Two Streams

Sediment input components were modified within the model. A key component was the soils input. This, along with the climate input data, is a key determinant as to whether overland flow will be generated. Components such as management are also important and were interrogated through the interface (Figure 5.31) and the SWAT database.

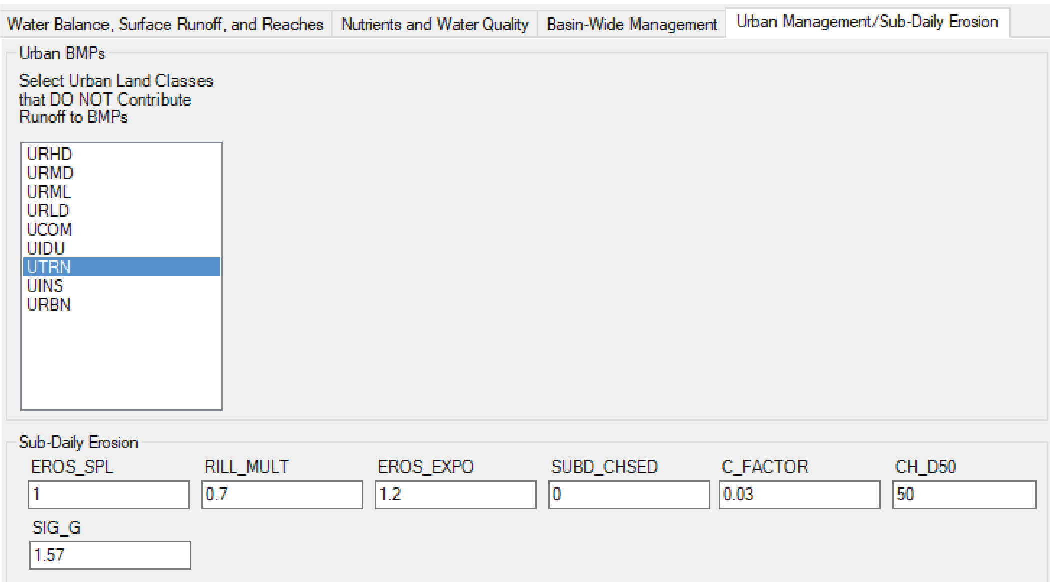

Figure 5.31 Runoff plots installed within the *Acacia mearnsii* stand at Two Streams

6: RESULTS AND DISCUSSION

This chapter details the relationship between rainfall and runoff and the impact on sediment yield and nutrient concentrations (nitrate, phosphate and carbon) at the different spatial scales obtained from the runoff plots at Two Streams and Fountainhill Estate. Rainfall simulation results have been provided for the Okhombe catchment. Additionally, the MIKE-SHE and SWAT model have been intensively applied at Two Streams and Fountainhill Estate.

6.1 Soil Loss and Sediment Yield at Two Streams

6.1.1 *Flow paths and storage mechanisms*

Previous studies in the Two Streams research catchment (Everson *et al*., 2006) provided an excellent opportunity to study soil water flow-paths in conjunction with detailed hydrological measurements on streamflow, evapotranspiration, rainfall and soil water contents monitored in the catchment since 2000. It is important to identify, define and quantify the pathways, connectivity's, thresholds and residence times of components of flow making up stream discharge (Van Tol *et al*., 2011). If these aspects are efficiently understood then the pathways that cause erosion and sedimentation can be better understood.

At Two Streams it was hypothesized by Kunene *et al.* (2013) that during the rainy season, infiltrated ET excess water mainly flows vertically and rapidly through deep recharge soils on the hillslopes to become stored in the saprolite, and then flows laterally to exit into the stream via responsive soils in the valley bottom.

The Two Streams catchment covers an area of approximately 73.3 ha and is drained by one perennial stream (Figure 6.1). Annual rainfall is approximately 898 mm, concentrated during the rainy season extending from November through March. All the hillslope soils (Figure 6.1) are deep (2 meters) and of the recharge type with rapid hydraulic conductivity, overlying well weathered sandstone saprolite generally to a depth of around 4 to 5 meters.

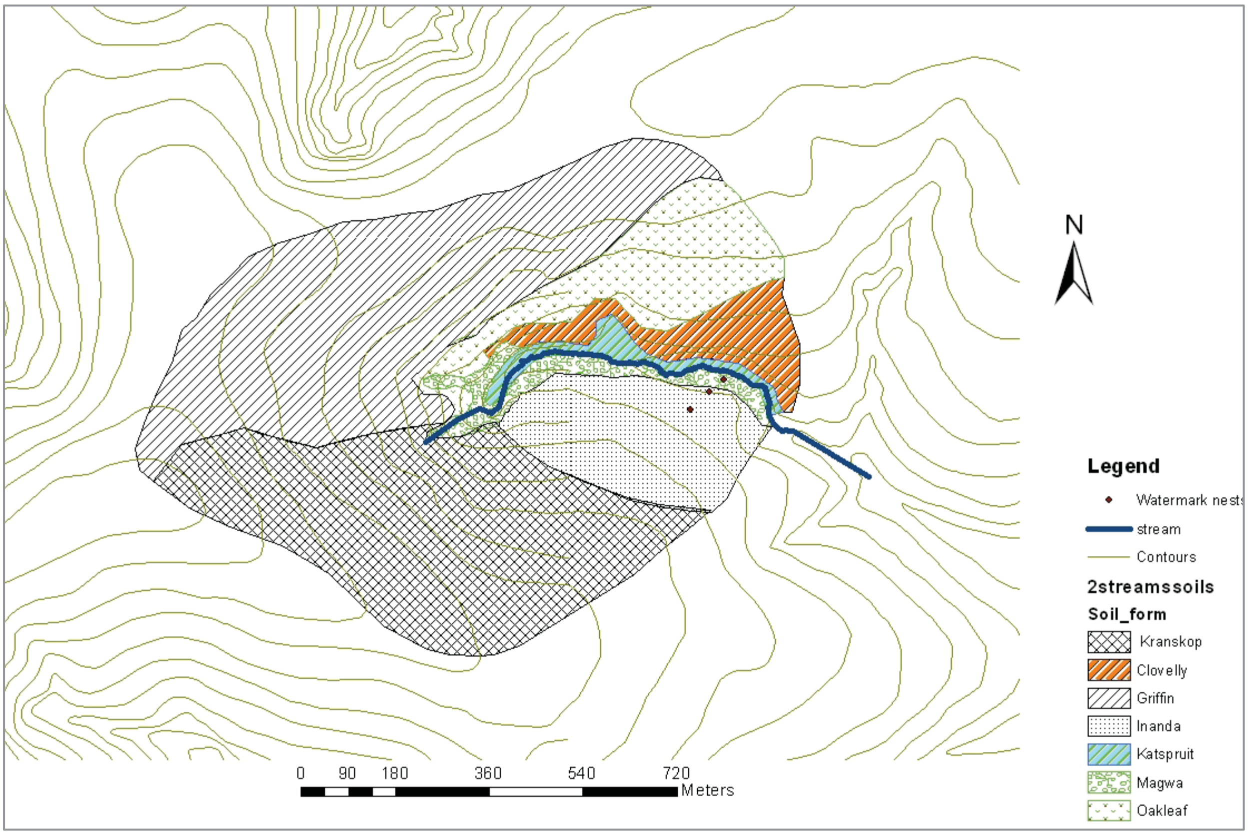

Figure 6.1 The catchment soil map with location of watermark sensors

From sampled profiles and hydrological and soil water data from Everson *et al* (2006), Kunene *et al*. 2013 were able to develop a conceptual hydropedological model that showed the dominant hillslope soil water pathways at Two Streams. This model (based on observed soil profile morphology and measured hydraulic properties) is illustrated in Figure 6.2. Infiltrated water will follow a vertical flow-path (Figure 6.2, arrow 1) to recharge the deep weathered saprolite. The hillslope soils are considered to be recharge types, since no redoximorphic features indicating periodic saturation, were found in the solum. However, overland flow (arrow 6) can be expected when rainfall intensities exceed the infiltrability of soils. For the present study this is an important observation as it will be the dominant erosion pathway at Two Streams. In the valley bottom, Katspruit soil with a reduction morphology is frequently saturated with water and saturation excess overland flow will be generated during rain events (arrow 2). The water in the deep saprolite is expected to flow laterally at the transition to less weathered and less permeable saprolite (arrow 3), and then exit via Katspruit soils into the stream. It is this water from the saprolite storage that causes prolonged conditions of saturation and the gleyed *gh* horizon of Katspruit soils of the valley bottom. Lateral inflow of water from the deep saprolite is expected to raise the water table in the Katspruit soil (arrow 4), resulting in vertical upward flow during rain seasons. Evidence of lateral movement of deep saprolite water is also provided for the hypothesis that water from the deep saprolite deposits the chemical constituents (Si, Al, Ca, etc) needed for the neoformation of clay minerals in the footslope resulting in the gleyed *on* and *gh* horizons of the Magwa and Katspruit soils, respectively. In the Magwa soil the fact that the K_s value of the *on* horizon is considerably lower than that of the *ye* horizon will promote a relatively moist water regime in the ye horizon, and presumably be the cause of its yellow colour (relatively high in goethite), compared to the red colour (heamatite dominant) of the B horizon of the Inanda soil. The latter colour throughout the horizon provides evidence that there is no significant drainage restriction between the Inanada soil and the weathered saprolite below. Vertical return flow from the deep groundwater system into the stream can also be expected in the valley bottom (arrow 5). The hillslope fits well into class 4 (a1) of the hydropedological classification of South African hillslopes (Figure 6.2).

At Two Streams during the rainy season, infiltrated ET excess water mainly flows vertically and rapidly through deep recharge soils on the hillslopes to become stored in the saprolite, and then flows laterally to exit into the stream via responsive soils in the valley bottom. Although this is the dominant predicted flow-path in an undisturbed state it is hypothesized in this study that overland flow (high erosion) (arrow 6 in Figure 6.2) will become dominant if poor management is practiced during harvesting. This can be expected when rainfall intensities exceed the infiltrability of soils.

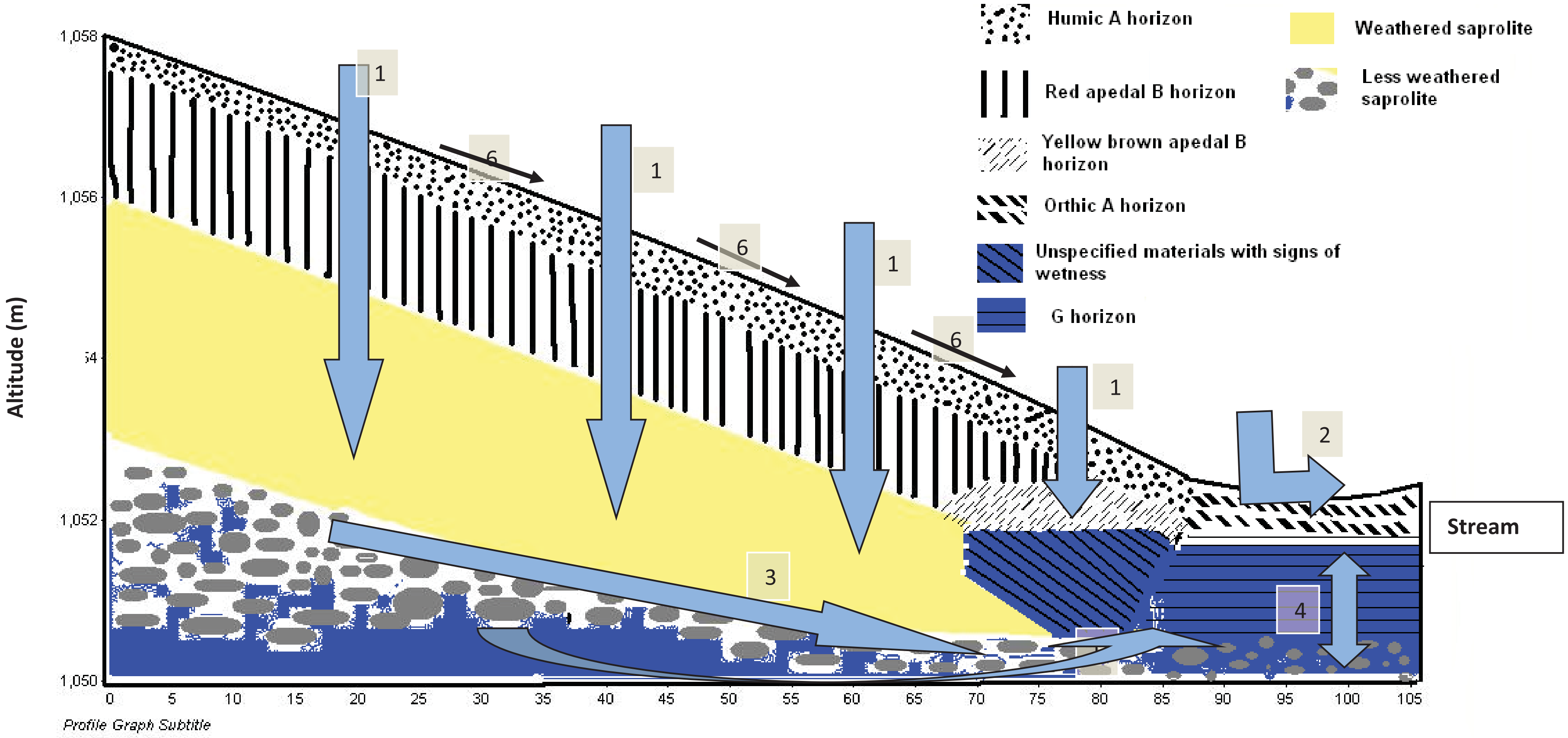

Figure 6.2 Conceptual model of a lower section of the modal hillslope in the Two Streams catchment (After Kunene et al. 2013)

6.1.2 Meteorological and catchment data

6.1.2.1 Precipitation

This study took place over fourteen months which included two summer rainfall seasons and a low winter rainfall period (Table 6.1). A rainfall season can be defined when rainfall is frequent and when most of a region's average annual rainfall occurs and a non-rainfall season, when rainfall is less frequent and not expected (Wang, 2002). The cumulative total rainfall over the study period was 1135.2 mm over 428 days. Total rain for the rainfall season of 2014-2015, November - February (four months) was 422.5 mm; 275.7 mm for the non-rainfall season of 2015 (eight months) and 437 mm for the rainfall season of 2015-2016 (four months) (Table 6.1). The annual cumulative rainfall for 2015 was 782 mm. When comparing the amount of rainfall to previous years; 2012 received (958 mm), 2013 (871 mm) and 2014 (712 mm). This study was undertaken in a relatively dry year (average rainfall 659-1139 mm) (Clulow *et al.*, 2011). The highest monthly rainfall occurred in the summer months, with an uncharacteristically high rainfall in July 2015 (Figure 6.3). Site visits took place after high rainfall events, with the majority of site visits taking place during the summer months. The AWS recorded an intense rainfall event on the 18th December 2015 with a total 114.6 mm of rainfall falling in the space of a few hours.

Table 6.1 Rainfall characteristics for the different rainfall seasons (2014-2016). Cumulative annual rainfall amount (Cum)

Season	Cum
	mm
November 2014-February 2015	422.5
March 2015-October 2015	275.7
November 2015-March 2016	567.0

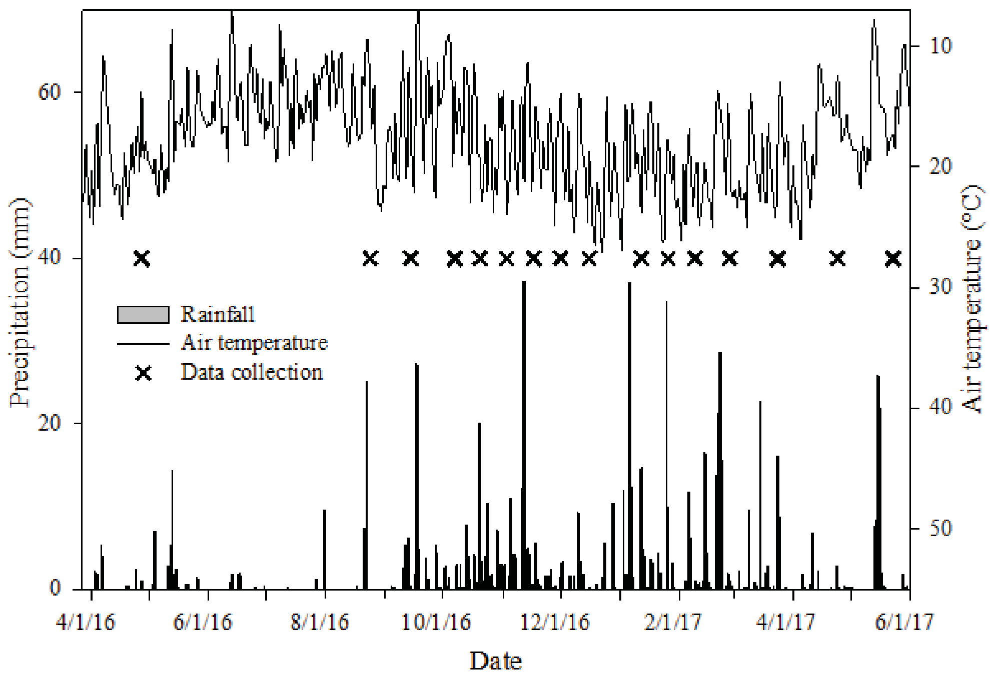

Figure 6.3 Monthly rainfall at Two Streams from December 2014 to March 2016

Rain gauges were set-up to determine the spatial variation in rainfall within the study site (assuming no evaporation and a consistent canopy cover), high rainfall events had greater variation between the rain gauges compared to small rainfall events, with an average variation of 2 mm of rainfall for a rainfall event (Table 6.2).

Table 6.2 Rainfall and interception records within the two dominant landuses at Two Streams

Site visit date	AWS (mm)	Days between collection	Rain gauge- *Acacia* (mm)	Rain gauge- Sugarcane (mm)	*Acacia* Interception (%)	Sugarcane Interception (%)
27/04/2016	50	53	33	nd	46	nd
24/08/2016	87	118	83	nd	6	nd
14/09/2016	15	17	12	nd	22	nd
07/10/2016	53	22	42	nd	22	nd
20/10/2016	44	12	31	29	30	34
03/11/2016	37	13	25	33	35	22
17/11/2016	85	13	65	74	23	13
01/12/2016	15	13	12	15	78	0
16/12/2016	21	15	21	20	98	9
12/01/2017	97	26	60	51	38	48
26/01/2017	66	13	64	34	4	49
09/02/2017	23	13	16	9	31	31
27/02/2017	106	17	84	32	21	70
24/03/2017	58	24	26	12	55	80
24/04/2017	23	30	23	15	1	36
23/05/2017	68	28	43	38	37	46
Average	**53**	**26.69**	**40**	**30**	**34**	**36**
Total	**855**	**427**	**645**	**366**		

A comparison between the Automatic Weather Station (AWS) and the in-field rain gauges, illustrates the vital role of canopy cover in intercepting rainfall. The AWS consistently recorded higher rainfall then the rain gauges. There was an average interception of 34.1%, assuming no evaporation from the rain gauges. Seasonality did not influence interception rates as the rainfall season 2014-2015 had an interception rate of 31.7%, the non-rainfall season of 2015 had an interception rate of 32.9% and the rainfall season of 2015-2016 had an interception rate of 36.98%. There were two site visits 3rd April 2015 and 12th Jan 2016 that had slightly lower interception rates than what was usually experienced 6.2% and 9.6% respectively this may have been due to evaporation from the rain gauges or human error by taking higher rain gauge readings then what actually was experienced.

6.1.2.2 Slope

The runoff plots at the bottom positions had the steepest gradient (9.30), with the top and middle slope positions having similar gradients (4.00 and 5.60 respectively). The exception being site 6 on the middle slope position with a 7.90 gradient (Table 6.3).

Table 6.3 Slope steepness of each runoff plot

Slope Position	Site number	Slope (°)	Average Slope(°)
Top	Site 1	4.1	4.03
	Site 2	4.2	
	Site 3	3.8	
Middle	Site 4	4.8	5.6
	Site 5	4.1	
	Site 6	7.9	
Bottom	Site 7	8.9	9.33
	Site 8	8.4	
	Site 9	10.7	

6.1.2.3 Soils

Soil analysis was undertaken by the Cedara soil analytical laboratory which provided information on the total carbon and nitrogen in the soil (Table 6.4). The total carbon (0.45%) and nitrogen (6.37%) concentrations were consistent for all runoff plots. Soil fertility provided information on the following elements: phosphorous, potassium, calcium, magnesium, zinc, manganese and copper. Furthermore, the number of cations, acid saturation and pH were measured (Table 6.5). The data were consistent across the catchment, with only site nine recording any notable change, with higher calcium and cations values and lower acid saturation. The soil texture was sandy silt at all runoff plots.

Table 6.4 Total percentage of soil nitrogen and carbon

Slope Position	Sample No.	Total % Nitrogen	Average Total % Nitrogen	Std. dev Total % Nitrogen	Total % Carbon	Average Total % Carbon	Std. dev Total % Carbon
Top	Site 1	0.43	0.46	0.042	5.96	6.67	0.71
	Site 2	0.45			6.68		
	Site 3	0.51			7.38		
Middle	Site 4	0.58	0.44	0.132	7.3	5.86	1.38
	Site 5	0.32			4.55		
	Site 6	0.41			5.73		
Bottom	Site 7	0.47	0.46	0.026	6.8	6.59	0.423
	Site 8	0.48			6.86		
	Site 9	0.43			6.1		
		Total Average	0.45	0.072		6.37	0.892

Table 6.5 Chemical analysis of soils

Slope Position	Sample ID	Sample density (g/mL)	P (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	Exch. acidity cmol/L	Total Cations cmol/L	Acid sat. %	pH (KCl)	Zn (mg/L)	Mn (mg/L)	Cu (mg/L)
	Site 1	0.86	14	37	216	32	2.56	4	64	3.71	4.8	21	1.8
Top	Site 2	0.86	11	61	151	30	2.9	4.06	71	3.67	2.3	14	1.5
	Site 3	0.81	14	53	155	22	3.02	4.11	73	3.58	3.9	17	1.6
	Site 4	0.83	12	40	131	17	2.27	3.16	72	3.82	0.6	28	1.4
Middle	Site 5	0.88	5	40	103	22	2.74	3.54	77	3.68	0.2	19	1.7
	Site 6	0.87	8	32	91	8	2.72	3.32	82	3.66	0.3	29	1.6
	Site 7	0.9	5	67	202	32	3.14	4.58	69	3.76	0.5	14	1.7
Bottom	Site 8	0.87	14	47	172	14	3.58	4.67	77	3.71	0.5	25	2.1
	Site 9	0.94	6	67	555	107	2.11	5.92	35	3.86	0.7	19	2.2

6.1.2.4 Vegetation

The Braun Blanquet classification method was used to determine the vegetation cover and abundance at each plot (Table 4.6). In the commercial forest the litter consisted of twigs and leaves that fell from the *Acacia mearnsii.* The species richness of the area was low with the dominant grass species in the commercial forest being *Eragrostis tef.*

Table 6.6 Vegetation abundance at each site using the Braun Blanquet method

	10 m^2					1 m^2		
Site number	Individual Trees	Average tree diameter at breast height (dbh) (mm)	Aerial Cover	Litter Cover	Grass Cover	Aerial Cover	Litter Cover	Grass Cover
Site 1	4	140,1	4	5	2	3	5	1
Site 2	4	148.4	4	5	r	3	5	r
Site 3	4	130.4	3	5	1	3	5	+
Site 4	3	124.2	3	5	2	3	5	3
Site 5	4	139.0	4	5	2	4	5	1
Site 6	4	118.5	3	5	2	3	5	2
Site 7	4	122.5	4	5	1	2	5	3
Site 8	4	139.4	4	5	1	3	5	5
Site 9	4	136.6	5	3	5	3	5	5

Average tree dbh in mm (n=100)	167.1

Note: The ratings for the Braun Blanquet are: r = very small cover, rare occurrence, + = cover less than 1%, 1 = cover between 1-5%, 2 = cover between 5-25%, 3 = cover between 25-50%, 4 = cover between 50-75% and 5 = cover more than 75%.

6.1.3 Runoff

This section provides details on the runoff at the different slope positions and spatial scales (Table 6.7). It also provides information of the measured water repellency as this determine if the rainfall was likely to infiltrate into the soil or run directly off the soil.

Table 6.7 Average runoff at the different plot locations. Three plot replicates are located at each site: top slope; middle slope and bottom slope. A total of nine 10 m^2 plots and 1 m^2 plots with fifteen rainfall events were recorded

	Top	Middle	Bottom
(n=15)			
Average 10 m^2	9.78 l/m^2	6.48 l/m^2	10.46 l/m^2
Average 1 m^2	8.87 l/m^2	7.49 l/m^2	13.49 l/m^2

The plots on the bottom slope position averaged the highest volume of runoff with the 10 m^2 plots averaging 10.46 l/ m^2 and the 1 m^2 plots 13.49 l/ m^2. There was a decline in runoff at the top slope with the 10 m^2 plots averaging 9.78 l/m^2 and the 1 m^2 plots averaging 8.87 l/m^2. The plots on the middle slope positions averaged the lowest volume of runoff with the 10 m^2 plots recording on average 6.48l l/m^2 and the 1 m^2 plots recording 7.49 l/ m^2. In terms of variation of runoff between the runoff plots, for high runoff events there was high variation between the runoff plot compared to small runoff events which had low variation (Figure 6.4). On the 18th December 2015 there was a maximum runoff event of 28 l/ m^2 for the 10 m^2 runoff plot and 24.71 l/ m^2 for the 1 m^2 runoff plots. The 23th February 2015 recorded the minimum runoff event of 0.42 l/ m^2 for the 10 m^2 runoff plot and 2.07 l/ m^2 for the 1 m^2 runoff plots, this was due to low rainfall and possibly from antecedent conditions reducing runoff. During the duration of the study (approximately fifteen months), a total of 1327 l (132.7 l/ m^2) of runoff ran off a single 10 m^2 plot whilst 139 l (139 l/ m^2) of runoff ran off a 1 m^2 runoff (Table 4.8). The commercial forest became increasingly less effective at reducing runoff as the amount of precipitation per storm increased. Pervious surfaces are highly affected by antecedent moisture conditions, as they will produce a greater rate of runoff when they are wet than when they are dry.

For the rainfall season of 2014-2015 (four months), the maximum runoff volume was 14.59 l/ m^2 at the 10 m^2 plots and 12.37 l/ m^2 at the 1 m^2 plots (both on 11th February 2015), the minimum runoff volume was 0.40 l/ m^2 at the 10 m^2 plots and 0.89 l/ m^2 at the 1 m^2 plots (both on 23rd February, 2015). For the non-rainfall season of 2015 (eight months), the maximum runoff volume was 21.79 l/m^2 at the 10 m^2 plots and 9.44 l/ m^2 at the 1 m^2 plots (both on 27th May 2015), the minimum runoff volume was 0.51 l/ m^2 at the 10 m^2 plots and 2.91 l/ m^2 at the 1 m^2 plots (both on 3rd April 2015). For the rainfall season of 2015-2016 (four months) the maximum runoff volume was 28.66 l/ m^2 at the 10 m^2 plots and 24.71 l/ m^2 at the 1 m^2 plots (18th December 2015). The minimum runoff volume was 0.42 l/ m^2 at the 10 m^2 plots and 2.06 l/ m^2 at the 1 m^2 plots (27th January 2016). Note there were two site visits that had a high amount of runoff the 27th May 2015 and 18th December 2015. The 18th December 2015 was due to an intense rainfall (114.6 mm) and the 27th May 2015 was possibly due to high rainfall (85 mm) but more likely due to antecedent moisture as the rainfall on that date was lower than some other rainfall events, thus it is more likely that rainfall occurred when there was already antecedent moisture present causing greater surface runoff. The AWS data shows that for the 27th May site visit there had been small but consistent rainfall events, this meant antecedent moisture was present and thus when rainfall did occur greater surface runoff was generated.

The threshold rainfall is the amount of rainfall is always required before any runoff occurs may be only in the range of 3 mm while in other catchments this value can easily exceed 12 mm, particularly where the prevailing soils have a high infiltration capacity. The fact that the threshold rainfall has first to be surpassed explains why not every rainstorm produces runoff. This is important to know when assessing the annual runoff-coefficient of a catchment area. This study required generally more than 10 mm of rainfall for runoff to accumulate in the JOJO tanks.

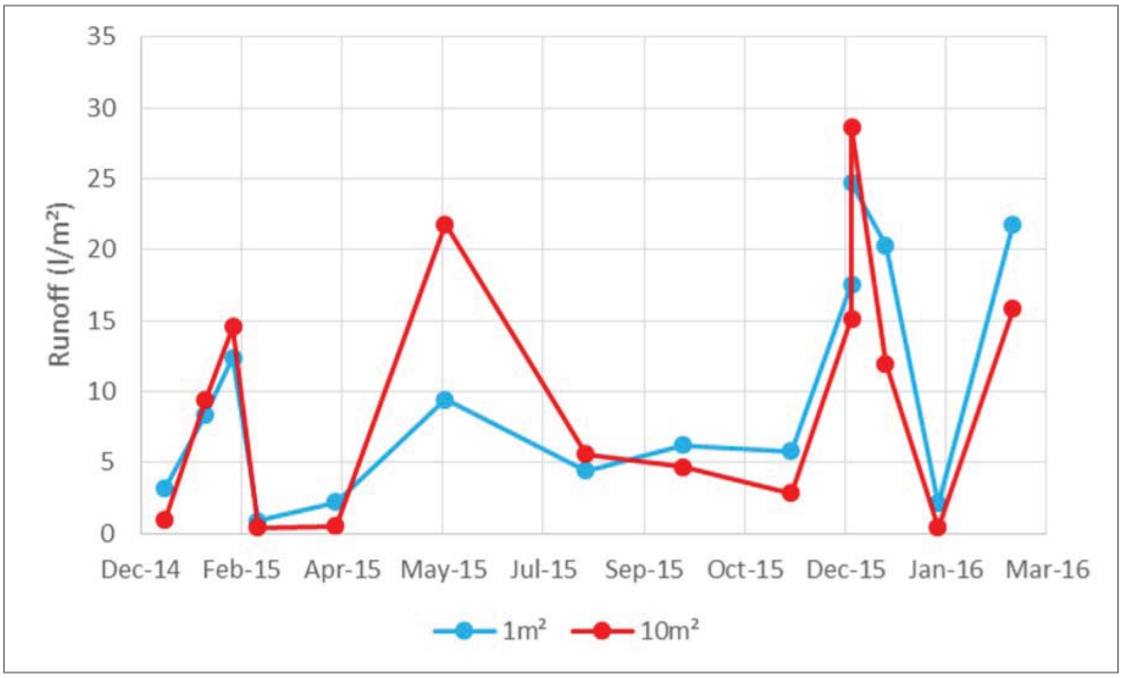

Figure 6.4 Average runoff at the 1 m^2 and 10 m^2 runoff plots

The runoff volume (l/m^2) off the 10 m^2 and 1 m^2 plots were similar during the summer months (Figure 6.4). In the winter period, the 10 m^2 plots produced a higher volume of runoff compared to the 1 m^2 plots, possibly as a consequence of the winter months lower rainfall amounts and intensities. The different seasons would have different processes, in summer rain-splash erosion is prominent due to higher intensity rainfall events, in winter the rainfall events are less intense and the process of runoff flow is likely to be prominent. The average runoff in 2015 was 9.50 l/m^2 for the 10 m^2 runoff plots and 8.65 l/m^2 for the 1 m^2 runoff plots.

Repellency was consistent for the plots over the study duration, with the repellency being tested at every site visit and remaining constant regardless of season. When the soil was dry, the soil was highly repellent, with it taking a drop of water over 5 minutes to infiltrate into the soil (Table 6.8). This highlights the soil being hydrophobic and the conditions in the catchment having low infiltration and high surface runoff, so when rainfall did occur, the rainfall that reached soil would runoff. Important to note that when the water repellency test was done on an area of that plot that had antecedent moisture, infiltration would occur immediately. These tests show that throughout the study, when a rainfall event did occur so in turn did high amounts of runoff, with low amounts being infiltrated. Table 6.8 has the same reading throughout the study.

Table 6.8 Water repellency of the soil at the different slope positions

Date	Top	Middle	Bottom
08-Jan-15	>5min	>5min	>5min
28-Jan-15	>5min	>5min	>5min
11-Feb-15	>5min	>5min	>5min
23-Feb-15	>5min	>5min	>5min
03-Apr-15	>5min	>5min	>5min
27-May-15	>5min	>5min	>5min
05-Aug-15	>5min	>5min	>5min
22-Sep-15	>5min	>5min	>5min
17-Nov-15	>5min	>5min	>5min
11-Dec-15	>5min	>5min	>5min
18-Dec-15	>5min	>5min	>5min
12-Jan-16	>5min	>5min	>5min
27-Jan-16	>5min	>5min	>5min
04-Mar-16	>5min	>5min	>5min

6.1.4 Sediment yield

This section provides details on the sediment yield at the different slope positions and spatial scales (Table 6.9). The average sediment yield is provided as it illustrates the differences between plot locations and sizes.

The slope position with the highest sediment yield was the middle slope position with the 10 m^2 plot producing 0.909 gl^{-1} and the 1 m^2 plots 0.804 gl^{-1} the middle slope position also recorded the lowest runoff, this may demonstrate that rain splash was the dominant cause of sediment loss and not runoff. There was a decline in sediment removal at the bottom plot position with the 10 m^2 plots producing 0.897 gl^{-1} and the 1 m^2 plots 0.834 gl^{-1} which was the slope position that had recorded the highest runoff volume. The slope position that had the lowest sediment eroded was the top slope positions with the 10 m^2 plots on average producing 0.837 gl^{-1} and the 1 m^2 plots 0.834 gl^{-1}.

Table 6.9 Sediment yield comparison (average volume) at the different plot locations (top, middle, and bottom) for the different plot

	Top	Middle	Bottom
(n=15)			
Average 10 m^2	0.837 gl^{-1}	0.909 gl^{-1}	0.897 gl^{-1}
Average 1 m^2	0.834 gl^{-1}	0.804 gl^{-1}	0.790 gl^{-1}

For the rainfall season of 2014-2015 (four months) (four events), the maximum sediment yield for a rainfall event was 0.811 gl^{-1} at the 10 m^2 plots and 0.802 gl^{-1} at the 1 m^2 plots, the minimum sediment yield for a rainfall event was 0.623 gl^{-1} at the 10 m^2 plots and 0.770 gl^{-1} at the 1 m^2 plots. For the non-rainfall season of 2015 (eight months) (four events), the maximum sediment yield for a rainfall event was 0.801gl^{-1} at the 10 m^2 plots and 0.801 mgl^{-1} at the 1 m^2 plots, the minimum sediment yield for a rainfall event was 0.740 gl^{-1} at the 10 m^2 plots and 0.749 gl^{-1} at the1 m^2 plots. For the rainfall season of 2015-2016 (four months (six events) the maximum sediment yield for a rainfall event was 1.784 gl^{-1} at the 10 m^2 plots and 1.090 gl^{-1} at the 1 m^2 plots. The minimum sediment yield for a rainfall event was 0.814 gl^{-1} at the 10 m^2 plots and 0.740 gl^{-1} at the 1 m^2 plots. Important to note that most of the maximum values recorded were during high rainfall events and the minimum values occurred during low rainfall events, these results point to rainfall as a key driver of sediment loss.

During the duration of the study (approximately fifteen months), on average a total of 1.38 kg (138 g/m^2) of sediment was removed from a 10 m^2 plot from runoff, whilst 0.119 kg (119 g/m^2) of sediment had been removed from a 1 m^2 runoff plot through runoff. The amount of sediment removed from the plots was correlated with the rainfall/runoff amount. With high rainfall/runoff associated with high sediment yield. Highest contributor to sediment yield came on the 18th December 2015 which was an intense rainfall event (114.6 mm in 2 hours), led to high runoff which in turn led to high sediment yield (Table 6.10).

Table 6.10 Total sediment volume from the runoff plots

Date	10 m² (g)	1 m² (g)
08-Jan-15	6.03	2.55
28-Jan-15	75.63	6.62
11-Feb-15	118.32	9.75
23-Feb-15	3.23	0.69
03-Apr-15	4.14	1.64
27-May-15	174.42	7.56
05-Aug-15	41.08	3.29
22-Sep-15	38.24	4.69
17-Nov-15	26.45	4.93
11-Dec-15	119.90	13.67
18-Dec-15	511.29	26.94
12-Jan-16	105.20	18.67
27-Jan-16	3.46	1.53
04-Mar-16	149.63	16.29
Total	**1377.00**	**118.85**
Average	**98.36**	**8.49**

There was generally low variation between the runoff plots (Figure 6.5). T tests confirmed these results. The sediment volume (gl^{-1}) from the 10 m^2 plot and 1 m^2 plots was similar throughout the study. With a sediment yield of 138 g/m^2 at a 10 m^2 plot compared to 119 g/m^2 at a 1 m^2 plot. Only the 18th of December (due to an intense rainfall event) showing a marked difference, with the 10 m^2 plots producing a significantly higher sediment volume (Figure 6.5).

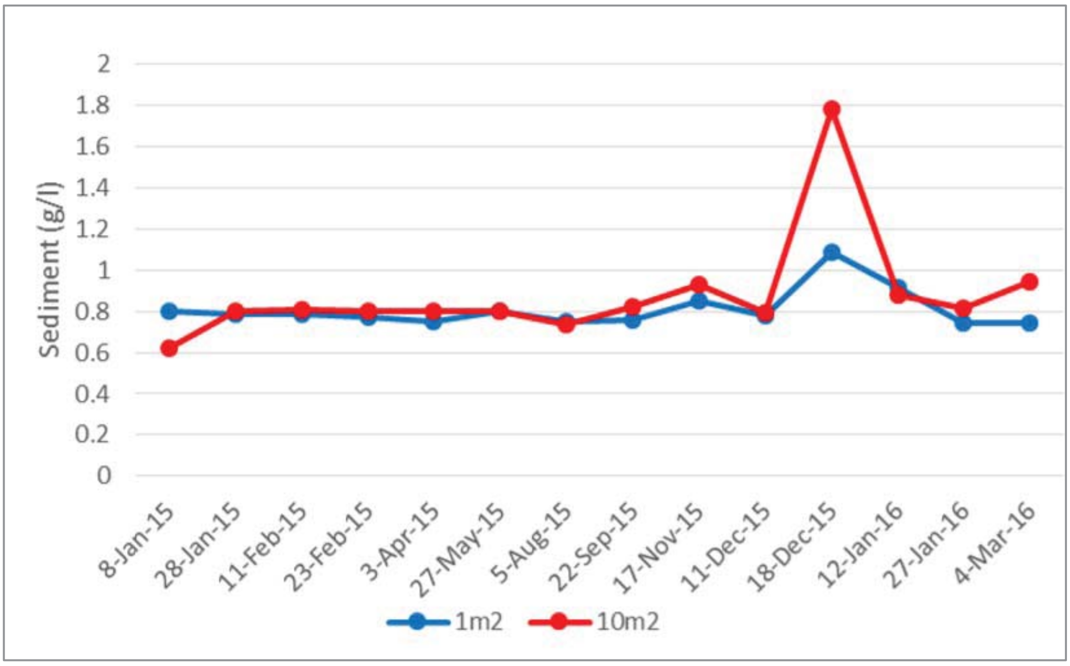

Figure 6.5 Relationship between 1 m^2 and 10 m^2 plots for sediment loss

The highest cumulative sediment yield was from the 34 ha catchment, followed by the 10 m^2 and then the 1 m^2 plots (Figure 6.6). Due to unfortunate circumstances the sampler at the weir was damaged during an intense rainfall event and was not fixed before the study ended, thus the 34 ha section of the graph has not being completed. It can be assumed though that it would continue to increase in the summer months. To obtain an accurate measurement it may be of use in the future to model sediment yield. The summer months had an increase in sediment yield due to the increase in rainfall.

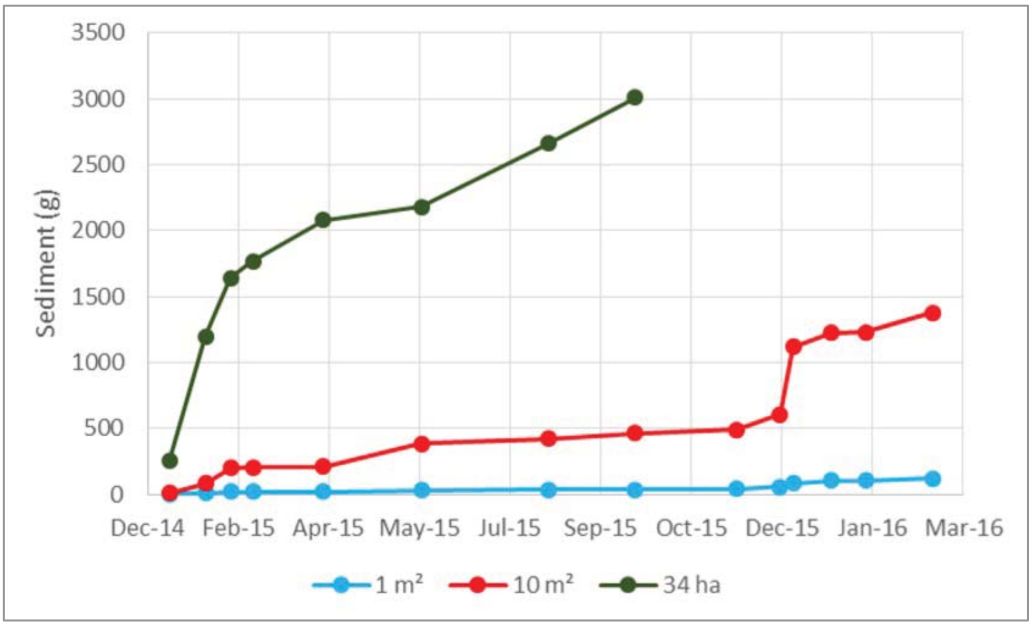

Figure 6.6 Cumulative sediment yield at the various scales (1 m^2, 10 m^2 and 34 ha)

6.1.5 Phosphate

Phosphate is regarded as a key contributor to eutrophication. This section provides details on the phosphate concentrations at the different slope positions and the different spatial scales (Table 6.11). The average phosphate concentration is provided as it illustrates the differences between plot locations and sizes.
The highest average concentration of phosphate was measured at the bottom slope position with the 10 m^2 plots recording on average 0.72 mgl^{-1} and the 1 m^2 plots recording 0.33 mgl^{-1} per event. There were lower values recorded in phosphate concentration.at the top slope with the 10 m2 lots recording on average 0.51 mgl^{-1} and the 1 m^2 recording 0.25 mgl^{-1} and the lowest phosphate concentration was recorded off the mid slope with the 10 m^2 plots recording on average 0.39 mgl^{-1} and the 1 m^2 plots recording 0.1 mgl^{-1}.

Table 6.11 Phosphate concentration (average volume in mgl^{-1}) at the different plot locations (top, middle, and bottom) for the different plot sizes

	Top	Middle	Bottom
(n=15)			
Average 10 m^2	0.51 mgl^{-1}	0.39 mgl^{-1}	0.72 mgl^{-1}
Average 1 m^2	0.25 mgl^{-1}	0.14 mgl-^{1}	0.33 mgl^{-1}

For the rainfall season of 2014-2015 (four months), the maximum phosphate concentration for a rainfall event was 1.60 mgl^{-1} at the 10 m^2 plots and 0.75 mgl^{-1} at the 1 m^2 plots, the minimum phosphate concentration for a rainfall event was 0.26 mgl^{-1} at the 10 m^2 plots and 0.15 mgl^{-1} at the 1 m^2 plots. For the non-rainfall season of 2015 (eight months), the maximum phosphate concentration for a rainfall event was 1.14 mgl^{-1} at the 10 m^2 plots and 0.58 mgl^{-1} at the 1 m^2 plots, the minimum phosphate concentration for a rainfall event was 0.29 mgl^{-1} at the 10 m^2 plots and 0.08 mgl^{-1} at the 1 m^2 plots. For the rainfall season of 2015 - 2016 (four months), the maximum phosphate concentration for a rainfall event was 0.81 mgl^{-1} at the 10 m^2 plots and 0.10 mgl^{-1} at the 1 m^2 plots. The minimum phosphate concentration for a rainfall event was 0.07 mgl^{-1} at the 10 m^2 plots and 0.03 mgl^{-1} at the 1 m^2 plots. The maximum values recorded were during low rainfall events and the minimum values occurred during high rainfall events, these results would point to the impact of dilution. The 10 m^2 plots recorded significantly greater concentration of phosphate compared to the 1 m^2 plots.

Events that had on average high phosphate concentration also had high variation in phosphate between the runoff plots for both the 10 m^2 and 1 m^2 plots. (Figure 6.7). Evidence of this is the first event measured in December 2014, which on average had a high phosphate but also high variation in phosphate values between the runoff plots, showing very little consistency in the P value measured at the runoff plots. This was common for all events that had on average a high phosphate concentration, P values were recorded for the collected rainfall from the rain gauges adjacent to each runoff plot. Overall the concentration was low (<0.06 mgl^{-1}) and it is assumed it would not impact upon the reading for each plot. Weir samples had a phosphate concentration of less than 0.06 mgl^{-1} throughout the duration of the study. The phosphate concentration (mgl^{-1}) from the 10 m^2 plot and 1 m^2 plots were similar at the start of the study, they then decline for 1 m^2 plots from February 2015 until the end of the study (Figure 6.7). Interesting to note that the 18th of December which was the highest rainfall event recorded one of the lowest concentrations of phosphate 10 m^2 = 0.14 mgl^{-1} and 1 m^2 = 0.08 mgl^{-1} for the different spatial scales, this may be due to dilution. Overall the 10 m^2 plots had a higher concentration of phosphate then the 1 m^2 plots, with a single exemption on the 27th May 2015.

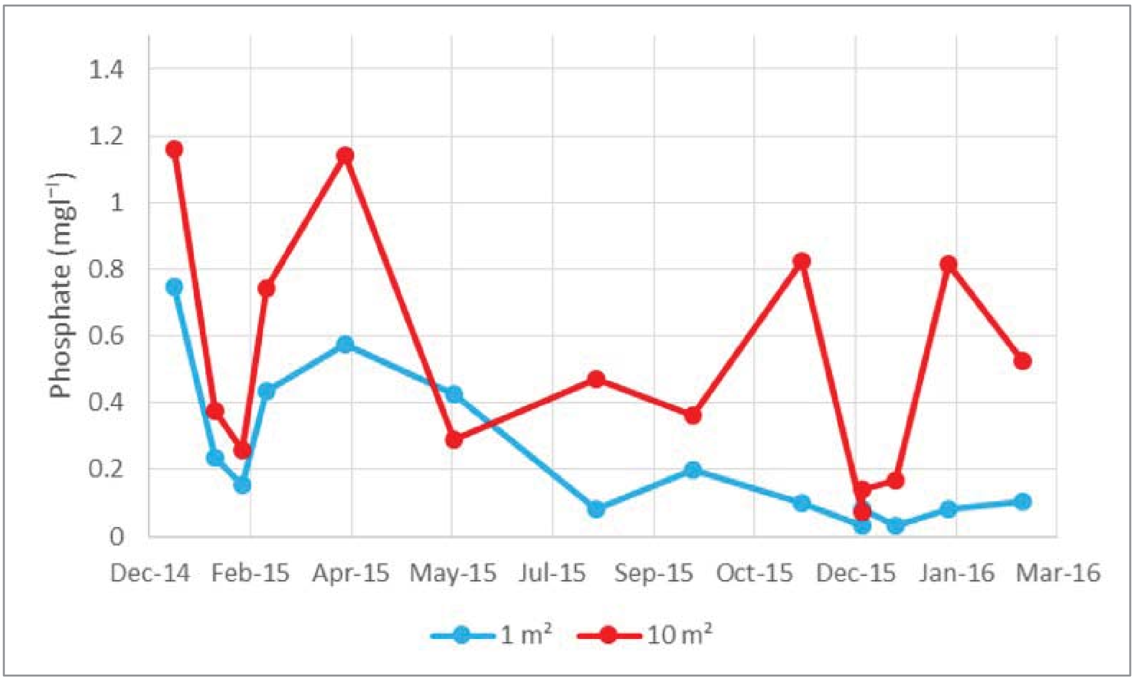

Figure 6.7 Relationship between 1 m^2 and 10 m^2 plots for phosphate

6.1.6 Nitrate

This section outlines the nitrate concentrations at the different slope positions and spatial scales, the impact that high rainfall and low rainfall has on the nitrate concentrations (Table 6.12). The average nitrate concentration is provided as it illustrates the differences between plot locations and sizes.

The highest average concentration of nitrate was measured at the mid slope position with the 10 m^2 plots recording on average 4.471 mgl^{-1} and the 1 m^2 plots 2.246 mgl^{-1} per event. There was a decline in nitrate concentration at the top slope with the 10 m^2 plots recording on average 4.872 mgl^{-1} and the 1 m^2 plots recording 2.246 mgl^{-1}. The lowest nitrate concentration was found at the bottom slope with the 10 m^2 plots recording on average 3.756 mgl^{-1} and the 1 m^2 plots recording 3.56 mgl^{-1}. Events that had high nitrate concentration also had high variation in nitrate between the runoff plots for both the 10 m^2 and 1 m^2 plots (Figure 6.8).

Table 6.12 Nitrate concentration (average volume in mgl^{-1}) at the different plot locations (top, middle, and bottom) for the different plot sizes

	Top	Middle	Bottom
(n=15)			
Average 10 m^2	4.872 mgl^{-1}	4.471 mgl^{-1}	3.756 mgl^{-1}
Average 1 m^2	2.246 mgl^{-1}	4.155 mgl^{-1}	3.560 mgl^{-1}

For the rainfall season of 2014-2015 (four months), the maximum nitrate concentration for a rainfall event was 5.50 mgl^{-1} at the 10 m^2 plots and 3.52 mgl^{-1} at the 1 m^2 plots, the minimum nitrate concentration for a rainfall event was 1.77 mgl^{-1} at the 10 m^2 plots and 1.60 mgl^{-1} at the 1 m^2 plots. For the non-rainfall season of 2015 (eight months), the maximum nitrate concentration for a rainfall event was 6.27 mgl^{-1} at the 10 m^2 plots and 6.19 mgl^{-1} at the 1 m^2 plots, the minimum nitrate concentration for a rainfall event was 2.40 mgl^{-1} at the 10 m^2 plots and 2.55 mgl^{-1} at the 1 m^2 plots. For the rainfall season of 2015-2016 (four months) the maximum nitrate concentration for a rainfall event was 5.33 mgl^{-1} at the 10 m^2 plots and 4.89 mgl^{-1} at the 1 m^2 plots. The minimum nitrate concentration for a rainfall event was 2.35 mgl^{-1} at the 10 m^2 plots and 2.01 mgl^{-1} at the 1 m^2 plots. The maximum values recorded were during low rainfall events and the minimum values occurred during high rainfall events, these results would point to the impact of dilution. The concentration of nitrate found at the different plot sizes were similar these were confirmed by running t tests.

Nitrate values were recorded for the collected rainfall from the rain gauges adjacent to each runoff plot. The concentration was consistently low (<1 mgl^{-1}) and it is assumed would not impact upon the reading for each plot. Weir samples had a nitrate concentration of less than 1 mgl^{-1} throughout the duration of the study. The nitrate concentration (mgl^{-1}) from the 10 m^2 plot and 1 m^2 plots were similar during the study with exceptions on 27th January 2016 and the 4th March 2016 (end of the study). The 18th of December which was the highest rainfall event recorded one of the lowest concentrations of nitrate (10 m^2 = 2.35 mgl^{-1} and 1 m^2 = 2.61 mgl^{-1}) (Figure 6.8). During the summer period the 10 m^2 plots had a higher concentration of nitrate then the 1 m^2 plots and in the winter period the 1 m^2 plots had a higher concentration of nitrate then the 10 m^2 plots.

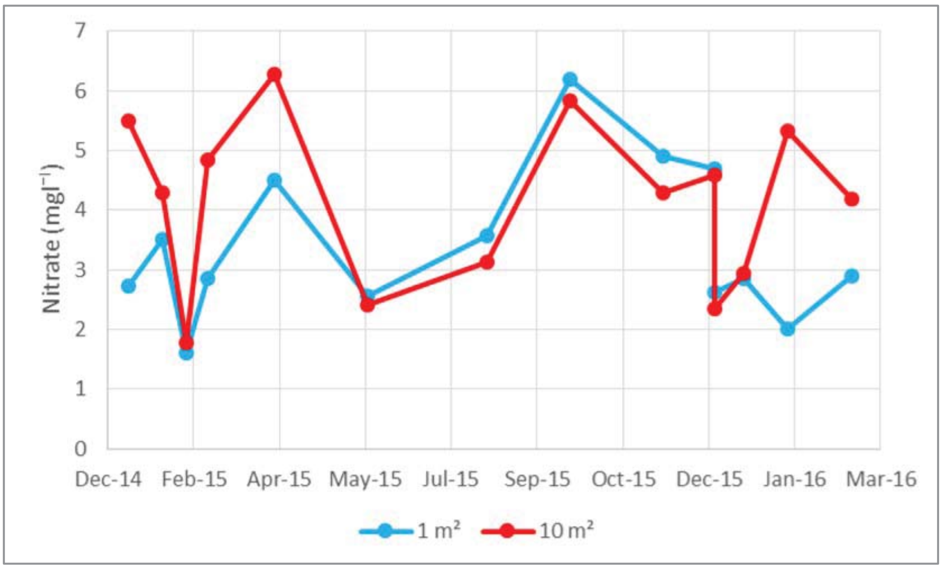

Figure 6.8 Relationship between 1 m^2 and 10 m^2 plots for nitrate

6.1.7 *Dissolved organic carbon*

Soil plays a key role in the carbon cycle with soil organic carbon being the basis of soil fertility. It releases nutrients for plant growth, promotes the structure, biological and physical health of soil, and is a buffer against harmful substances. Soil organic carbon is divided into dissolved organic carbon and particulate organic carbon. This section provides details on the dissolved organic carbon concentrations at the different slope positions and the spatial scales (Table 6.13). The average dissolved organic carbon concentration is presented as it illustrates the differences between plot locations and sizes.

The highest concentration of dissolved organic carbon was measured at the mid slope position with the 10 m^2 plots recording 23.39 mgl^{-1} and the 1 m^2 plots recording 22.12 mgl^{-1} per event. There was a decline in dissolved organic carbon concentration at the top slope with the 10 m^2 plots recording on average 19.25 mgl^{-1} and the 1 m^2 plots recording 17.38 mgl^{-1} and the lowest dissolved organic carbon concentration was found at the bottom slope with the 10 m^2 plots recording on average 16.92 mgl^{-1} and the 1 m^2 plots recording 18.05 mgl^{-1}. Events that had high dissolved organic carbon concentration had greater variation in dissolved organic carbon between the runoff plots for both the 10 m^2 and 1 m^2 plots (Figure 6.9).

Table 6.13 Dissolved organic carbon concentration (average volume in mgl^{-1}) at the different plot locations (top, middle, and bottom) for the different plot sizes

	Top	Middle	Bottom
(n=15)			
Average 10 m²	19.25 mgl^{-1}	23.39 mgl^{-1}	16.92 mgl^{-1}
Average 1 m²	17.38 mgl^{-1}	22.12 mgl^{-1}	18.05 mgl^{-1}

For the rainfall season of 2014-2015 (four months), the maximum DOC concentration for a rainfall event was 14.68 mgl^{-1} at the 10 m^2 plots and 11.79 mgl^{-1} at the 1 m^2 plots, the minimum DOC concentration for a rainfall event was 8.28 mgl^{-1} at the 10 m^2 plots and 8.86 mgl^{-1} at the 1 m^2 plots. For the non-rainfall season of 2015 (eight months), the maximum DOC concentration for a rainfall event was 24.37 mgl^{-1} at the 10 m^2 plots and 24.13 mgl^{-1} at the 1 m^2 plots, the minimum DOC concentration for a rainfall event was 9.18 mgl^{-1} at the 10 m^2 plots and 11.52 mgl^{-1} at the 1 m^2 plots. For the rainfall season of 2015-2016 (four months) the maximum DOC concentration for a rainfall event was 40.93 mgl^{-1} at the 10 m^2 plots and 38.68 mgl^{-1} at the 1 m^2 plots. The minimum DOC concentration was for a rainfall event 12.75 mgl^{-1} at the 10 m^2 plots and 14.51 mgl^{-1} at the 1 m^2 plots. The maximum values recorded were during low rainfall events and the minimum values occurred during high rainfall events, these results could point to the role of dilution.

DOC values were recorded for the collected rainfall from the rain gauges adjacent to each runoff plot. Overall the concentration was low (<2 mgl^{-1}) and it is assumed it would not impact upon the reading for each plot. Weir samples had a low DOC concentration with a maximum concentration of 2.56 mgl^{-1} throughout the duration of the study.

The DOC concentration (mgl^{-1}) from the 10 m^2 plot and 1 m^2 plots were similar throughout the study (Figure 6.9). During the summer months the 10 m^2 plots had a higher DOC concentration than the 1 m^2 plots and in the winter months the 1 m^2 plots had a higher DOC concentration than the 10 m^2 plots. However, the 18th of December which was the highest rainfall event recorded had a relatively low concentration of DOC (10 m^2 = 12.75 mgl^{-1} and 1 m^2 = 14.15 mgl^{-1}).

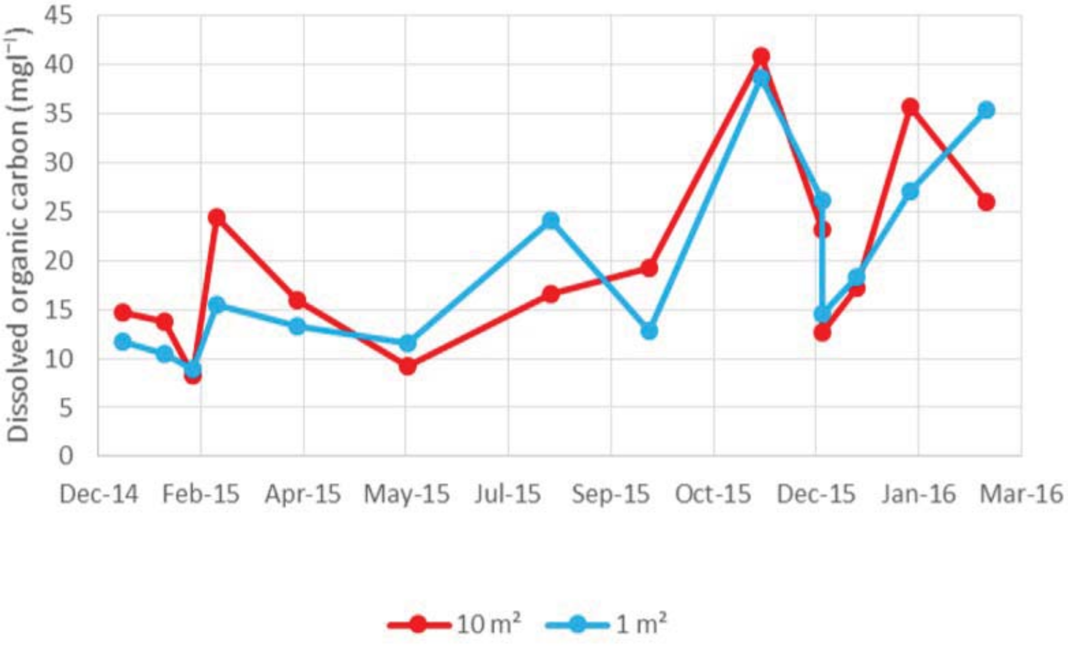

Figure 6.9 Relationship between 1 m2 and 10 m^2 plots for dissolved organic carbon

6.1.8 *Particulate organic carbon*

This section provides details on the particulate organic carbon concentrations at the different slope positions and spatial scales (Table 6.14). The average particulate organic carbon is presented as it illustrates the differences between plot locations and sizes.

The highest concentration of particulate organic carbon yield from the plots came from the mid slope position with the 10 m^2 plots on average having a 0.116 gl^{-1} yield and the 1 m^2 plots having a 0.92 gl^{-1} yield. There was a decrease in particulate organic carbon removed at the top slope with the 10 m2 plots having a 0.104 gl^{-1} yield and the 1 m^2 having a 0.094 gl^{-1} yield. The slope position with the lowest particulate organic carbon yield was the bottom slope with the 10 m^2 plots having a 0.076 gl^{-1} yield and the 1 m^2 plots having a 0.074 gl^{-1} yield. Events that had high particulate organic carbon concentration also had high variation in particulate organic carbon between the runoff plots for both the 10 m^2 and 1 m^2 plots (Figure 6.10).

Table 6.14 Particulate organic carbon concentration comparison (average volume in gl^{-1}) at the different plot locations (top, middle, and bottom) for the different plot sizes

	Top	Middle	Bottom
(n=15)			
Average 10 m^2	0.104gl^{-1}	0.116gl^{-1}	0.076gl^{-1}
Average 1 m^2	0.094 gl^{-1}	0.092gl^{-1}	0.074 gl^{-1}

For the rainfall season of 2014-2015 (four months), the maximum POC yield for a rainfall event was 0.097 gl^{-1} at the 10 m^2 plots and 0.124 gl^{-1} at the 1 m^2 plots, the minimum POC yield for a rainfall event was 0.045 gl^{-1} at the 10 m^2 plots and 0.039 gl^{-1} at the 1 m^2 plots. For the non-rainfall season of 2015 (eight months), the maximum POC yield for a rainfall event was 0.054gl^{-1} at the 10 m^2 plots and 0.069 mgl^{-1} at the 1 m^2 plots, the minimum POC yield for a rainfall event was 0.034 gl^{-1} at the 10 m^2 plots and 0.037 gl^{-1} at the1 m^2 plots. For the rainfall season of 2015-2016 (four months) the maximum POC yield for a rainfall event was 0.500 gl^{-1} at the 10 m^2 plots and 0.173 gl^{-1} at the 1 m^2 plots. The minimum POC yield for a rainfall event was 0.060 gl^{-1} at the 10 m^2 plots and 0.046 gl^{-1} at the 1 m^2 plots. The maximum yields were recorded during high rainfall events and the minimum yields during low rainfall events, these results point to rainfall as a key driver of Particulate Organic Carbon loss.

POC values were recorded for the collected rainfall from the rain gauges adjacent to each runoff plot. Overall the concentration was low (<0.07 gl^{-1}) and it is assumed it would not impact upon the reading for each plot. Weir samples had a low POC volume with a maximum amount of 0.48 gl^{-1} recorded throughout the duration of the study.

The particulate organic carbon volume (gl^{-1}) from the 10 m^2 plot and 1 m^2 plots was similar throughout the study (Figure 6.10), only on 18th December 2015 (due to the intense rainfall) was there a significant increase in particulate organic carbon, with the 10 m^2 plots producing significantly more particulate organic carbon then the 1 m^2 plots. The last trip on the 3rd of March had a significant difference in particulate organic carbon, in this instance the 1 m2 plots produced a significantly higher volume (10 m^2 = 0.499 gl^{-1} and 1 m^2 = 0.173 gl^{-1}).

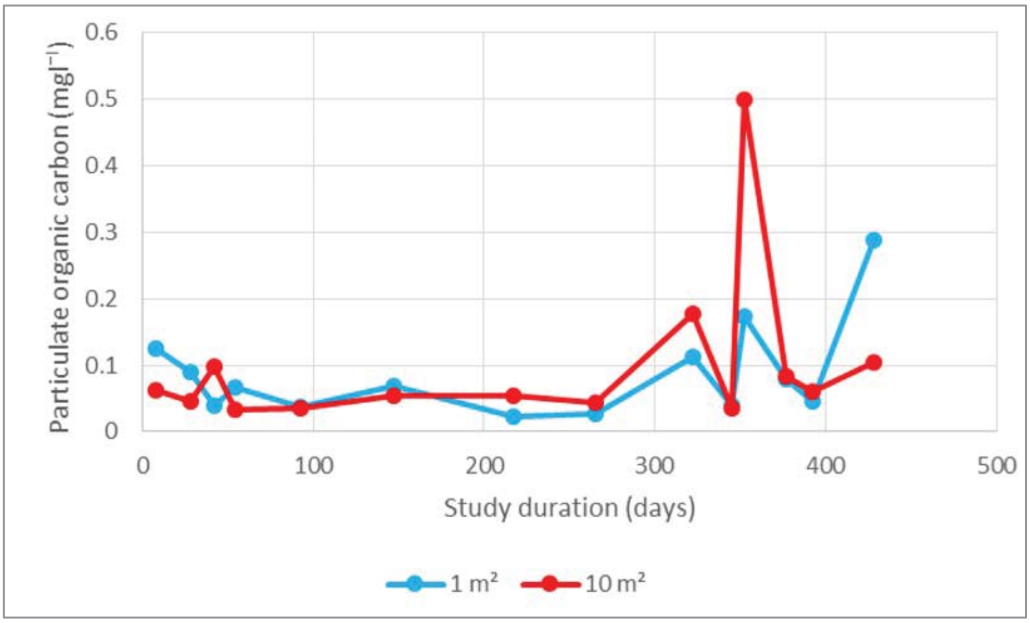

Figure 6.10 Relationship between 1 m^2 and 10 m^2 plots for particulate organic carbon

The cumulative particulate organic carbon yields at the different spatial scales was highest at the 34 ha catchment, followed by the 10 m^2 plots and then the 1 m^2 plots (Figure 6.11). The sampler at the weir was damaged due to an intense rainfall and was not fixed before the study ended, thus the 34 ha section of the graph has not been completed. It can be assumed though that it would continue to increase in the summer months. To obtain an accurate measurement it may be of use in the future to model the POC lost. The summer months experienced the most visible increase in POC due to the increased rain and runoff.

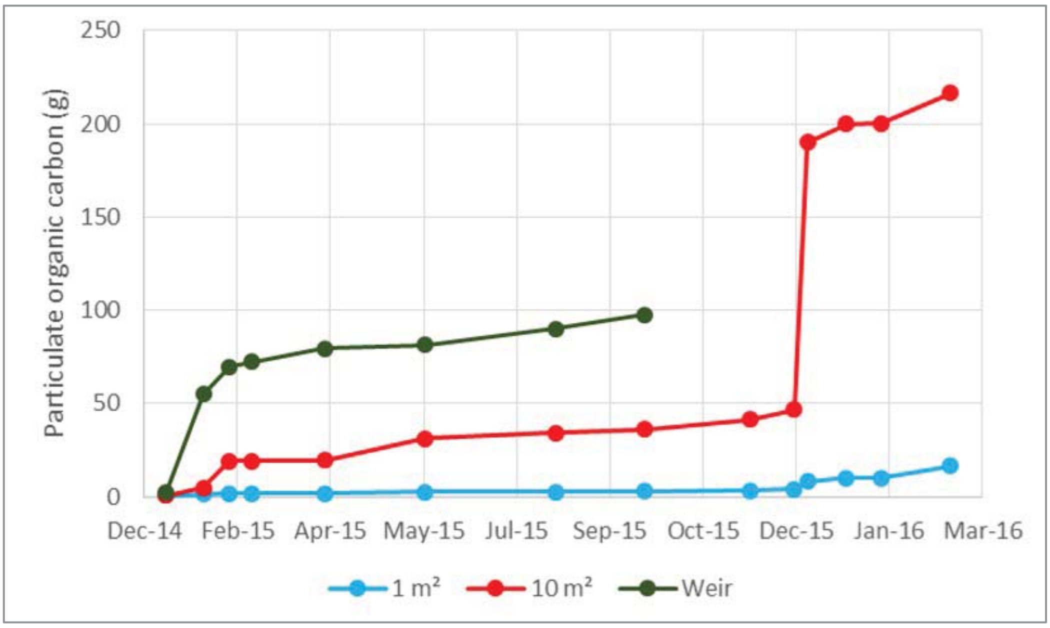

Figure 6.11 Cumulative particulate organic carbon yield at the various scales (1 m^2, 10 m^2 and 34 ha)

6.1.9 Streamflow

To determine the stream flow per day a rating table was formulated by Gush *et al* (2002) for the catchment. This included using the stream height data measured at the v-notch weir and converting to stream flow.

There is a possibility that for some of the data, when downloaded, the offset values were not entered into the logger correctly, as an irregularity in the graph occurred. The 34 ha catchment showed a relatively constant stream flow over the study duration, during the period of December 2014 to March 2015 there was a major increase in stream flow, due to the increase in rainfall events. When that summer period ended the streamflow reduced (Figure 6.12). Samples from the ISCO sampler were taken from the sampler and analysed when there was a significant enough change in stream height (± 5 cm). As mentioned previously, the concentrations of phosphate (<0.06 mgl^{-1}), nitrate (<1 mgl^{-1}) and dissolved organic carbon (<2 mgl^{-1}) were consistent throughout the study. An average of 0.79 gl^{-1} of sediment and 0.016 gl^{-1} of particulate organic carbon per event were measured from the weir.

An unfortunate issue occurred with the logger in November 2015 and this took a few weeks to fix. When it was fixed a flood event occurred caused by the intense rainfall on the 18th December 2015 flooding all the equipment and extensively damaging it. Only in mid-2016 did the loggers begin logging stream height again. With the summer months bringing increased rainfall it can be assumed that there would be an increase in the stream flow similar to what was experienced during the December 2014 to March 2015 period.

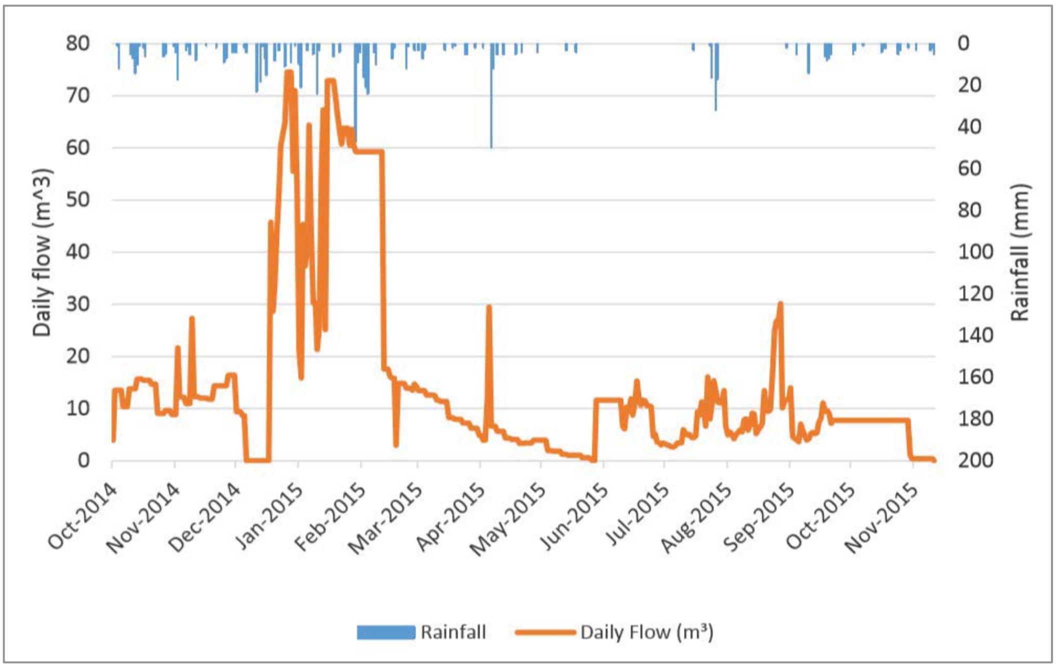

Figure 6.12 Stream flow record from October 2014 to October 2015

6.2 Soil Loss and Sediment Yield at Fountainhill Estate

6.2.1 Meteorological and catchment data

6.2.1.1 Precipitation

The cumulative rainfall data recorded on the AWS collected over 240 days is 305.2 mm over two seasons (Table 6.19). The highest recoded rainfall was 99 mm in September, with the lowest recorded rainfall event being in June (0.8 mm). Majority of site visits took place after high rainfall events, with one site visit taking place in winter and majority taking place in spring and summer months (Figure 6.13).

Table 6.15 Cumulative rainfall data from May to December 2018

Rainfall	Cumulative data (mm)
01-May	15,6
01-Jun	16,4
01-Jul	21,7
01-Aug	56,8
01-Sep	155,9
01-Oct	210,4
01-Nov	242,8
01-Dec	305,2

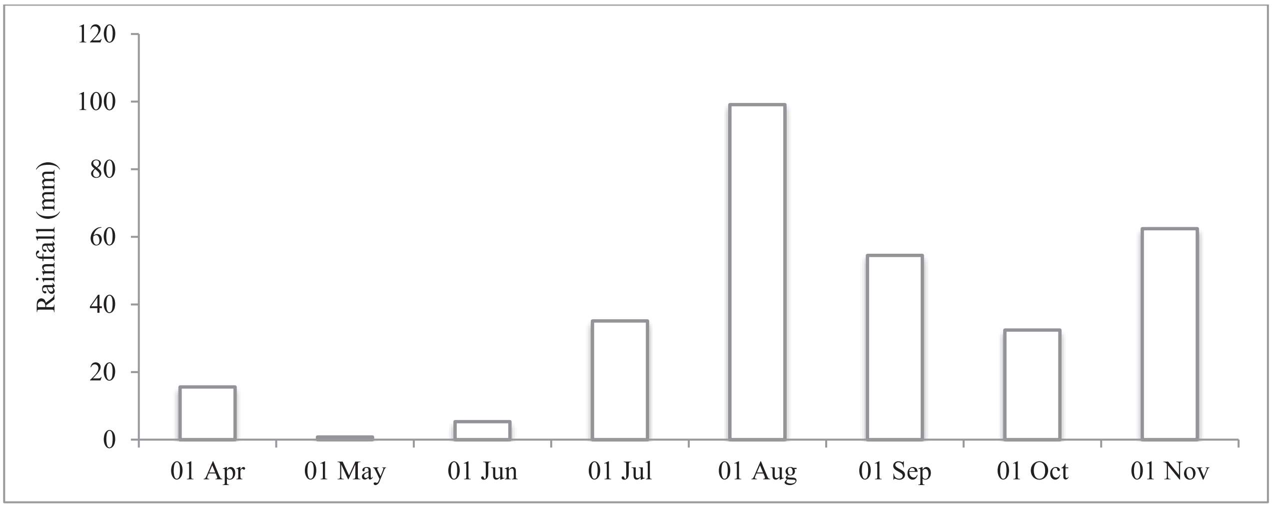

Figure 6.13 Monthly rainfall data from May 2018 to December 2018 at Fountain Hill estate

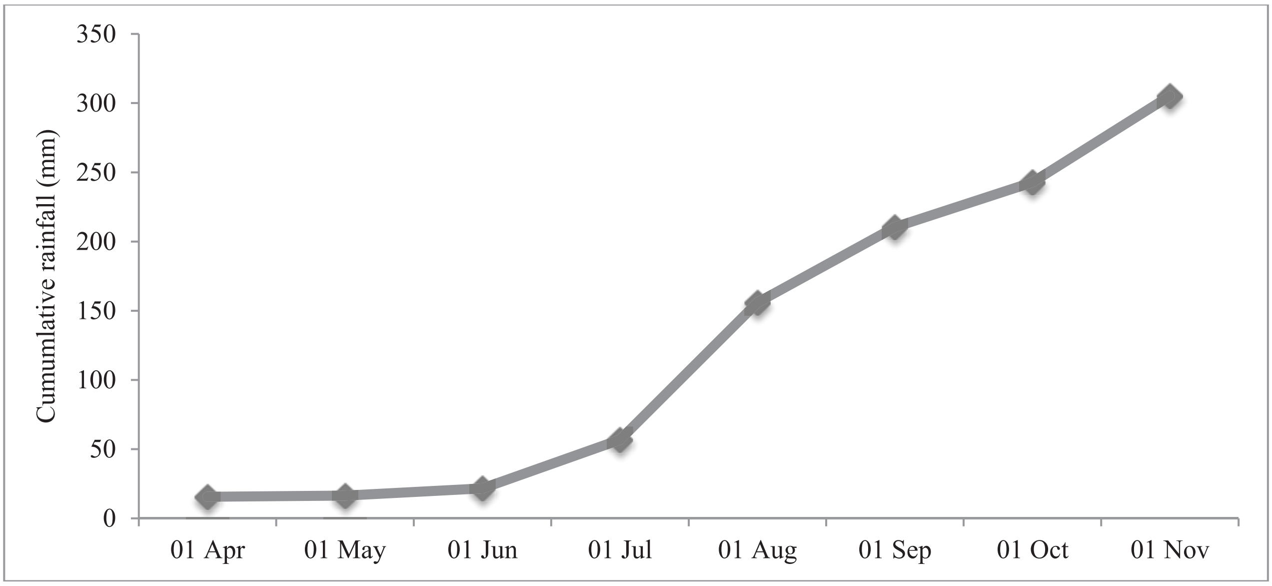

Figure 6.14 Cumulative rainfall data with marked points per site visit

6.2.1.2 Slope

Runoff plots positioned on the top slope of pasture had the steepest gradient of (7.07°), while natural grassland runoff plot positions had the lowest gradient of an average of 3,30° followed by till and no-till maize sites with a gradient of 4,60° and 5,33° respectively (Table 6.16).

Table 6.16 Average slope steepness per runoff plot

Land use	Site number	Slope (°)	Average slope (°)
Natural grass	Site 1	3.40	3.30
	Site 2	3.20	
	Site 3	3.40	
Pasture	Site 1	8.20	7.07
	Site 2	6.50	
	Site 3	6.50	
No-till	Site 1	5.20	5.33
	Site 2	5.30	
	Site 3	5.50	
Till	Site 1	4.20	4.60
	Site 2	5.40	
	Site 3	4.20	

6.2.1.3 Soil

Soil samples were taken for analysis at Cedara soil analytical laboratory, which was inclusive of soil texture, total carbon and nitrogen and soil fertility. The pasture had the highest total nitrogen (0.331%) and total carbon concentrations (4.05%), in comparison to natural grassland plots which had the lowest total nitrogen (0.008%) and total carbon concentrations (0.005%). Maize under no-till management practice had the highest total nitrogen (0.074%) and total carbon concentrations (1.33%), in comparison to maize under tillage management practice, which had the lowest total nitrogen (0.042%) and total carbon concentrations (0.773%). The soil texture for maize under tillage and Natural grassland were classified as loamy sand, while maize under no-tillage and pasture were classified as sandy clay. The soil fertility tests (Table 6.17) analyzed for P, K, Ca, Mg, Exchange acidity, Total cations, acid saturation, pH, Zn, Mn and Cu with a trend where across (P, K, Ca, Mg, Total cations, Zn) found under pasture had the highest results, followed by maize under no tillage and interchangeably between maize under tillage and natural grassland soils. The exchange acidity, acid saturation and Mn were found to be the lowest under pasture grassland. Maize under tillage and natural grassland has notable the lowest concentrations where maize under no tillage and pasture had the highest notable concentrations.

Table 6.17 Total percentage of soil carbon and nitrogen

Site	Sample No.	Total % Nitrogen	Average Total % Nitrogen	Std. dev Total % Nitrogen	Total % Carbon	Average Total % Carbon	Std. dev Total % Carbon
Tillage	Site 1	0.060	0.042	0.016	0.968	0.773	0.170
	Site 2	0.033			0.657		
	Site 3	0.032			0.695		
No-till	Site 1	0.095	0.074	0.021	1.54	1.33	0.221
	Site 2	0.073			1.35		
	Site 3	0.053			1.10		
Pasture	Site 1	0.246	0.331	0.100	3.13	4.05	0.968
	Site 2	0.304			3.96		
	Site 3	0.442			5.06		
Natural grassland	Site 1	0.000	0.008	0.013	0.463	0.555	0.249
	Site 2	0.000			0.365		
	Site 3	0.023			0.837		
Total Average			**0.113**	**0.042**		**1.68**	**0.379**

Table 6.18 Soil fertility

Your sample ID	Sample density (g/mL)	P mg/L	K mg/L	Ca mg/L	Mg mg/L	Exch. Acidity cmol/L	Total cations cmol/L	Acid sat. %	pH (KCl)	Zn (mg/L)	Mn mg/L	Cu mg/L
TS1	1.44	53	85	252	29	0.63	2.34	27	3.70	3.2	50	1.8
TS2	1.46	43	66	117	26	0.67	1.63	41	3.74	1.6	31	1.1
TS3	1.35	43	159	284	41	0.71	2.86	24	3.69	1.9	65	2.5
NTS1	1.18	52	236	592	151	0.29	5.09	6	4.16	8.4	8	3.0
NTS2	1.26	44	192	681	185	0.19	5.60	3	4.21	9.1	8	3.4
NTS3	1.28	40	192	497	137	0.27	4.37	6	4.12	7.1	5	2.4
PS1	1.08	53	64	1152	512	0.08	10.21	1	5.50	11.6	3	1.5
PS2	0.96	24	80	1449	709	0.11	13.38	1	5.66	33.9	3	2.2
PS3	0.98	92	455	1523	513	0.09	13.08	1	5.26	25.7	4	4.2
NGS1	1.40	3	38	161	48	0.26	1.56	17	4.30	0.4	4	0.2
NGS2	1.39	6	58	170	56	0.37	1.83	20	4.11	0.2	5	0.4
NGS3	1.36	5	123	265	74	0.18	2.43	7	4.52	1.0	5	0.5

6.2.2 *Runoff*

The highest runoff recorded within the 1 m^2 between the monitoring period of May 2018 to December 2018 was 25 l/m^2 under maize tillage (Figure 6.15), followed by maize under no tillage (10.43 l/m^2). These findings were further illustrated on 10 m^2 plots where 155 l/m^2 of runoff was recorded under maize tillage between May 2018 to December 2018. Maize under no-tillage had a lower runoff value of 19.8 l/m^2. The lowest runoff record within the 1 m^2 plots was under pasture where 0.l/m^2 was consistently recorded. Runoff from the natural grassland plots were comparatively low with the lowest recorded runoff on 7 December 3018 (0.68 l/m^2). However, within the 10 m^2 plots, natural grassland had the 2nd highest runoff (44 l/m^2) for 3 rainfall events (Figure 6.16), whereas, pasture experienced one runoff event (4 May 2018) of 25 l/m^2 and no runoff was recorded for the following rainfall events.

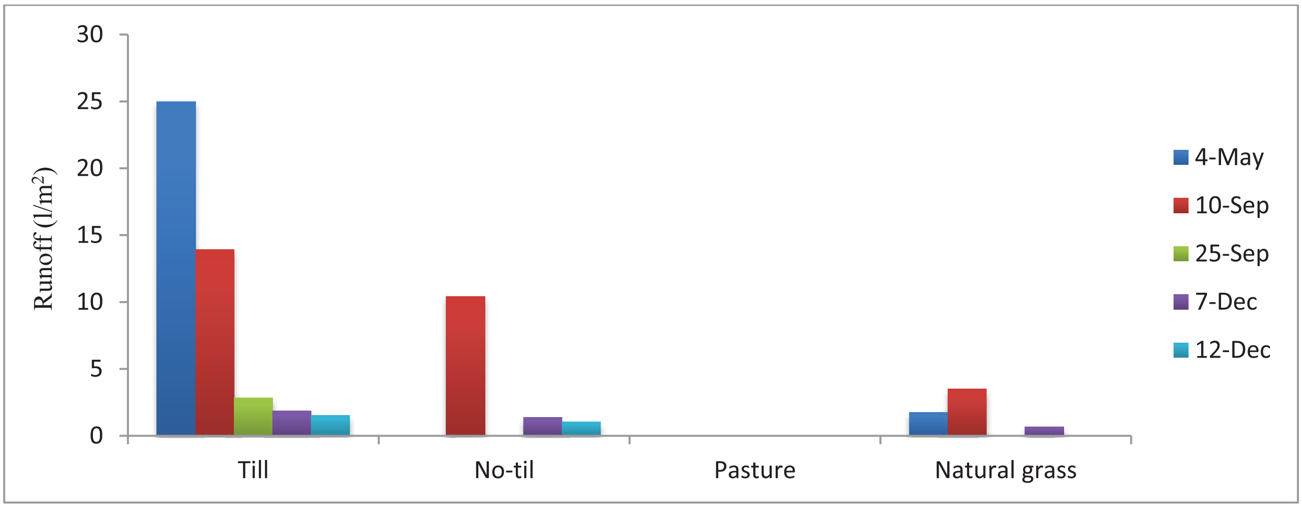

Figure 6.15 Average runoff for 1 m^2 plots

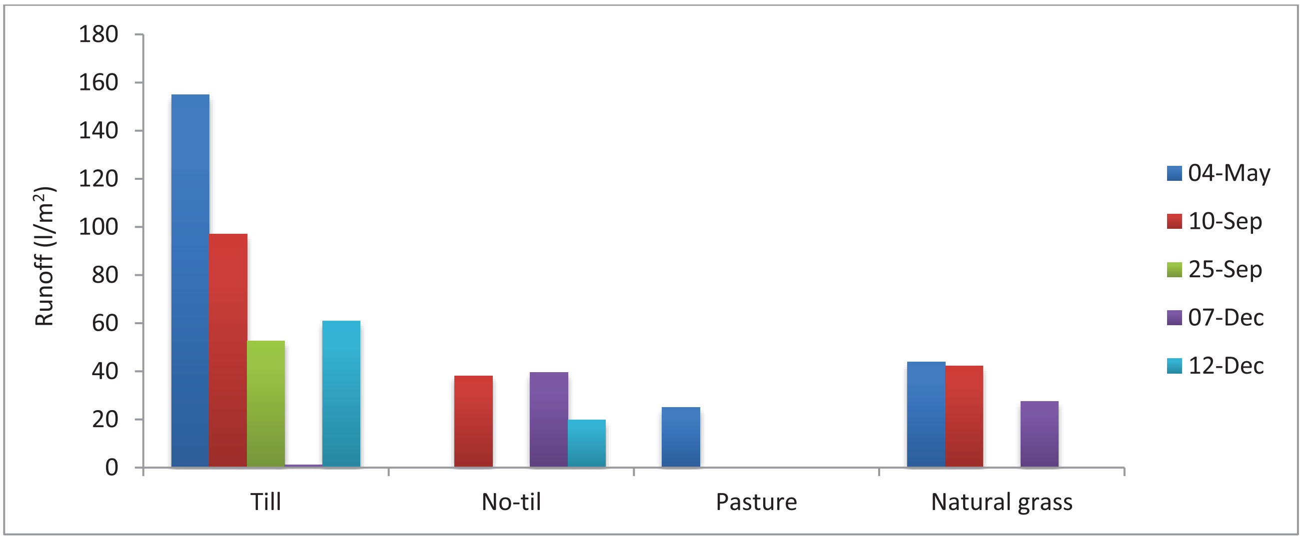

Figure 6.16 Average runoff for 10 m^2 plots

6.2.3 Phosphate

During the month of December, maize under tillage had the highest concentration of phosphate on both 1 m^2 and 10 m^2 plots, where eutrophication being a key indicator or phosphate was evident. 21.2 l/m^2 and 19.5 1/m^2 was recorded on 1 m^2 plots on 7 and 12 December 2018 followed by 6.4 1/m^2 under no tillage maize. On the 10 m^2 plots no-tillage maize had the highest phosphate concentration consistently with 13.03 l/m^2 being recorded on 7 December 2018 in comparison to till maize had the lowest concentration of 0.47 l/m^2 (4 May 2018). Natural grassland had the lowest concentration of phosphate (4 May 2018) of 0.36 l/m^2 compared to 10 September which had a high concentration of 7.1 l/m^2 which had the highest monthly rainfall event of 99 mm (Figure 6.17) and a mouse was found in the 25 L bucket.

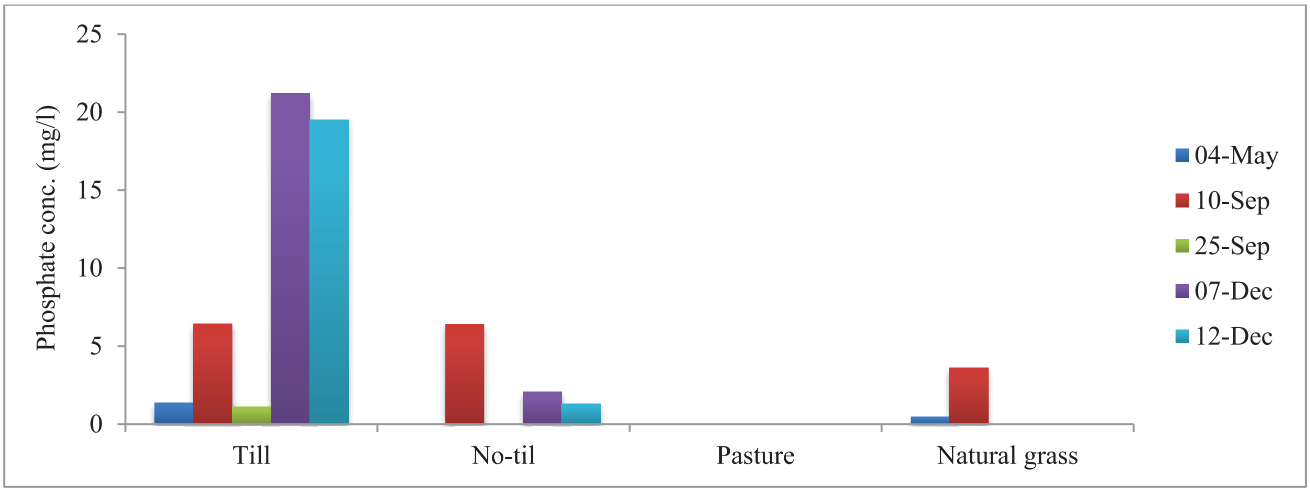

Figure 6.17 Average phosphate for 1 m^2 plots

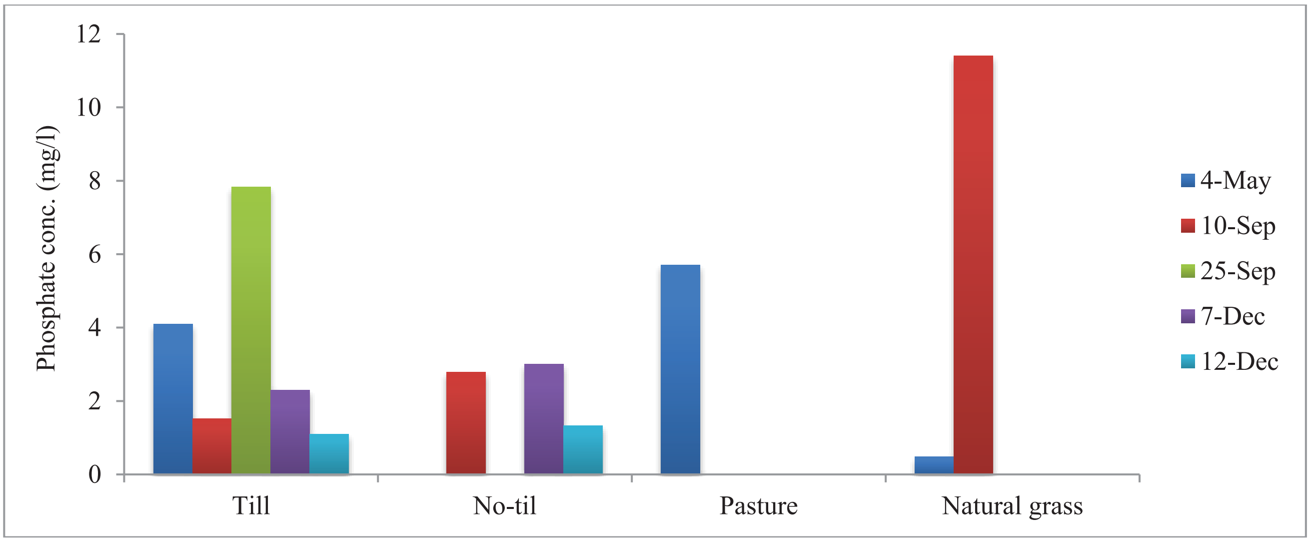

Figure 6.18 Average phosphate for 10 m^2 plots

6.2.4 Nitrate concentration

Within the maize plot, nitrate concentration under tillage practices and natural grassland in 1 m^2 plots were found to have the highest concentration (11.4 l/m^2 & 7.8 l/m^2) which was found to be contaminated by a deceased mouse. Furthermore, on the 10 m^2 the highest concentration was found on the no tillage maize plots (14 l/m^2) which was also contaminated by a deceased mouse. Natural grassland was found to have the lowest concentration of 1.4 l/m^2.

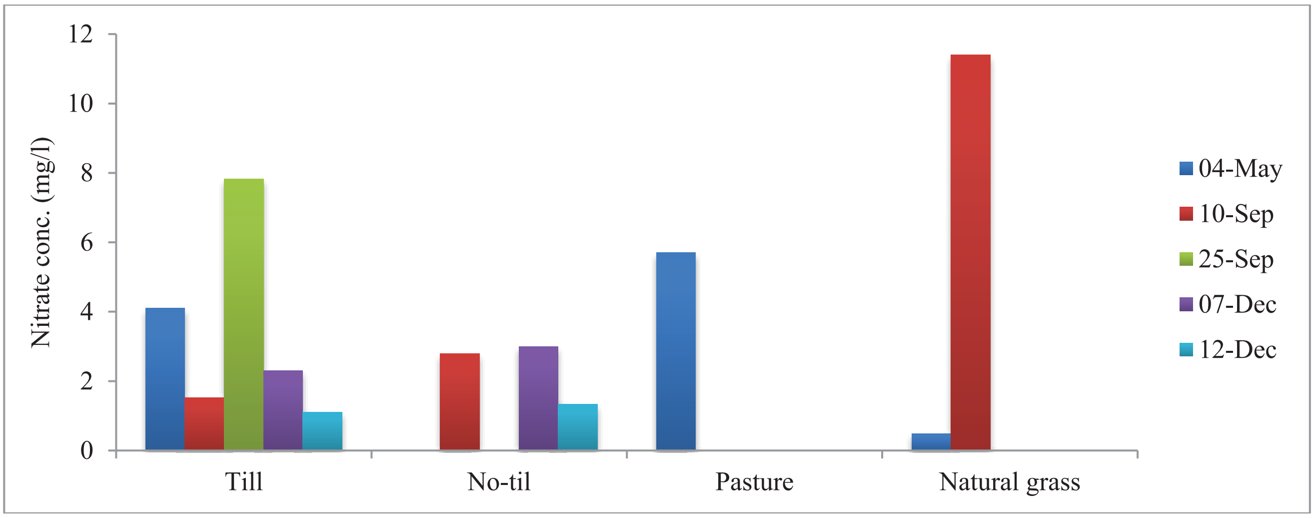

Figure 6.19 Average nitrate for 1 m^2 plots

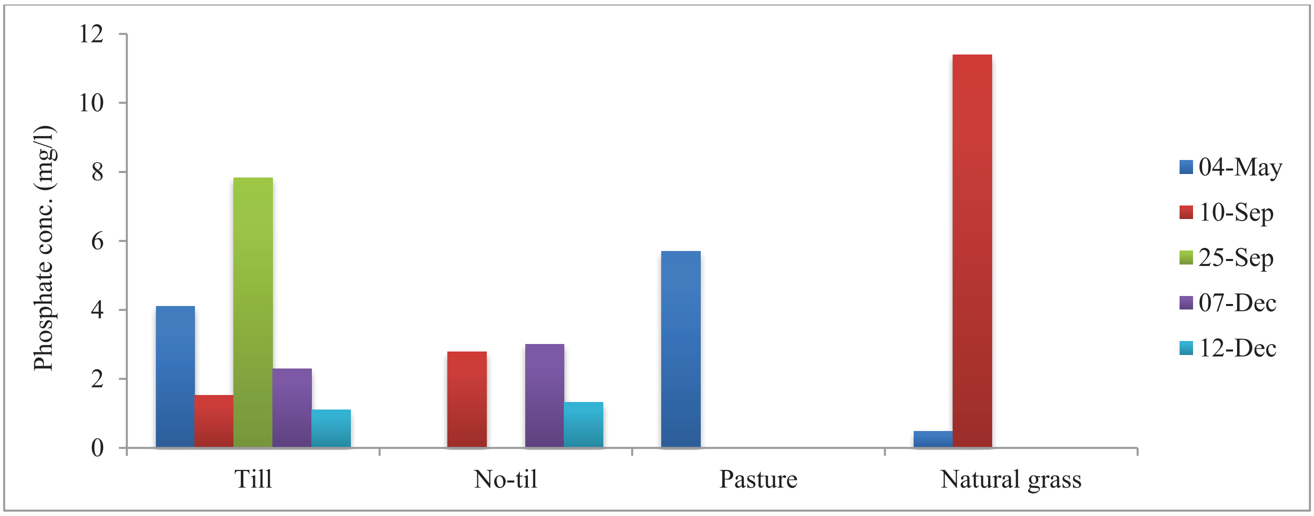

Figure 6.20 Average nitrate for 10 m^2 plots

6.3 Rainfall Simulation at Okhombe

The rainfall simulations were conducted on the cattle access paths, rehabilitated access paths and natural grassland. The community workshop was held at the local school attended by approximately 60 community members, including local leadership, government officials and community herdsman. The workshop explored the community's experiences with land degradation and how it has affected their lives. The community explained some of the issues with regards to erosion, how it had affected their lives and what measures the community had attempted to control land degradation. The community went on to explain the success of the implemented measures and how the community needs to do more to reduce the level of land degradation in the area. The second step in the workshop was to run the simulation for the community members to first see what the researches were doing in the area and second to explain some of the driving factors of the erosion process to the community members. The final step in the community workshop was to re-engage with the community regarding the land degradation problem in the area to see if after thinking about the driving factors their perception of the issue had changed. The community members were asked to help highlight, on an aerial photograph of the area, where the land degradation issues were of greatest concern and why those regions in particular.

The results from the rainfall simulation (Table 6.19 and Table 6.20) show runoff values in percentage for simulations run on the cattle access paths and rehabilitated cattle access paths with the sediment load in the runoff collected (gl^{-1}). Each simulation (R) had an inhibition rainfall simulation (I) conducted prior to commencement of the rainfall simulation (R).

Table 6.19 Runoff percentage and sediment (gl^{-1}) from runoff plots placed on cattle access paths

Cattle Access Path							
Inhibition (%)			**Simulation (%)**			**Sediment gl^{-1}**	
Time	**I1**	**I4**	**Time**	**R1 (27 mmh^{-1})**	**R4(80 mmh^{-1})**	**R 1**	**R 4**
2:30	51.15	0	5	99.08	75.4	3.05	3.29
5	100	0	10	100	76.3	3.37	11.87
7:30	100	17.29	15	100	87.5	3.56	4.57
10	100	47.49	20	100	84.85	3.05	16.33

Table 6.20 Runoff percentage and sediment (gl^{-1}) from runoff plots placed on rehabilitated cattle access paths

Rehabilitated Cattle Access Path							
Inhibition (%)			**Simulation (%)**			**Sediment gl^{-1}**	
Time	**I7**	**I11**	**Time**	**R7(42 mmh^{-1})**	**R11(56 mmh^{-1})**	**R 7**	**R 11**
2:30	15.8	0	5	76.37	90.68	1.32	1.22
5	100	0	10	100	100	1.43	1.23
7:30	100	57.35	15	100	100	1.64	1.26
10	100	91.92	20	100	100	1.64	1.12

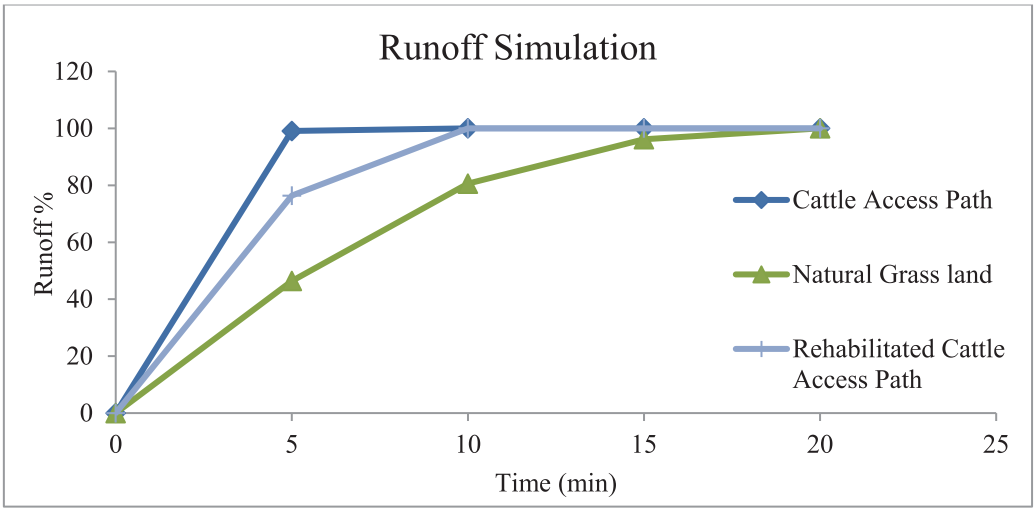

Figure 6.21 Average runoff rates across runoff plots placed on cattle access paths, rehabilitated access paths and natural grassland

The community workshop held with the community was very successful, there was a large turnout and the community members were eager to discuss the issues of land degradation. After a brief discussion on the land degradation issue in the community and the mitigation measure that are being implemented the rainfall simulation was run for the community members to see. The pre-rainfall simulation discussion was to provide a brief overview of the issue of land degradation in the community area from the perspective of the community members. The community members explained where they thought land degradation was an issue in the area and the community members went on further to explain the mitigation and rehabilitation techniques that had been utilized.

The rainfall simulation worked well as a spatial tool for visually demonstrating the processes of erosion and the driving forces. The first simulation was set up prior to the community arriving for the workshop on a plot with low basal cover. With the community members around the simulator the first simulation was run. Almost instantly runoff began with a high sediment concentration. Concepts such as raindrop induced detachment and transportation was explained to the community members. The community members entered into long discussions around the processes and where in their community area they had witnessed or evidence of transportation and detachment was. During the rainfall simulation demonstration, the erosion processes and driving factors were explained to the community members. The community members could ask questions and point in the plot to where erosion was taking place. Immediately discussion arose as to what would happen if the plot was moved to a steeper slope or a slope with less vegetation. The advantage of the small plot size means the simulation can easily be moved to various areas land use types to demonstrate different factors. The plot was moved to a more vegetated slope to demonstrate to the community how good basal cover can assist in mitigation the rate of degradation. The community members were interested to see the change from a bare plot to a vegetated plot. The simulation was run again and the community observed and commented on the difference between the two simulations. The runoff on the second plot took a bit longer to begin indicating infiltration was taking place. This was explained to the community members. The runoff contained far less sediment yield than the previous simulation on the bare ground. The concept of interception and reduced surface flow velocity due to vegetative cover was examined.

From the change in plot position a discussion arose from the community members with regards the mitigation and rehabilitation techniques they had been implementing. The community members were discussing how they now understand why they need to put in the mitigation measures as they now understand the driving factors behind the erosion. The discussion after the second simulation was useful as community members discussed the mitigation measure they had been utilizing and where various measures would be more successful than other places due to the driving forces of land degradation they had just witnessed. Work on land degradation has been going on for many years in the region and the feedback from the workshop was that now the community members better understand what causes the erosion in their area.

After witnessing and discussing the simulations and erosion demonstration one community member raised an observation with regards removal of alien vegetation from the catchment which is an on-going social up-liftmen program (Le Maitre *et al*, 2002). The community member noted that often where alien vegetation had been removed gullies had begun to form and land degradation accelerated. From watching the simulations on vegetated and on bare ground the community member had come to the realisation that the removal of the alien invasive species had accelerated the land degradation due to the loss of vegetative cover. Further to this the community member inquired if there were other species of plant which could be grown in the areas where the alien vegetation had been removed to reduce the rate of degradation. The community had observed that iLothane (*Buddleja salvifolia*) grew in the areas that had severe form of land degradation and that these species aided the binding of soil and reduction of soil losses.

From the discussion and simulations, the community members were shown some aerial photographs of the area and asked to identify land degradation issues. The community members pointed out all the cattle access paths and how now after the simulation they can see the problem with moving the cattle up steep slopes and issues surrounding overgrazing.

The findings above present a difficult situation to develop a mitigation plan. The community members can see the change in erosion rates from vegetated to non-vegetated sites and steep verse gentle slopes however the livestock need to graze and to access the grazing land on top of the plateaus steep slopes must be traversed. The use of the steep slopes results in the formation of cattle paths with low basal cover which accelerates the rate of land degradation. One solution was to fence the cattle paths off to prevent cattle movement, however the cattle move around the fence creating another degradation issue along the side of the previous degradation problem (Everson *et al*, 2007).

The runoff results (Table 6.19 and Table 6.20) from the simulations carried out in the Okhombe valley on cattle access paths and rehabilitated sites suggest a similarity in runoff experienced on the cattle path verse the rehabilitated site. The runoff starts at a similar time after the beginning of the simulation and quickly increases to 100% runoff. The soil analysis of the soils surrounding the runoff plots described the soil as clay having a clay content greater than 60%. The high clay content in the soil could be the reason for the low infiltration and high runoff rates documented during the rainfall simulations.

The sediment concentration (Table 6.19 and Table 6.20) are lower for the rehabilitated cattle access path as opposed to the cattle access path, where the concentration on the rehabilitated path is less than $2gl^{-1}$ and the concentration on the rehabilitated site varies from $3gl^{-1}$ to $16gl^{-1}$. The rehabilitated site has approximately 100% basal cover whereas the cattle path has 0-5% basal cover. The basal cover is the primary reason for the difference between the sediment concentrations as the vegetation will help to bind the soil, slow down surface runoff and intercept raindrops to reduce raindrop induced detachment.

The results from the rainfall simulations show how susceptible and sensitive the area is to land degradation. The runoff rates are high due to the soil properties, any disturbance in terms of vegetative cover (overgrazing or trampling) or channelling from cattle access paths will result in some form of land degradation. This makes mitigation of land degradation through controlled grazing and access paths a complex issue.

The social, cultural and economic value of livestock to the community is high and this needs to be considered in any management plan. The cattle need to graze on the plateaus however any movement up the slopes can result in erosion paths. One potential mitigation measure that could be considered is path design with reference to paths designed in the Drakensberg reserve for soil erosion control on hiking trails and controlling the movements of the cattle to specifically designed paths.

Rainfall simulations can be used as a comparison with other similar sized plots and simulation protocol. The data collected is plot specific and so comparisons can be made between different areas. To use the rainfall simulator for comparison studies it is imperative that the same method protocol be implemented and correct calibration is carried out. Another consideration is the equipment needed to run a successful rainfall simulation is bulky and difficult to move easily. A few assistants are needed to move the equipment around from plot to plot. The site needs to be fairly accessible by vehicle to help transport the equipment.

The erosion rates quantified by means of rainfall simulation are site specific and unique to that particular runoff plot. The advantage of this is the ability to run comparative tests or experiments in a micro-environment, where various erosion mitigation measures effectiveness can be tested. This was the case in the Okhombe where rainfall simulation was used to establish a baseline erosion rate to compare rehabilitation techniques. The simulation affords to the scientist the ability to establish standardised quantitative information regarding erosion rates for comparison with other runoff plots with different parameters. Kose (1998) utilised rainfall simulation to determine certain factors for the USLE equation as it was expensive and difficult to obtain natural erosion rates from rainfall events.

One advantage of rainfall simulation is a visual demonstration of erosional processes. The rainfall simulation can be used as a demonstration as well as scientific quantification of erosion rates. This tool was used with great success in the Okhombe community as community members were able to visually see the impacts vegetation cover had on erosion rates and rainfall intensity and slope gradient. Furthermore, the simulation provided a good opportunity to initiate a dialogue with community members with regards to soil erosion processes. Its visual and its real and one can easily alter some set parameters to demonstrate impact. However, the simulation as a tool for quantifying and understanding erosion rates does have some limitations, such as plot size, calibration, and water use. These limitations must be understood and integrated into the community demonstration and on-site field work. By way of example, a single rainfall simulation experiment uses approximately 400 litres of water that has to be collected from a nearby clean source (using river / dam water could clog mechanics and level of macro- and micro-nutrients would be high and need to be measured prior to the experiment). In a water scare region one must take cognisance and be sensitive to water usage, hence for our workshop we re-used the water during the demonstrations and collected all un-used water and clean water for the community to use.

6.4 Erosion and Sediment Yield Modelling using MIKE SHE

6.4.1 MIKE SHE pre– calibration and validation model outputs

6.4.1.1 Comparing modelled outputs to observed records

The observed ET_A record (used to compare to the model ET_A record), is based on data previously recorded from the black wattle class (29°12’19.2’’S; 30°39’1.3’’E; Clulow *et al.*, 2011), over the period 01 October 2011 to 25 October 2013 (Figure 6.22). Over this 756-day period, the total observed ET_A amounted to 2287.7 mm. Daily observed ET_A ranged from 0 mm to 8.10 mm, with an average rate of 3.03 mm (standard deviation = 1.59). The modelled ET_A record, modelled for the same location over the same time period (Figure 6.22), had a total ET_A rate of 1899.91 mm, ranging from 0.05 mm to 6.24 mm, with an average rate of 2.51 mm (standard deviation of 1.42).

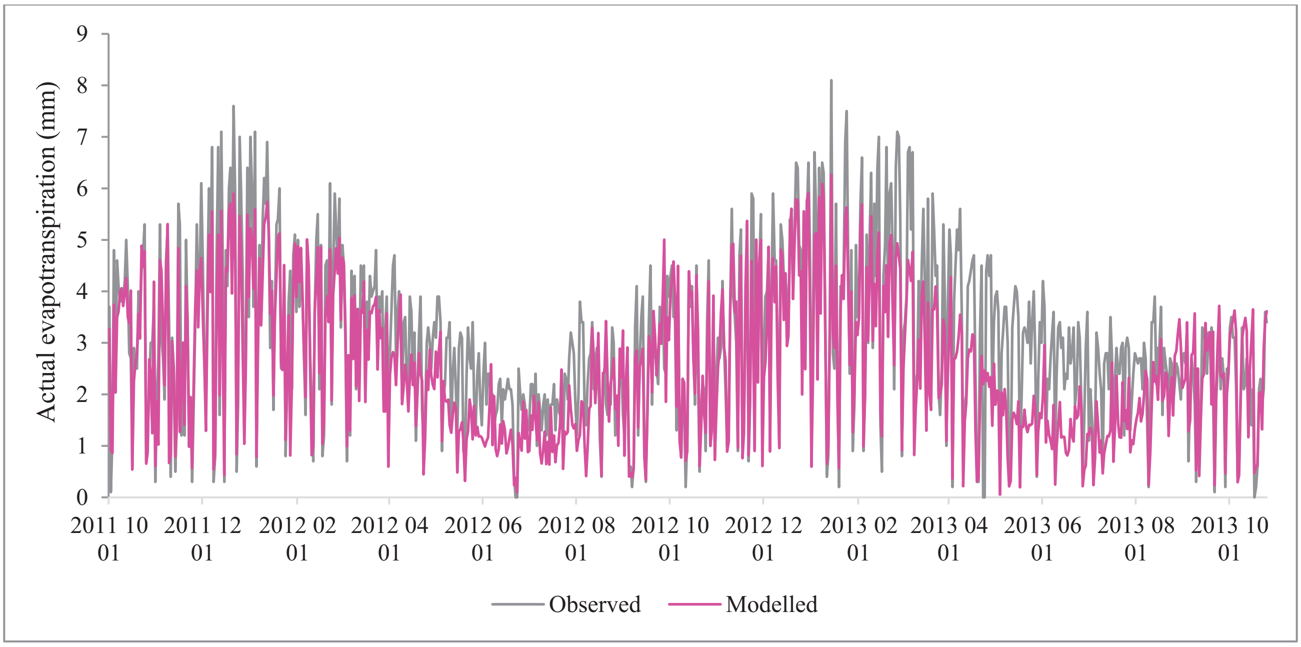

Figure 6.22 The observed and modelled actual evapotranspiration recorded from 01 October 2011 and 25 October 2013 for the Two Streams sub-catchment (29°12'19.2''S; 30°39'1.3''E).

The accumulated observed and modelled ET_A records showed that the model underestimated the ET_A by 10.14% in 2011, 13.30% in 2012 and 23.36% in 2013 and by 16.82% for the total period (01 October 2011 to 25 October 2013; Figure 6.23).

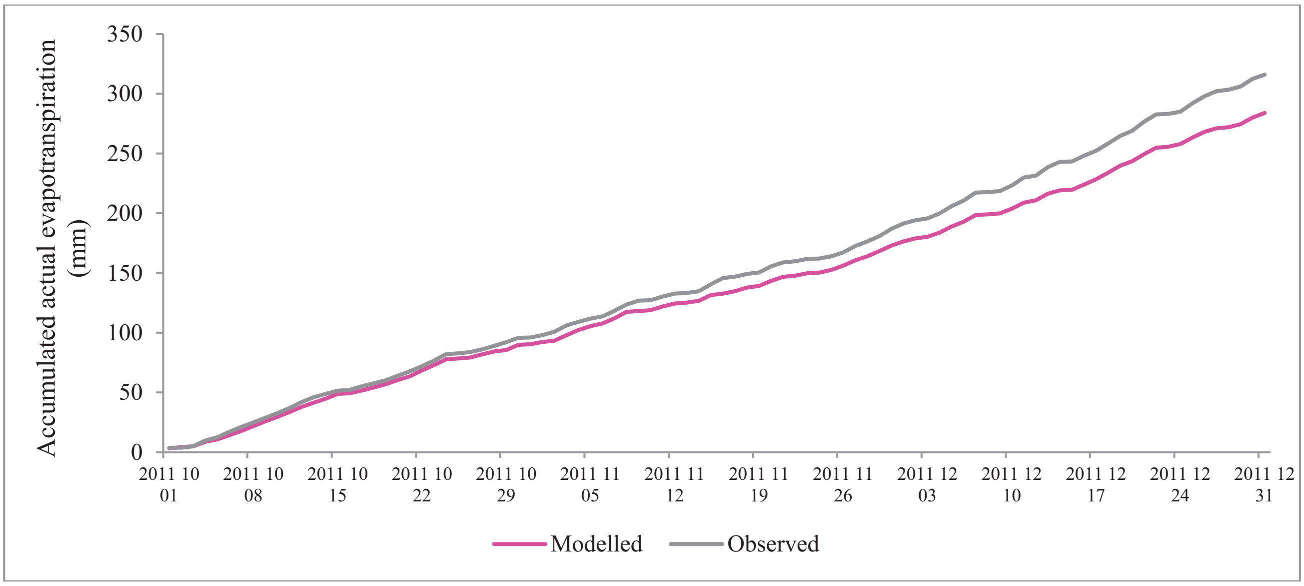

Figure 6.23 Accumulated actual evapotranspiration (mm) records (both observed and modelled) for the period 1 October 2011 to 25 October 2013.

Correlating the observed and modelled ET_A records, they showed a significant ($P < 1.00 \times 10^{-4}$), strong positive linear correlation (Figure 5.6), r = 0.86 and a RMSE of 0.93, indicating a good fit between the observed and modelled ET_A rates. However, based on the two-sample Wilcoxon signed-ranks test, the two records were significantly different from one another ($P = 4.02 \times 10^{-10}$).

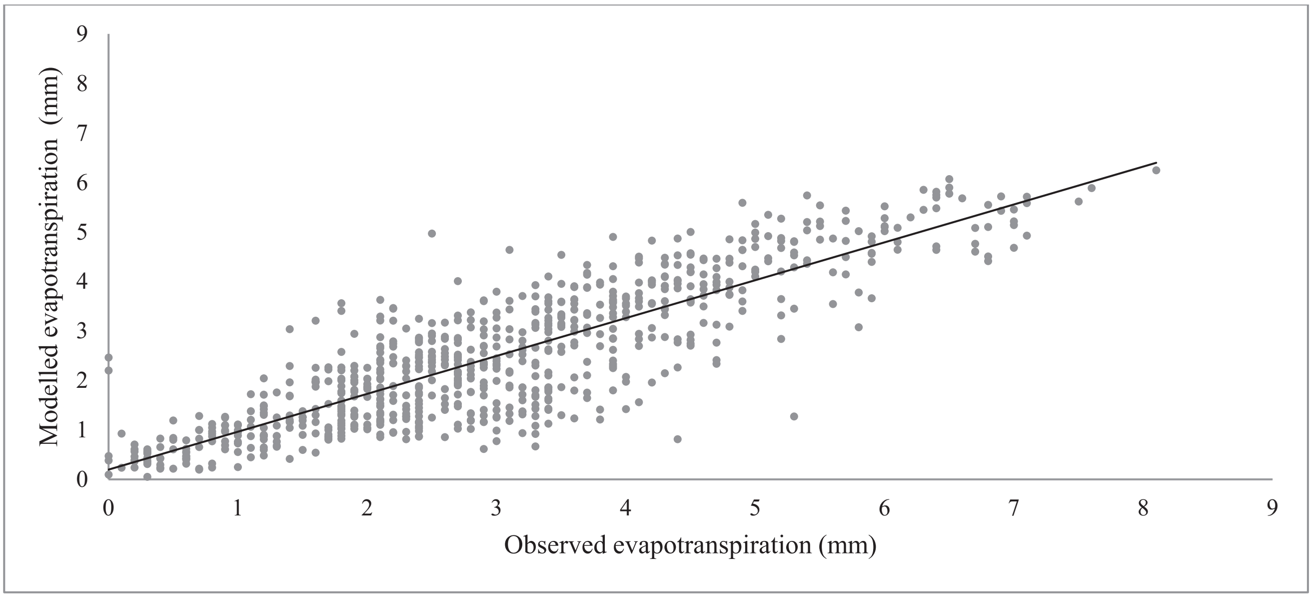

Figure 6.24 Scatter plot comparing the observed and modelled evapotranspiration (mm) rates between 01 October 2011 and 25 October 2013

The observed streamflow record for the sub-catchment river extended from 14 February 2007 to 09 December 2013 (Figure 6.25). Over this observed period, low rates of streamflow were recorded, averaging 6.72 x 10^{-4}m^3.s^{-1} and ranging from 1.70 x 10^{-5}m^3.s^{-1} to 5.10 x 10^{-3}m^3.s^{-1}. Peak daily streamflow events occurred on the 28th of February 2009 (5.10 x 10^{-3}) and on the 16th and 26th of October 2013 (4.90 x 10^{-3} respectively). There was evidence of cyclic fluctuation in the observed streamflow record indicative of seasonality, with the summer months having notably higher streamflow rates than the winter months (Figure 6.25). The modelled streamflow for the sub-catchment amounted to 0 m^3.s^{-1} over the study period, indicating that no streamflow was detected by the model (Figure 6.25). As such, no relationship between the observed and modelled streamflow records could be determined.

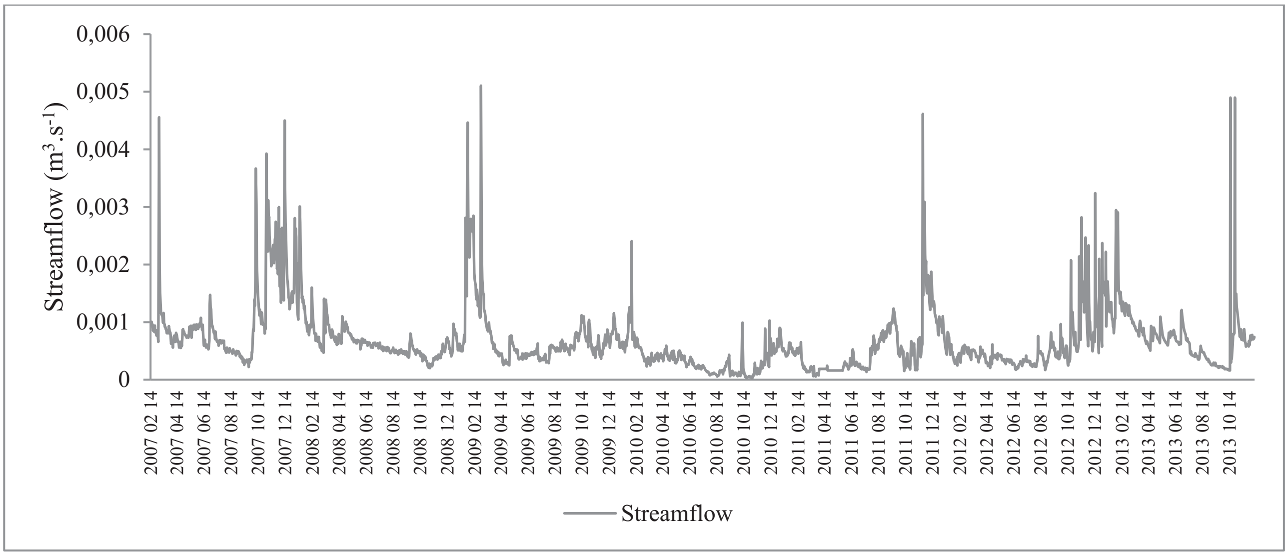

Figure 6.25 Observed streamflow records taken at the weir in the Two Streams sub-catchment, for the period 14 February 2007 to 09 December 2013

6.4.1.2 Initial MIKE SHE water balance summary

A total water balance summary diagram was produced for the modelled area (Figure 6.26) to provide a visual depiction of the flows and storages of water within the modelled area and to identify and quantify model calculation error in the system, calculated through balancing all water inflows and outflows (DHI software, 2012). All values depicted in the water balance diagram have been rounded off to whole numbers and are measured in millimetres (mm). The site water balance diagram had an error of 139 mm (Figure 6.26), suggesting that the model generated more water than that available in the modelled system. Findings from the water balance calculation showed: total ET_A to account for 99.06% of the total precipitation, a total loss in sub-surface storage (1454 mm) and a movement of 12 mm of water from the SZ to OL section (infilt. incl. Evap; Figure 6.26). Furthermore, there was no change in OL storage or in canopy storage and a movement of 150 mm of water out of the modelled area from the OL component (Figure 6.26). The water balance diagram provided no indication of any interaction between the modelled stream and the adjacent or connected hydrological components of OL, and subsurface water zones (Figure 6.26).

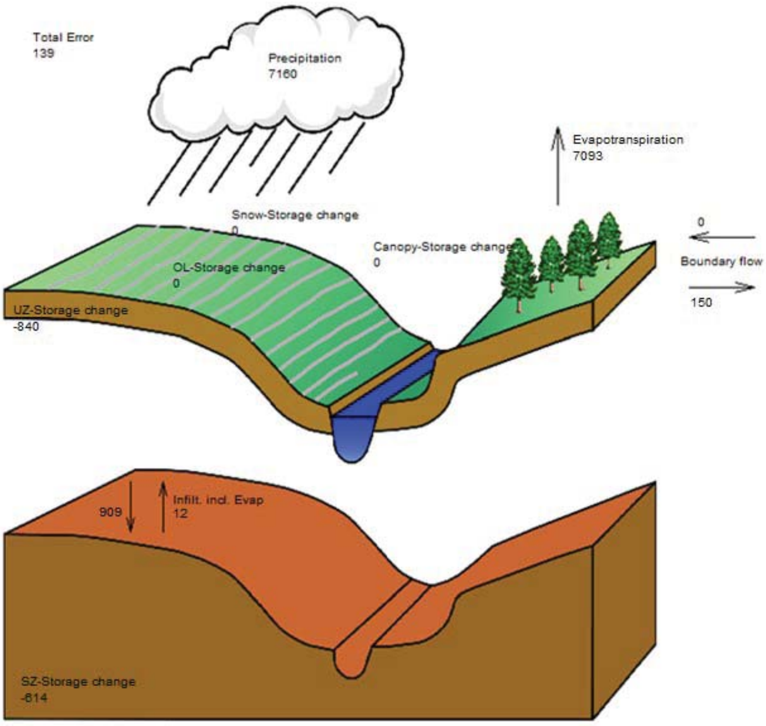

Figure 6.26 MIKE SHE accumulated water balance diagram showing the normalized flows (mm) within the modelled area over the simulated period (14 February 2007 to 02 October 2016) for the MIKE SHE current scenario (pre-calibration) run

To investigate the cause of the model error (139 mm) from the water balance diagram (Figure 6.26), the four MIKE SHE water balance sections (CI, OL, UZ and SZ) were considered separately and individual section errors were determined (Table 6.21). On inspection of the individual section errors, majority of the error was concentrated in the OL section, 99.83% (Table 6.21). This error can predominantly be attributed to water moving out of the model area as OL boundary outflow (150 mm) and to the water moving from the SZ to the OL section (12 mm; Figure 6.26). From the diagram and streamflow results it is clear no water is being held by, the river (discussed further below).

Table 6.21 Water balance error of the MIKE SHE current scenario model

Water balance components	CI	OL	UZ	SZ	Total
Accumulated error (mm)	0.22	138.94	0.02	-0.01	139.17

6.4.1.3 Correcting the MIKE SHE river component

Based on the pre-calibration model run, it appears the MIKE 11 river component was incorrectly modelled. To determine why this occurred and to correct for it, input data and processed data (inputs processed by the model prior to model run) were reassessed. Within the *river and lakes* processed data module there is a *bank minus ground* section which indicates how the river layer overlays the topography within each grid cell of the model, i.e. topography minus river cross-sectional height (DHI software, 2012). The output of this section showed the river to be located between approximately 4 m and 26 m above the ground surface (Figure 6.27), essentially floating above the land, explaining why no streamflow was being generated by the model. This error arose predominately from user error and calculation difficulty within the MIKE Hydro software where initially the river was incorrectly geo-reference and thus did not align with the topography layer. Furthermore, the cross-sections were spaced too far apart (five cross-section profiles were generated over the 750 m river) to accurately capture the stream shape.

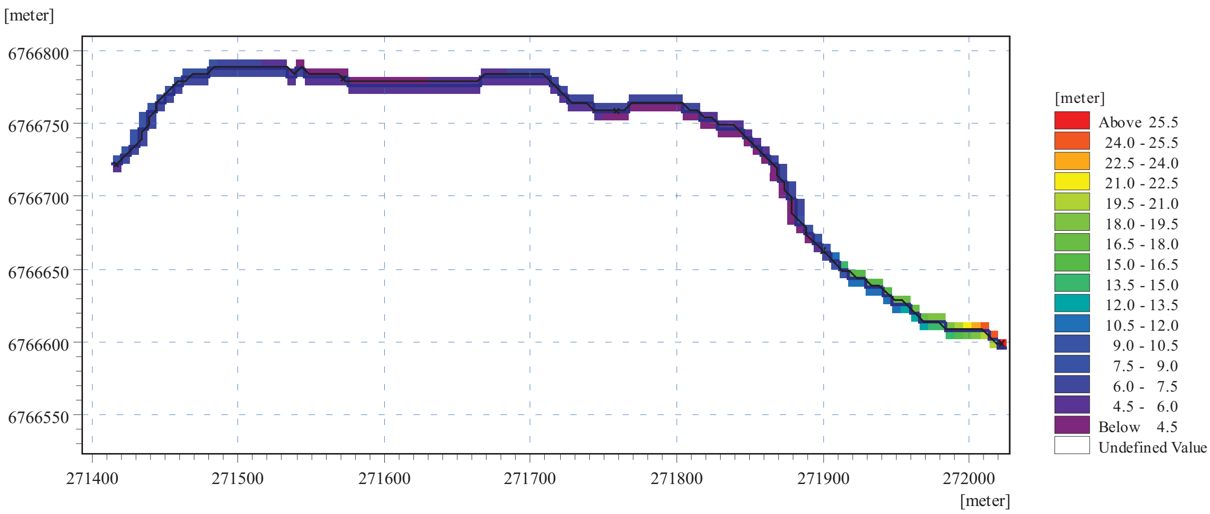

Figure 6.27 Model screen display of the river bank level minus ground level map produced in the processed data section of the MIKE SHE simulation

To correct for this error, the river was correctly geo-referenced to WGS 1984 UTM 36S projected coordinate system and reintroduced into MIKE Hydro and an additional four cross-sections were added (amounting to nine cross-sections along the course of the river), to provide greater detail on the river (Figure 6.28). The new cross-sections were further refined by smoothing their edges, as the cross-sections were computer generated and had terraced sides not representative of natural stream banks, and where necessary stream bank vertical heights were evened out where uneven stream banks led to elevation discrepancies between the topography and river layers.

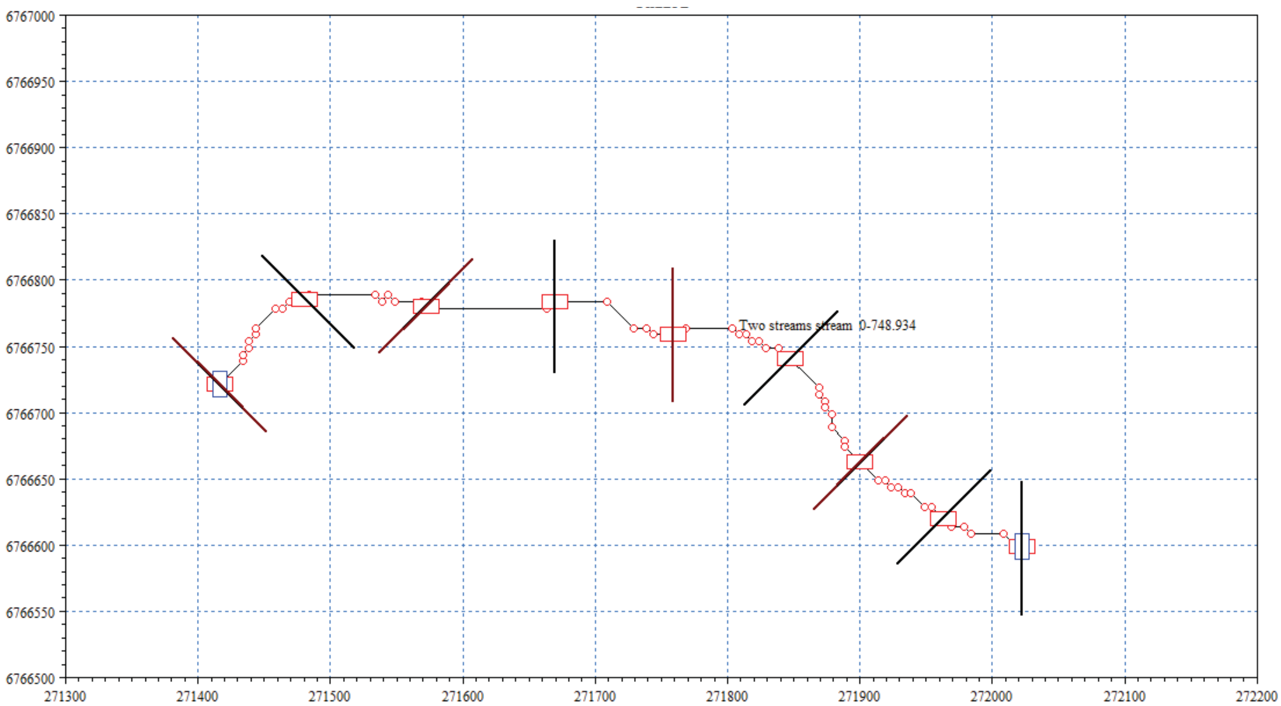

Figure 6.28 Model screen display showing the locations of the new cross-sections generated along the length of the Two Streams stream. The x- and y-axis represent the MIKE SHE geographically positioned grid

Once the new cross-sections were finalised, the pre-processing of data in MIKE SHE was run. The new *bank minus ground* section was greatly improved (Figure 6.29) with the river being located between 1.2 m above the ground and 4.4 m below the ground. This was sufficient for this study as the topography layer has a grid size of 5 m x 5 m, and thus the discrepancy between topography and streamflow would fall within one grid size, which is the highest accuracy at which the modelled data can be considered. Furthermore, the river appears to fall predominantly between -1.2 m and 0 m below ground, with only small portions falling outside of this range (Figure 6.29).

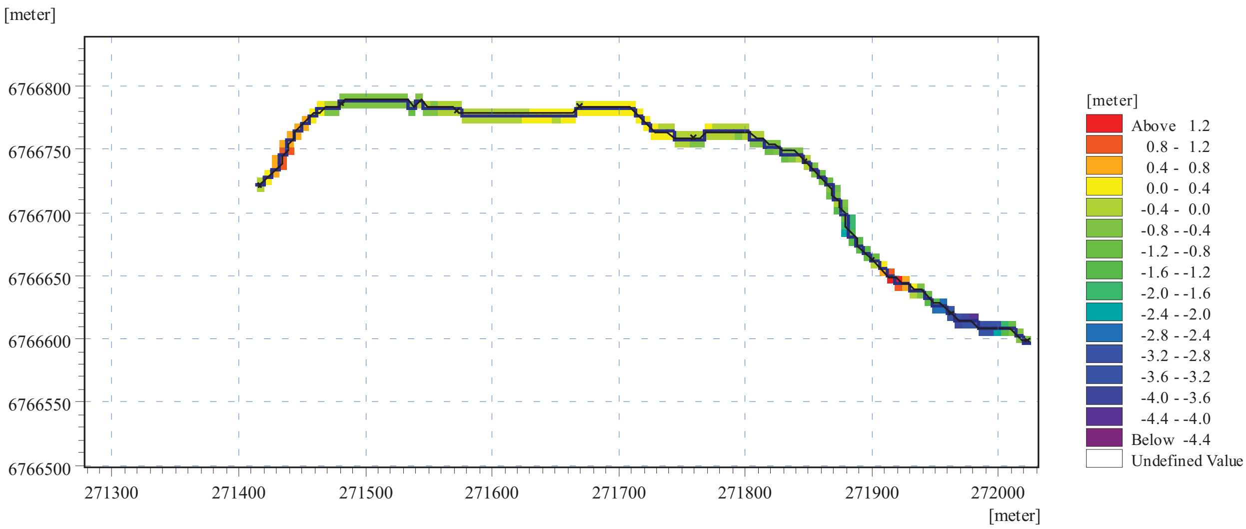

Figure 6.29 Model screen display of the river bank level minus ground level map produced in the processed data section of the MIKE SHE simulation once the cross-sections were altered

6.4.1.4 *Alterations to the model simulation run time*

In addition to the river changes, the model time step control properties were also refined, to decrease model run time, as the model was taking in excess of three days to run, making output generation a lengthy process and not practical due to the requirements of the set-up, calibration and validation processes to run numerous iterations. Originally the run time settings were left to their default values, these default values were altered to decrease the model run time, particularly decreasing the maximum OL and UZ time steps, reducing overall runtime to approximately a day.

6.4.2 MIKE SHE current scenario calibration results

Once the above alterations were made, the refined calibrated MIKE SHE current scenario model was run. From the calibrated model outputs, the modelled ET_A record did no change significantly from the initial run, with only a minor increase in total modelled ET_A from 1899.91 mm to 1907.78 mm. No further attempts were made to refine the modelled ET_A as attempts to improve model fit would require a trial and error approach, which would not provide a true representation of the response of the model to the input data.

The calibrated, modelled streamflow record (Figure 6.30), showed a marked improvement from the initial MIKE SHE model run and produced an average streamflow of 3.68 x $10^{-4}m^3.s^{-1}$ (standard deviation of 1.14 x 10^{-3}) for the total simulated period, with the streamflow ranging from 0 $m^3.s^{-1}$ and 1.20 x $10^{-2}m^3.s^{-1}$ (Figure 6.30). There was a total of 2 995 days out of a total 3519 days (approximately 85% of the total days) where no streamflow was modelled.

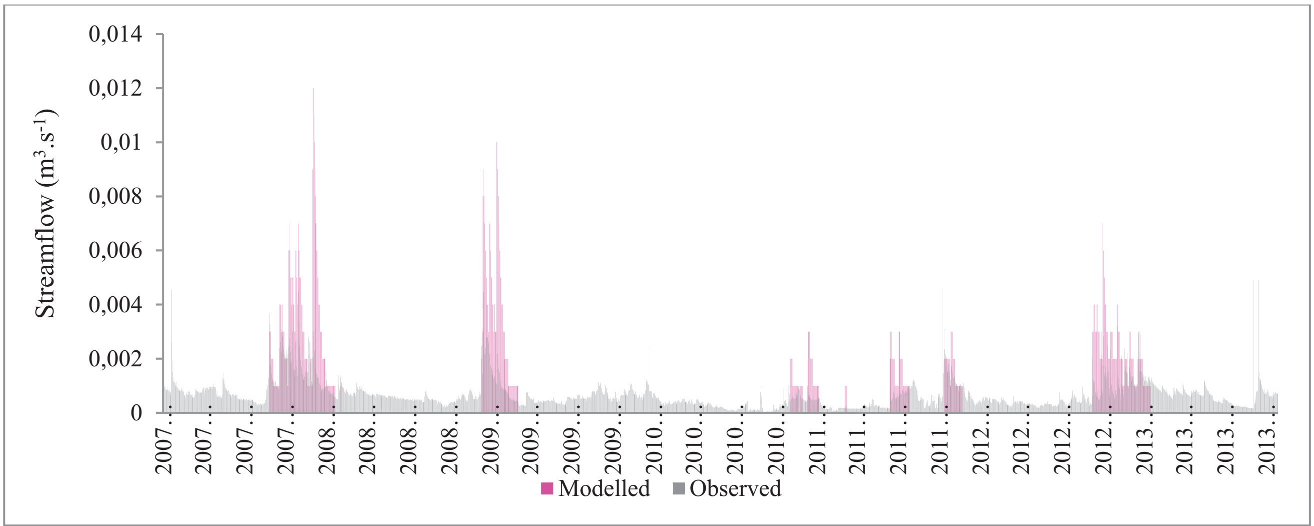

Figure 6.30 Modelled and observed streamflow records, following model calibration, taken at the weir in the Two Streams sub-catchment, for the period 14 February 2007 to 09 December 2013

Comparing the observed and calibrated modelled streamflow records, the total observed streamflow amounted to 1.67 $m^3.s^{-1}$, which is equivalent to 182.30 mm per day, whilst the total modelled streamflow amounted to 1.28 $m^{-3}.s^{-1}$ (139.97 mm per day), over the observed streamflow record time period from 14 February 2007 to 09 December 2013. This is a 0.39 $m^{-3}.s^{-1}$ (42.33 mm per day) under-prediction in streamflow and even though it is an insignificant quantity it does constitute a 23.22% under-prediction.

Considering only the days over the observed streamflow period (14 February 2007 to 09 December 2013) when the model detected streamflow (510 days), the modelled streamflow exceeded the observed streamflow by 0.63 mm (49.22% of modelled streamflow). Thus, for the 510 days the model detected streamflow, the modelled streamflow exceeded the observed streamflow, more so then when considering the total observed streamflow record time period (Figure 6.31). The stepped response in the modelled accumulated streamflow (Figure 6.31) shows how rainfall was only experienced over some periods, with extended periods of no rainfall as is expressed in the daily rainfall record (Figure 6.31).

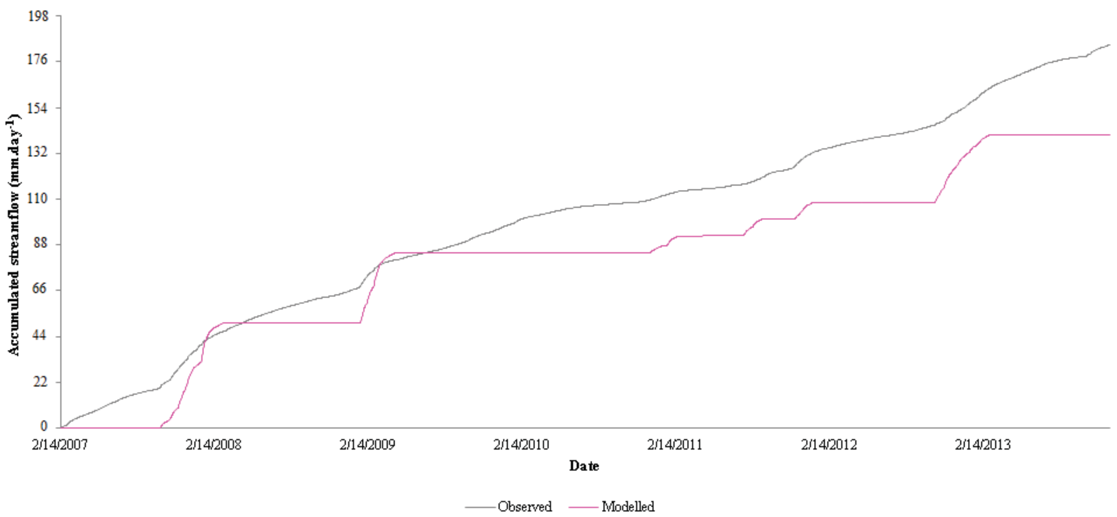

Figure 6.31 Accumulated streamflow records (mm.day^{-1}), both observed and modelled, for the period 14 February 2007 to 09 December 2013

Correlating the calibrated, modelled streamflow record to the observed streamflow record over the observed period, from 14 February 2007 to 09 December 2013, the two records show a significant ($P < 1.00 \times 10^{-4}$), positive linear correlation (Figure 6.32), r = 0.67. However, based on the two-sample Wilcoxon signed-ranks test, the observed and modelled streamflow records were significantly different from one another ($P < 1.00 \times 10^{-4}$). Correlating the streamflow records (both observed and modelled) to the rainfall record both streamflow records did not correlate well to the rainfall record, r = 0.31 and r = 0.21 for the observed and modelled streamflow records respectively. Both Pearson's correlations were significant ($P < 1.00 \times 10^{-4}$).

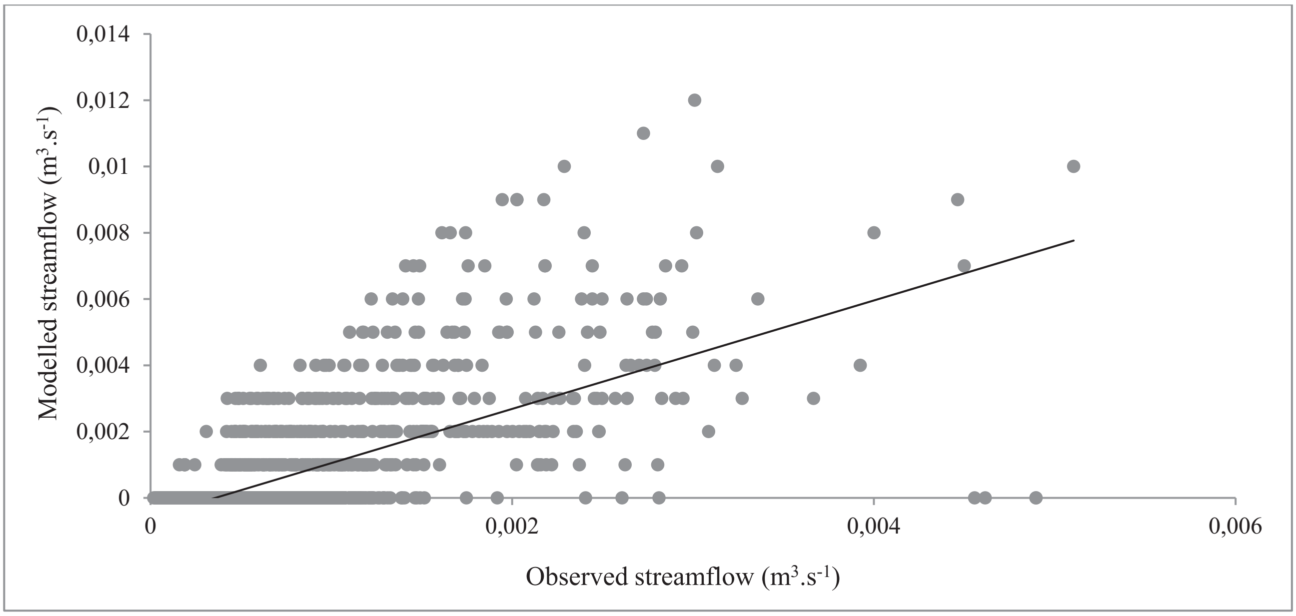

Figure 6.32 Scatter plot of the relationship between the observed and modelled streamflow records (m^3.s^{-1}) for the weir in the Two Streams sub-catchment, over the period 14 February to 9 December 2013

Further comparing the observed and modelled streamflow records, the eight months with the least difference between modelled and observed streamflow produce differences ranging from 3.21×10^{-4}m^3.s$^-$

^{1} to 8.88 x $10^{-3}m^3.s^{-1}$ (Table 6.22). The month with the smallest difference between observed and modelled streamflow was April 2011, with an average RMSE of 3.66 x 10^{-4} (Table 6.22).

Table 6.22 Monthly streamflow records showing the greatest similarity between the observed and modelled records – over days when rainfall was detected by the model

Month	Observed streamflow ($m^3.s^{-1}$)	Modelled streamflow ($m^3.s^{-1}$)	Differences (Observed – modelled)	Difference between observed and modelled (%)	Monthly average RMSE
October 2007	4.01 x 10^{-2}	3.60 x 10^{-2}	4.15 x 10^{-3}	10.22	6.98 x 10^{-4}
January 2009	3.71 x 10^{-2}	4.00 x 10^{-2}	-2.95 x 10^{-3}	7.25*	1.91 x 10^{-3}
April 2009	1.16 x 10^{-2}	1.70 x 10^{-2}	-5.45 x 10^{-3}	31.76*	4.54 x 10^{-4}
December 2010	1.59 x 10^{-2}	2.20 x 10^{-2}	-6.06 x 10^{-3}	27.73*	7.53 x 10^{-4}
February 2011	1.21 x 10^{-2}	2.10 x 10^{-2}	-8.88 x 10^{-3}	42.38*	6.60 x 10^{-4}
April 2011	5.32 x 10^{-3}	5.00 x 10^{-3}	3.21 x 10^{-4}	6.02	3.66 x 10^{-4}
July 2011	7.68 x 10^{-3}	1.50 x 10^{-2}	-7.32 x 10^{-3}	48.80*	9.38 x 10^{-4}
February 2013	4.01 x 10^{-2}	3.90 x 10^{-2}	1.11 x 10^{-3}	2.74	3.19 x 10^{-4}

**Differences where the modelled streamflow exceeded the observed streamflow.*

The streamflow records of the eight months with the greatest differences between observed and modelled streamflow had differences ranging from 2.72 x $10^{-2}m^3.s^{-1}$ to 8.85 x $10^{-2}m^3.s^{-1}$ (Table 6.23). The greatest monthly difference is observed for January 2008, with an average RMSE of 4.29 x 10^{-3} (Table 6.23).

Table 6.23 Monthly streamflow records showing the greatest difference between the observed and modelled records – over days when rainfall was detected by the model

Month	Observed streamflow ($m^3.s^{-1}$)	Modelled streamflow ($m^3.s^{-1}$)	Differences (Observed – modelled)	Difference between observed and modelled (%)	Monthly average RMSE
November 2007	7.21 x 10^{-2}	0.11	-3.49 x 10^{-2}	34.45*	1.92 x 10^{-3}
December 2007	5.81 x 10^{-2}	0.13	-6.79 x 10^{-2}	55.31*	2.41 x 10^{-3}
January 2008	5.25 x 10^{-2}	0.14	-8.85 x 10^{-2}	62.50*	4.29 x 10^{-3}
February 2009	5.70 x 10^{-2}	0.13	-7.60 x 10^{-2}	56.15*	3.03 x 10^{-3}
March 2009	3.27 x 10^{-2}	0.12	-8.23 x 10^{-2}	72.75*	3.36 x 10^{-3}
August 2011	2.08 x 10^{-2}	4.80 x 10^{-2}	-2.72 x 10^{-2}	56.67*	1.09 x 10^{-3}
November 2012	3.62 x 10^{-2}	9.70 x 10^{-2}	-6.08 x 10^{-2}	62.68*	2.33 x 10^{-3}
December 2012	3.16 x 10^{-2}	7.00 x 10^{-2}	-3.84 x 10^{-2}	54.86*	1.46 x 10^{-3}

**Differences where the modelled streamflow exceeded the observed streamflow.*

Considering the 50 days experiencing the largest amount of rainfall, nine of these days show a good response in streamflow (i.e. an increase in rainfall was reflected by an increase in streamflow), whilst 27 days do not show a good response in streamflow (Table 5.9). Thus, individual peaks in rainfall are not well reflected in streamflow.

6.4.3 MIKE SHE water balance

Within MIKE SHE the total ET rate comprises of: Et, Es, Ei, Ep and evaporation from the SZ (DHI software, 2012). All of these components are investigated below except for evaporation from the SZ as no evaporation occurred directly from the SZ.

For each vegetation class, ET comprised predominately of Et, accounting for more than 60% of total ET for all three vegetation classes (Table 6.24). Total Et is highest for the black wattle class (4604.01 mm) and lowest for the riparian (4231.35 mm) and all Et rates are significantly different ($P = 1.67 \times 10^{-11}$), when compared together (Table 6.25), however, comparing the outputs two at a time, the sugarcane and riparian rates are not significantly different (P = 0.11; Table 6.25). The Et total outputs show strong seasonal differences, with the summer months accounting for more than 60% of the total output, for each vegetation class, this is verified through the two-sample Wilcoxon's signed ranks test which found the seasonal differences to be statistically significant (P < 2.20 x 10-16; Table 6.25).

Table 6.24 Totals of each evaporation component including overall simulated total and seasonal totals for the summer and winter season

ET component	Vegetation class	Total (mm)	Total as % of total ET	Summer (mm)	Summer (% of total)	Winter (mm)	Winter (% of total)
E_t	Sugarcane	4330.44	62.83	2783.26	63.23	1592.18	36.77
	Riparian	4231.35	60.49	2987.75	70.61	1243.6	29.39
	Black wattle	4604.01	63.88	2782.82	60.44	1821.19	39.56
E_s	Sugarcane	1377.69	19.99	879.11	63.81	498.58	36.19
	Riparian	1622.59	23.19	1082.36	66.71	540.23	33.29
	Black wattle	1523.18	21.13	962.03	63.16	561.15	36.84
E_i	Sugarcane	1168.33	16.95	881.8	75.48	286.53	24.52
	Riparian	1124.34	16.07	840.61	74.76	283.73	25.24
	Black wattle	1066.92	14.80	801.08	75.08	265.84	24.92
E_p	Sugarcane	16.38	0.24	15.05	91.88	1.33	8.12
	Riparian	17.31	0.25	15.85	91.57	1.46	8.43
	Black wattle	12.83	0.18	11.73	91.43	1.1	8.57

Es rates contribute between 19.99 and 21.13 % of total ET for the three vegetation classes and are highest for the riparian class (1622.59 mm) and lowest for sugarcane (1377.69 mm; Table 6.24). All Es outputs are significantly different ($P = 6.37 \times 10^{-12}$), when compared together and when compared two at a time, the riparian and black wattle class outputs are not significantly different (P = 0.16; Table 6.25). Similarly to Et, and all of the other ET component outputs, Es shows strong, significant ($P < 2.20 \times 10^{-16}$) seasonal differences (Table 6.25), with the summer months accounting for more than 60 % of the total Es rates for all three vegetation classes (Table 6.24).

Ei rates account for approximately 15 % of total ET for all of the vegetation classes (Table 6.24) and are highest for the sugarcane class (1168.33 mm) and lowest for the black wattle class (1066.92 mm), however these rates are not significantly different for any of the vegetation classes (P = 0.75; Table 6.25). Seasonally, the summer months account for more than 70 % of the total Ei output (Table 6.24), and the summer and winter Ei rates are significantly different for all three vegetation classes ($P = < 2.20 \times 10^{-16}$; Table 6.25).

The Ep rates are very low for all three vegetation classes, contributing very little to total ET rates (< 0.30 %; Table 6.24). They are highest for the riparian class (17.31 mm) and lowest for black wattle (12.83 mm), however the riparian and black wattle class outputs are not significantly different (P = 0.40; Table 6.25) More than 90 % of the total Ep outputs occur over the summer months, for all three vegetation classes, with less than 1.50 mm occurring over the winter months (Table 6.24). The strong seasonal distinction is verified through the lack of significance between the seasons of each vegetation class ($P < 2.20 \times 10^{-16}$; Table 6.25).

Table 6.25 Statistical significance of the total and seasonal transpiration, soil evaporation, evaporation from interception and evaporation from ponded water outputs of the sugarcane, riparian and black wattle vegetation classes, compared using the Kruskal Wallis test by ranks and the two-sample Wilcoxon's signed ranks non-parametric tests

ET components		Statistical test employed	Outputs compared	P-value	Are the outputs significantly different?**
E_t	Comparing total	Kruskal Wallis test by ranks	All three	$P = 1.67 \times 10^{-11}$	Yes
		Two-sampled Wilcoxon's signed ranks test	Sugarcane and riparian	$P = 0.11$	No
			Sugarcane and black wattle	$P < 2.20 \times 10^{-16}$	Yes
			Riparian and black wattle	$P = 1.20 \times 10^{-11}$	Yes
	Comparing summer and winter	Two-sampled Wilcoxon's signed ranks test	Sugarcane	$P < 2.20 \times 10^{-16}$	Yes
			Riparian	$P < 2.20 \times 10^{-16}$	Yes
			Black wattle	$P < 2.20 \times 10^{-16}$	Yes
E_s	Comparing total	Kruskal Wallis test by ranks	All three	$P = 6.37 \times 10^{-12}$	Yes
		Two-sampled Wilcoxon's signed ranks test	Sugarcane and riparian	$P = 3.77 \times 10^{-11}$	Yes
			Sugarcane and black wattle	$P = 1.85 \times 10^{-8}$	Yes
			Riparian and black wattle	$P = 0.16$	No
	Comparing summer and winter	Two-sampled Wilcoxon's signed ranks test	Sugarcane	$P < 2.20 \times 10^{-16}$	Yes
			Riparian	$P < 2.20 \times 10^{-16}$	Yes
			Black wattle	$P < 2.20 \times 10^{-16}$	Yes
E_i	Comparing total	Kruskal Wallis test by ranks	All three	$P = 0.75$	No
		Two-sampled Wilcoxon's signed ranks test	Sugarcane and riparian	$P = 0.62$	No
			Sugarcane and black wattle	$P = 0.42$	No
			Riparian and black wattle	$P = 0.95$	No
	Comparing summer and winter	Two-sampled Wilcoxon's signed ranks test	Sugarcane	$P < 2.20 \times 10^{-16}$	Yes
			Riparian	$P < 2.20 \times 10^{-16}$	Yes
			Black wattle	$P < 2.20 \times 10^{-16}$	Yes

ET components		Statistical test employed	Outputs compared	P-value	Are the outputs significantly different?**
E_p	**Comparing total**	Kruskal Wallis test by ranks	All three	P = 0.01	Yes
		Two-sampled Wilcoxon's signed ranks test	Sugarcane and riparian	P = 0.04	Yes
			Sugarcane and black wattle	$P = 3.86 \times 10^{-3}$	Yes
			Riparian and black wattle	P = 0.40	No
	Comparing summer and winter	Two-sampled Wilcoxon's signed ranks test	Sugarcane	$P < 2.20 \times 10^{-16}$	Yes
			Riparian	$P < 2.20 \times 10^{-16}$	Yes
			Black wattle	$P < 2.20 \times 10^{-16}$	Yes

**Coloured blocks indicate relationships of insignificant difference.*
***Where vegetation classes are significantly different (yes) – P < 0.05 and where vegetation classes are not significantly different (no) – P > 0.05.*

The findings made in the daily outputs support the previous findings made on seasonality with the Et and Es outputs, for all vegetation classes, showing cyclical fluctuations that show seasonal differences, where the winter months experience lower rates than the summer months (Figure 6.33). The Ep outputs show seasonal differences in daily data, however, over the winter seasons little to no Ep occurs for any of the vegetation classes (Figure 6.33). For all three vegetation classes, the majority of the simulated days do not experience any Ep (Figure 6.33). For the sugarcane output, 82.92% of the simulated days (2918 days) record no Ep, for the riparian, 79.54% (2799 days) and for the black wattle, 82.24% (2894 days). The daily Ei outputs also show seasonal differences, however these are more evident during the times when the rates are more erratic, between 2007 and 2009, 2011 and 2012 and periods in 2013 and 2016 (Figure 6.3).

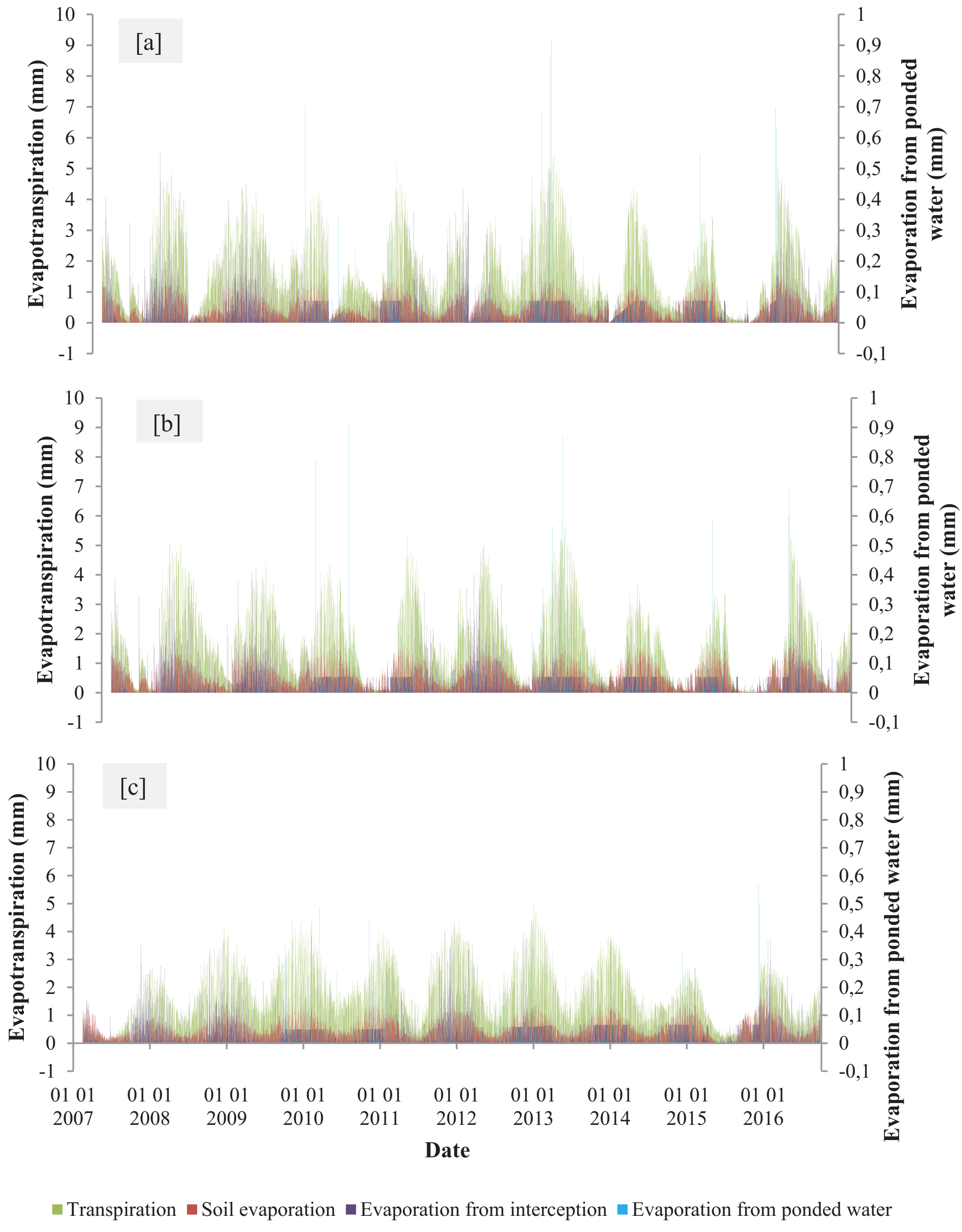

Figure 6.33 Daily time series outputs of the components of the evapotranspiration outputs: transpiration, soil evaporation, evaporation from interception and evaporation from ponded water (separate vertical axis), for the [a] sugarcane, [b] riparian, and [c] black wattle class

The annual Et rates show the sugarcane and riparian classes to have similar rates, whilst the black wattle rates differ, most noticeably in 2010 where annual Et increases from the previous year, whilst for the other class a decrease is experienced (Figure 6.34). The black wattle output has a noticeably higher annual Et in 2013, in comparison to the other classes, and a noticeably lower rate in 2007 (Figure 6.34). The annual black wattle Et range is the largest (493.72 mm) and sugarcane the smallest (275.82 mm). The annual Es outputs of all three vegetation classes follow similar trends with 2007 and 2016 experiencing lower rates that the rest of the simulated years (Figure 6.34). However, overall the sugarcane Es rates are noticeably lower than those of the other classes (Figure 6.34). The riparian class had the largest annual Es range (63.67 mm) and sugarcane the smallest range (45.06 mm). The annual Ei rates of all three vegetation classes showed similar trends, with the largest difference observed between 2007 and 2008 and the smallest between 2010 and 2012 (Figure 6.34). The sugarcane class has the largest range in annual Ei (97.77 mm) and black wattle the smallest (79.65 mm). The annual Ep outputs also all show a similar trend (Figure 6.34), with the highest annual range seen in the sugarcane class (4.43 mm) and the lowest in the black wattle (2.67 mm).

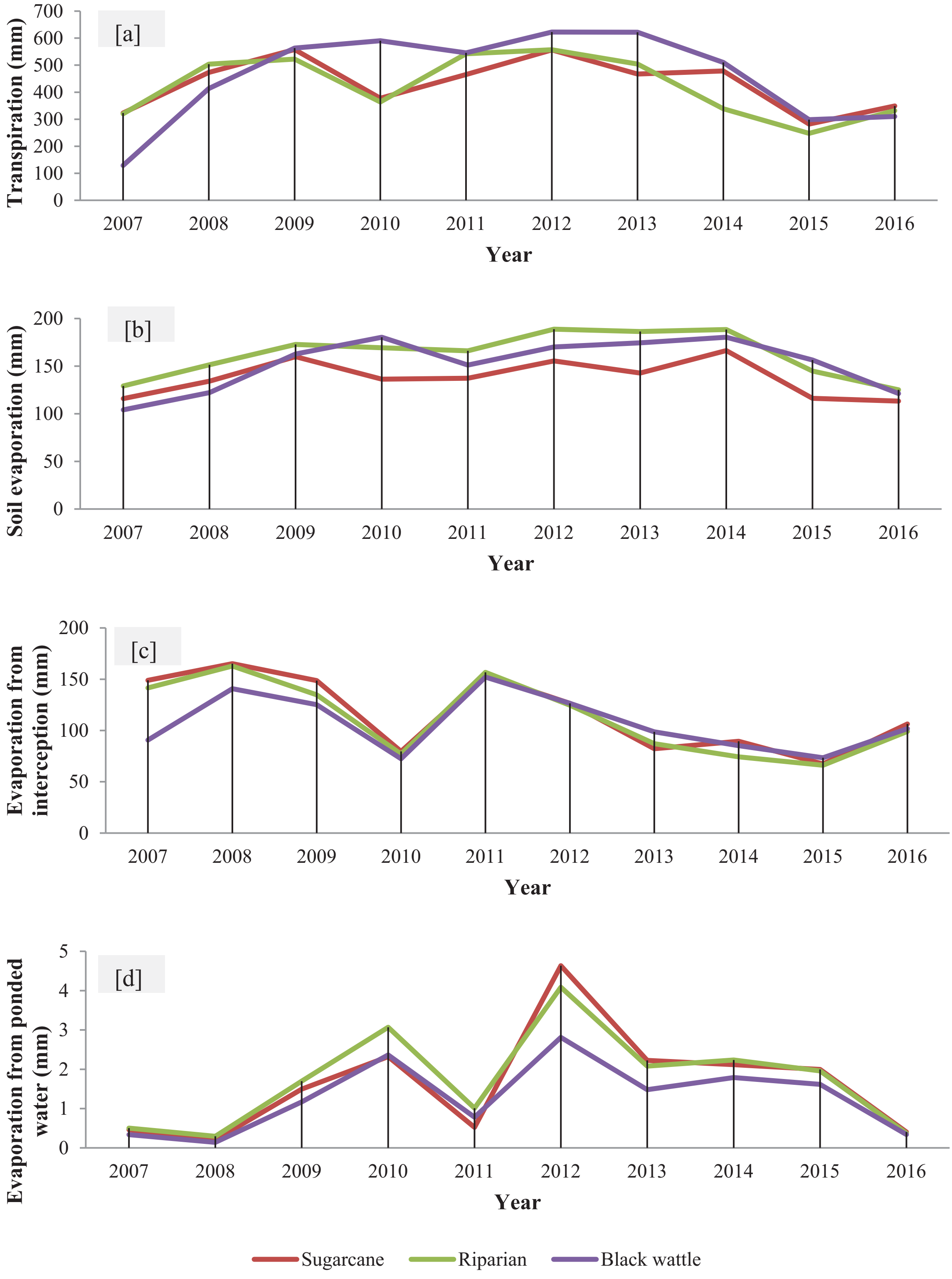

Figure 6.34 Annual rates of [a] transpiration, [b] soil evaporation, [c] evaporation from interception and [d] evaporation from ponded water for the sugarcane, riparian and black wattle vegetation classes over the total simulated period (14 February 2007 to 02 October 2016)

6.4.4 MIKE SHE depth of overland flow

The depth of OL outputs are low for all three vegetation classes, accounting for approximately 3.00 x 10^{-5} % of the total precipitation (Table 6.26). The riparian class has the highest total depth of OL (2.55 x 10^{-3} mm) and black wattle the lowest (1.95 x 10^{-3} mm; Table 6.26). All depth of OL outputs are significantly different from one another, based on the Kruskal Wallis test by ranks ($P < 2.20 \times 10^{-16}$; Table 6.26), however when comparing the vegetation class outputs using the two-sample Wilcoxon's signed ranks test the sugarcane and riparian outputs are not significantly different ($P = 0.07$; Table 6.26).

Table 6.26 Accumulated total, summer (October to March) and winter (April to September) depth of overland flow values for the sugarcane, riparian and black wattle vegetation classes, captured over the simulation period (14 February 2007 to 02 October 2016)

Accumulated rates	Sugarcane	Riparian	Black wattle
Total depth of OL (mm)	2.26 x 10^{-3}	2.55 x 10^{-3}	1.95 x 10^{-3}
Total depth of OL as % of total rainfall	3.16 x 10^{-5}	3.56 x 10^{-5}	2.72 x 10^{-5}
Summer depth of OL (mm)	1.68 x 10^{-3}	1.90 x 10^{-3}	1.36 x 10^{-3}
Summer depth of OL as % of total depth of OL	74.35	74.57	69.83
Winter depth of OL (mm)	5.80 x 10^{-4}	6.45 x 10^{-4}	5.83 x 10^{-4}
Winter depth of OL as % of total depth of OL	25.65	25.43	30.17

The total depth of OL values are higher for the summer months (than the winter months) accounting for between 70 and 75 % of the total outputs for all three vegetation classes (Table 6.27). However, despite the differences in total seasonal depth of OL, the black wattle output shows no significant difference between seasons ($P = 0.82$; Table 6.27).

Table 6.27 Statistical significance of the total and seasonal depth of overland flow outputs of the sugarcane, riparian and black wattle vegetation classes, compared using the Kruskal Wallis test by ranks and the two-sample Wilcoxon's signed ranks non-parametric tests

	Statistical test employed	Outputs compared	P-value	Are the outputs significantly different?**
Total depth of OL	Kruskal Wallis test by ranks	All three	$P < 2.20 \times 10^{-16}$	Yes
	Two-sampled Wilcoxon's signed ranks test	Sugarcane and riparian	$P = 0.07$	No
		Sugarcane and black wattle	$P < 2.20 \times 10^{-16}$	Yes
		Riparian and black wattle	$P < 2.20 \times 10^{-16}$	Yes
Comparing summer and winter depth of OL	Two-sampled Wilcoxon's signed ranks test	Sugarcane	$P = 2.92 \times 10^{-14}$	Yes
		Riparian	$P = 2.67 \times 10^{-11}$	Yes
		Black wattle	$P = 0.82$	No

**Coloured blocks indicate relationships of insignificant difference.*
***Where vegetation classes are significantly different (yes) – P < 0.05 and where vegetation classes are not significantly different (no) – P > 0.05.*

The annual depths of OL values are highest in 2014 for the sugarcane and riparian vegetation classes and highest in 2013 for the black wattle class, and lowest in 2016 for all three vegetation classes (Figure 6.35). There is a peak in the annual depth of OL outputs for all three vegetation classes in 2010, followed by a steep decline in annual values in 2011 (Figure 6.35). The daily depth of OL outputs show a peak rate significantly greater than all other simulated days on the 28th of January 2015 (Figure 6.35), with this single day accounting for 6.72 % (sugarcane), 8.95 % (riparian) and 5.40 % (black wattle) of the total respective OL values (Table 6.28).

Table 6.28 Daily depth of overland flow for the 28th of January 2015 for the sugarcane, riparian and black wattle vegetation classes

Vegetation class	Date of highest simulated daily depth of OL	Depth of OL (mm)	Total simulated daily depth of OL (mm)	Highest simulated as % of total
Sugarcane	28 January 2015	1.52×10^{-4}	2.26×10^{-3}	6.72
Riparian	28 January 2015	2.28×10^{-4}	2.55×10^{-3}	8.95
Black wattle	28 January 2015	1.05×10^{-4}	1.95×10^{-3}	5.40

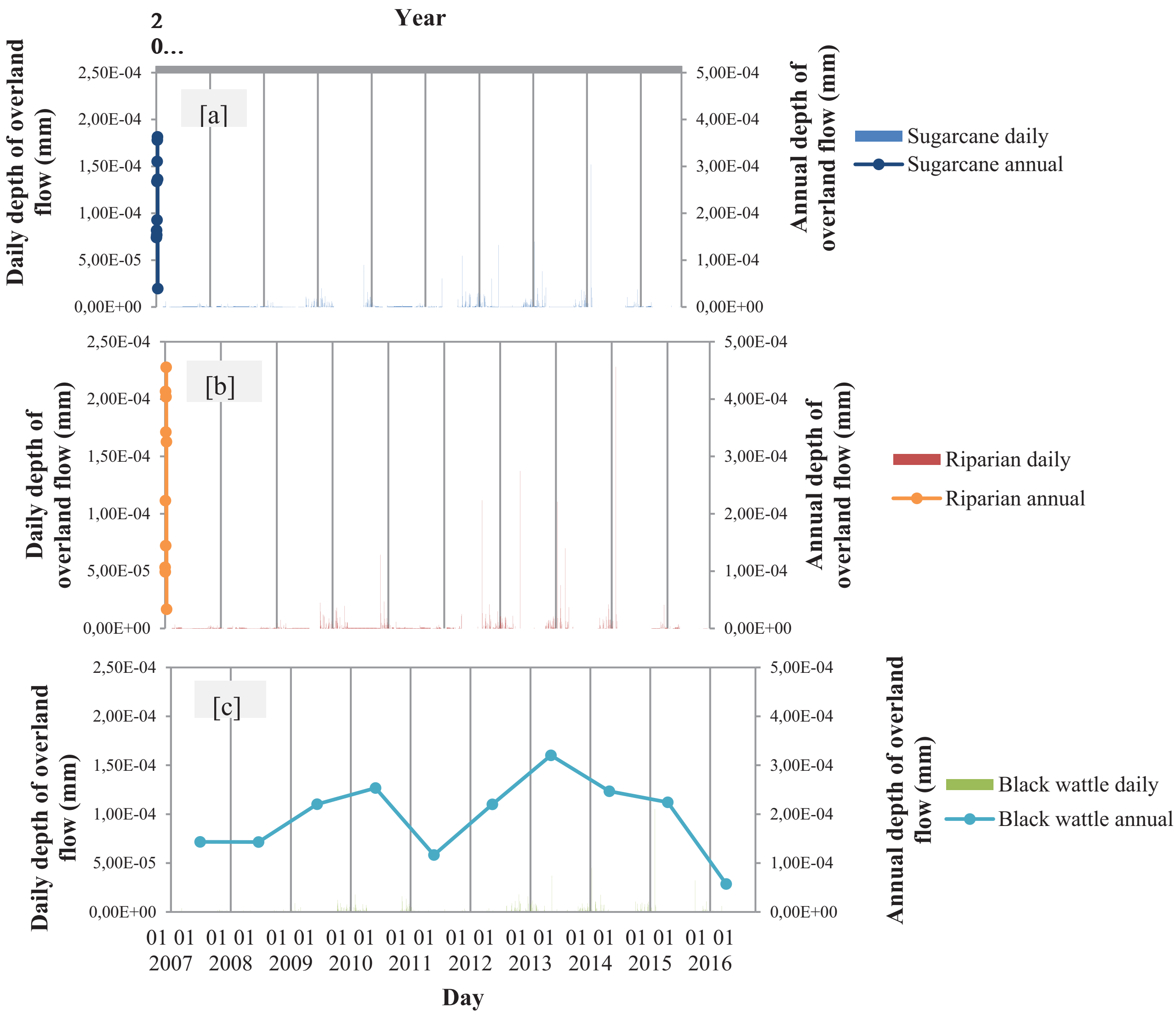

Figure 6.35 Daily and annual depth of overland flow outputs for the [a] sugarcane, [b] riparian and [c] black wattle vegetation classes, modelled over the total simulation period (14 February 2007 to 02 October 2016)

To identify the cause of this peak in depth of OL, climatic conditions are considered. On the 28th of January 2015 daily rainfall was 27.3 mm, this was the highest rainfall experienced in January 2015 which had an average rainfall of 2.17 mm and a total rainfall of 67.4 mm (Figure 6.36). However, this was lower than the highest daily rainfall experienced over the simulation of 75.7 mm (12 December 2015). The daily average temperature was approximately 16˚C which was lower than the monthly average of 20˚C (Figure 6.36). Thus, for January 2015, the 28th experienced the highest rainfall and relatively low temperatures.

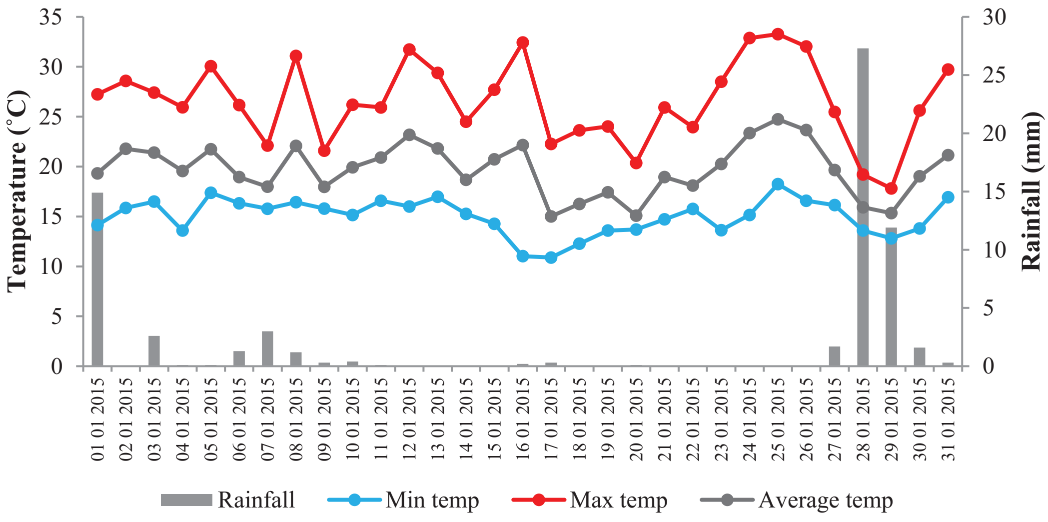

Figure 6.36 Daily rainfall (mm) and temperature (˚C) measures for January 2015

This could suggest that more water was available for OL as less water was evaporated due to the lack of radiant energy – the average ET was lowest for the 28th of January 2015 in comparison to the rest of the month, amounting to 0.95 mm (Figure 6.37), this is much lower than the averaged ET for January 2015 (2.86 mm). The IUZ rate was greatest for the 28th of January 2015, in comparison to the rest of the month (Figure 6.37), justifying why, despite being the largest rate of depth of OL, over the simulation period, the rate was still minute.

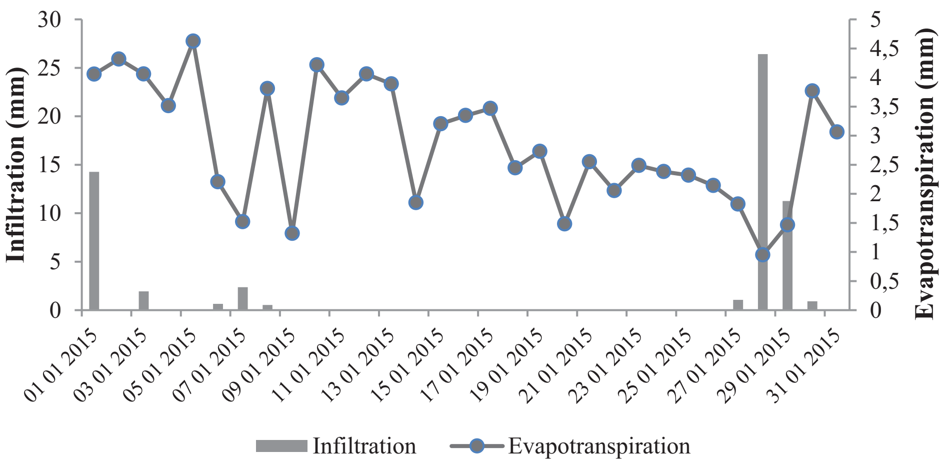

Figure 6.37 Daily average infiltration (mm) and average evapotranspiration (mm) measures for January 2015.

The spatial variation in the depth of OL for the 28th of January 2015 is investigated further (Figure 6.38) showing discrete homogeneous patches. Each patch corresponds to the different soil types of the sub-catchment, with the Magwa and Clovelly soils having higher rates of depth of OL (> 2.60 x 10^{-4}) and the Oakleaf soil having lower rates of depth of OL (< 2.00 x 10^{-5}; Figure 6.38).

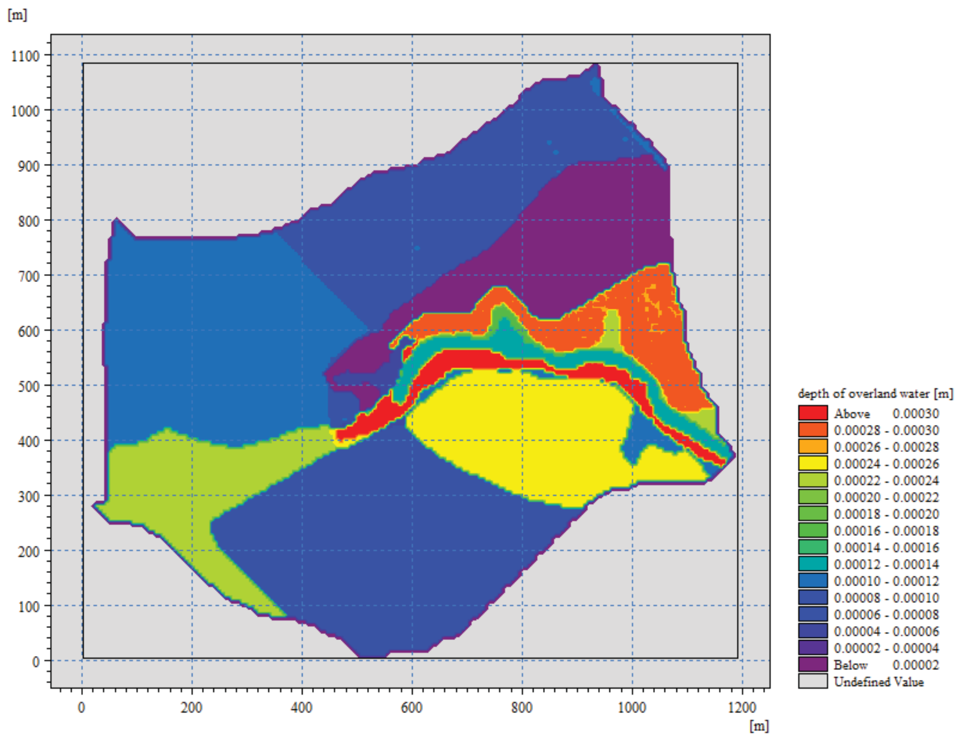

Figure 6.38 Model screen display of the spatial explicit depth of overland flow for the 28th of January 2015, for the study site.

Depth of OL and IUZ are expected to be interlinked processes having a resultant impact on each other, as if more IUZ occurs there should be less water available as OL. Correlating the annual depth of OL rates to those of IUZ, all vegetation classes show insignificant, weak linear correlations, r = 0.06 (sugarcane), 0.05 (riparian) and 8.37×10^{-4} (black wattle; Table 6.29). The amount of OL (i.e. water present on the ground surface) will impact the amount of evaporation taking place, where the more water present on the surface is expected to allow for greater rates of evaporation. Thus, to investigate this relationship further the annual depth of OL rates and the Ep rates are correlation for all three-vegetation class and found to have significant, strong positive linear correlations, r =, 0.71 (sugarcane), 0.81 (riparian) and 0.70 (black wattle; Table 6.29).

Table 6.29 Correlating depth of overland flow with annual infiltration and evaporation from ponded water rates of the three vegetation classes: sugarcane, riparian and black wattle.

Correlation	Vegetation class	Relationship	Pearson's correlation coefficient (r)	Significance of the Pearson's correlation
Depth of OL and I_{UZ}	Sugarcane	Positive	0.06	P = 0.86
	Riparian	Negative	0.05	P = 0.89
	Black wattle	Positive	8.37×10^{-4}	P = 0.99
Depth of OL and E_p	Sugarcane	Positive	0.71	P = 0.02
	Riparian	Positive	0.81	P = 0.01
	Black wattle	Positive	0.70	P = 0.03

** Coloured blocks indicate Pearson's correlation coefficients that are not significant (P > 0.05).*

6.5 Erosion and Sediment Yield Modelling using SWAT

The results focus on improving model performance, particularly in the sediment yield component. A large component of this is calibration and validation of models. The spatially explicit and time series output cover both Two Streams and Fountain Hill Estate.

6.5.1 Sensitivity Analysis

After thorough pre-processing of the required input for ArcSWAT model, flow simulation was performed for eleven years of recording periods starting from 1989 through 1999. The three years of which were used as a warm up period and the simulation was then used for sensitivity analysis of hydrologic parameters and for calibration of the model. The sensitivity analysis was made using a built-in SWAT-CUP sensitivity analysis tool that uses the Latin Hypercube One-factor-Ata-Time (LH-OAT). After the analysis, the mean relative sensitivity of the parameters was used to rank the parameters.

Table 6.30 Sensitivity analysis of the ArcSWAT input

Parameter	Description	Sediment Yield	
		Rank	Default
USLE_P	USLE support practice factor	1	1
Alpha_Bf	Baseflow alpha factor (days)	2	0.048
Slope	Average slope steepness (m/m)	3	Variable
Canmx	Maximum canopy storage (mm)	4	0
Ch_K2	Channel effective hydraulic conductivity (mm/hr)	5	0
Ca2	Initial SCS CN II value	6	Variable
Ch_N2	Mannings “n” for main channel	7	0.014

6.5.2 Model Calibration

The aim of model calibration is to achieve a reduction in model uncertainty by efficiently extracting information contained in the calibration data. It involves the comparison of model simulation with an observed data on predefined objective function and adjusting parameters to improve closeness. ArcSWAT model can be calibrated both manually and automatically. The manual calibration is most widely used calibration and involves visual comparison of observed and simulated data. The model calibration and validation was undertaken on two of the catchments. SWAT-CUP was used to perform this process using observed streamflow. Sequential Uncertainty Fitting was used as the statistical tool. The findings show a reasonable fit between the simulated and observed streamflow. For peak events, the model was under-simulating the streamflow. The post-calibration simulation (Figure 6.39) provided an improved simulation but with some inconsistencies between peak events. This is likely due to the impact of land management, which is very sensitive for such a small catchment area. There were some missing streamflow records which were subsequently patched using the simulated data.

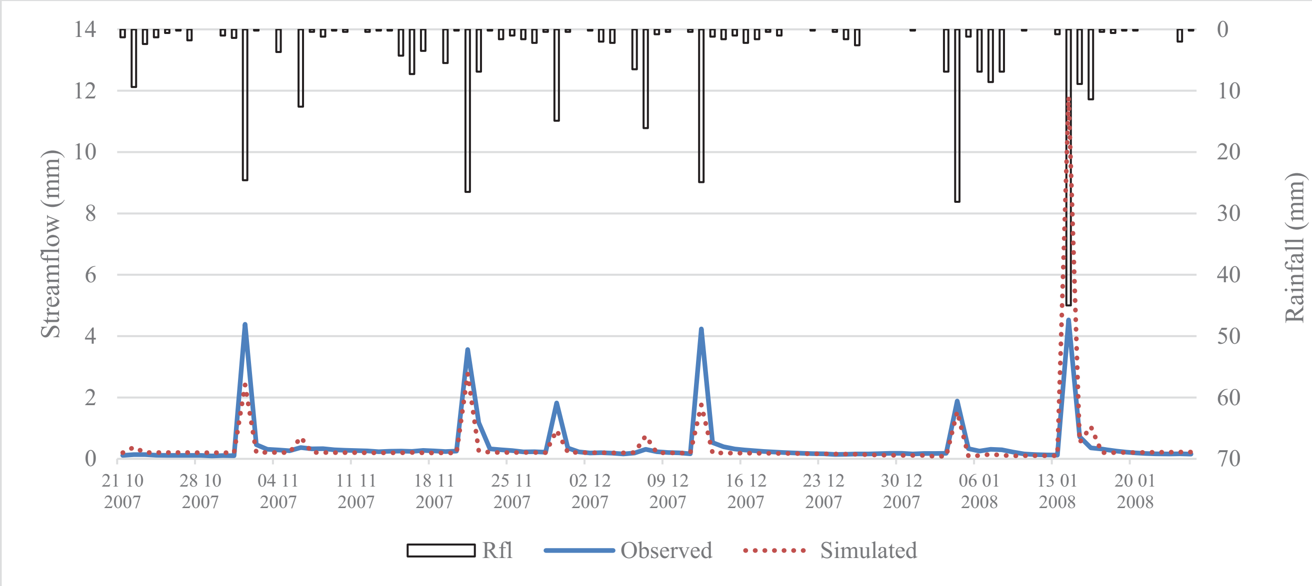

Figure 6.39 Model calibration using observed streamflow data

Observed sediment data, were obtained for the site. The data is provided in Table 6.31. This showed a peak load of 26.94 $g.m^{-2}$. This data has been extrapolated to $t.ha^{-1}$. However, the authors are waiting for more data to become available under different land uses. Once these data are available, a calibration and parameterization will be performed on the catchment model.

Table 6.31 Observed sediment loads within the *Acacia mearnsii* stand at Two Streams

Date	10 m^2 (g)	1 m^2 (g)
08-Jan-15	6.03	2.55
28-Jan-15	75.63	6.62
11-Feb-15	118.32	9.75
23-Feb-15	3.23	0.69
03-Apr-15	4.14	1.64
27-May-15	174.42	7.56
05-Aug-15	41.08	3.29
22-Sep-15	38.24	4.69
17-Nov-15	26.45	4.93
11-Dec-15	119.90	13.67
18-Dec-15	511.29	26.94
12-Jan-16	105.20	18.67
27-Jan-16	3.46	1.53
04-Mar-16	149.63	16.29
Total	**1377.00**	**118.85**
Average	**98.36**	**8.49**

6.5.3 Annual Water Balance

The annual water balance is the most summarized output from SWAT (Figure 6.40 and Figure 6.41). It provides a good visual representation as to how rainfall is partitioned through the hydrological cycle. The results at Two Streams (Figure 6.40) show high amounts of total evaporation lost through vegetation and surface evaporation. Some recharge to the shallow aquifer occurs and very little to the deep aquifer. Surface runoff in this area is high compared to the other contributions to streamflow. Similar findings were simulated at FHE. However, due to no commercial forestry, the ratio of rainfall to ET was lower that at Two Streams.

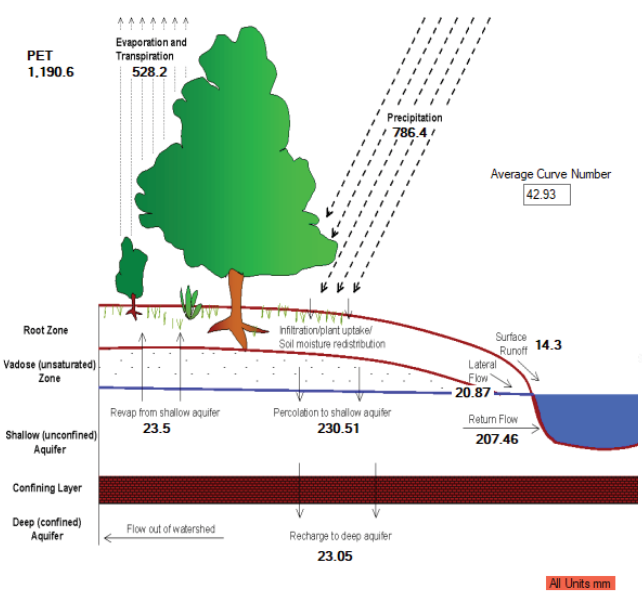

Figure 6.40 Simulated hydrological cycle at Two Streams (left) and Fountainhill Estate (right)

The in-stream sediment change (Figure 6.41) was much lower at Two Streams than FHE. However, the loads simulated from these two catchments are largely dependent on the catchment area. With this contrast in Catchment area, the sediment loads are still significantly higher at FHE.

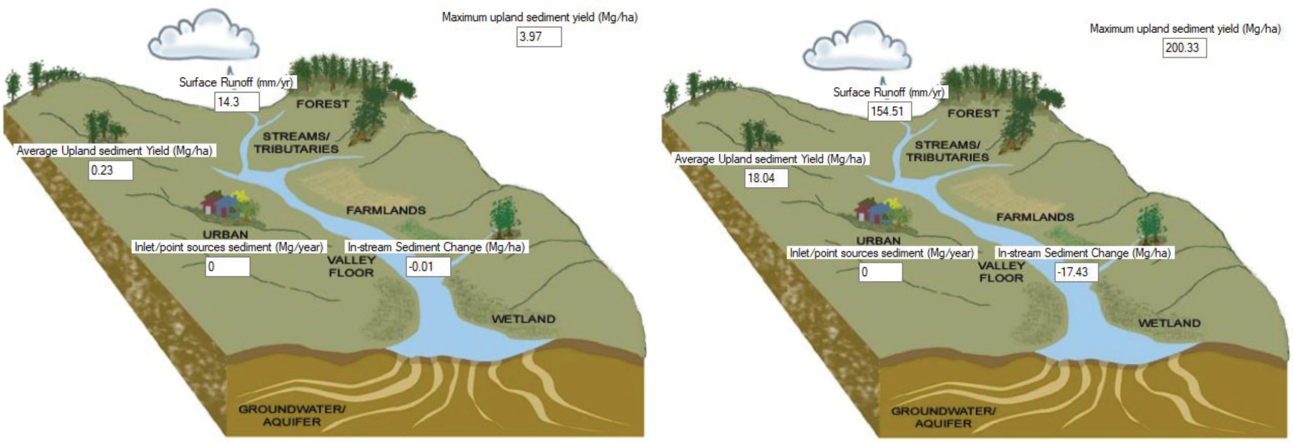

Figure 6.41 Simulated sediment cycle at Two Streams (left) and Fountainhill Estate (right)

Table 6.32 provides an overview of the monthly hydrological components produced from the Two Streams catchment. This table along with the schematic of the hydrological cycle indicate that the flow from this catchment is low. This is due to its small catchment area of 0.75 km^2. The total evaporation is high and exceeds the rainfall in the winter months. Sediment yield is generally low due to the catchment size.

Table 6.32 Monthly hydrological results

	Rainfall (mm)	Surface Flow (mm)	Lateral Flow (mm)	Water Yield (mm)	Total Evaporation (mm)	Sediment Yield (mm)	Potential Evaporation (mm)
Jan	132.58	22.27	0.94	27.52	60.17	0.03	118.89
Feb	91.99	16.99	0.91	26.26	66.54	0.02	98.76
Mar	83.89	11.64	0.79	24.49	69.86	0.02	86.57
Apr	53.59	7.31	0.59	16.56	56.42	0.01	69.99
May	21.97	1.63	0.36	7.51	40.65	0	58.32
Jun	14.12	0.28	0.18	2.55	24.83	0	52.47
Jul	17.99	2.78	0.14	3.51	20.71	0	67.44
Aug	32.69	1.7	0.18	2.31	34.64	0	89.84
Sep	51	2.86	0.21	3.44	43.77	0.01	88.19
Oct	92.82	5.66	0.38	6.31	68.05	0.01	95.31
Nov	114.55	8.96	0.62	10.58	88.71	0.03	104.96
Dec	136.06	17.2	0.79	20.04	101.01	0.01	119.46

6.5.4 Spatially Explicit Output

Generating spatial output data are a useful approach as it allows for data to be quickly and easily relayed to clients, GIS users and various decision makers. The difficulty is reducing the time series to a manageable level for display purposes. Annual data of specific output parameters can be spatially output. Seasonal changes can also be displayed (e.g. monthly maps). Furthermore, percentage change between scenarios can be calculated and displayed. This allows for the identification of sensitive areas or areas where management will have the largest benefit.

The results from the topographic reports suggest relatively high variations in slope and elevation. An important reason for the detailed terrain input and HRU creation is that output data can be linked back to the spatial distribution within the catchment. Surface runoff at Two Streams was greatest along road surfaces and within the higher sloped riparian areas. Additionally, more runoff was generated under the sugarcane field compared to the plantation areas (Figure 6.42). This finding is as a result of land management and vegetation type (e.g. more interception from the plantation areas).

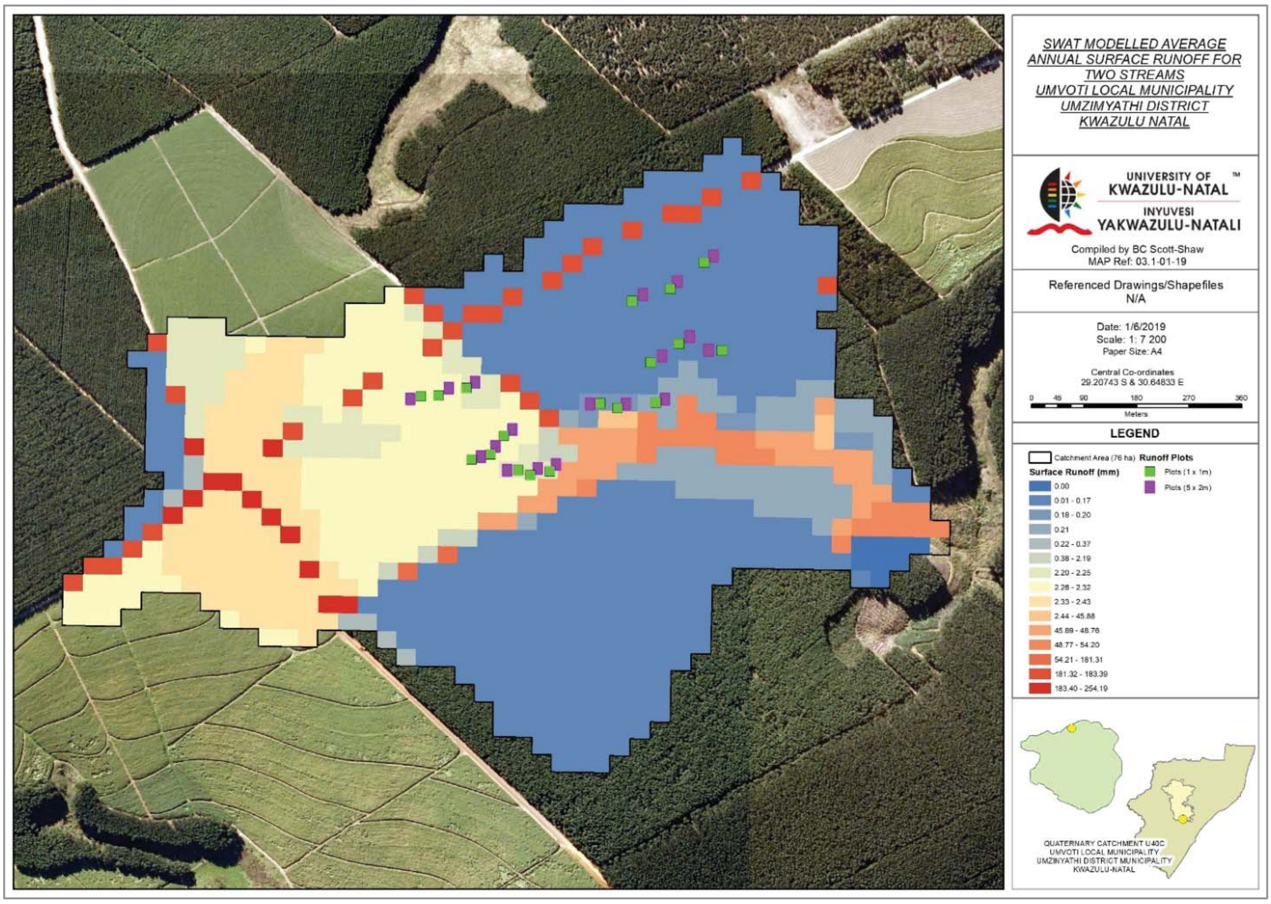

Figure 6.42 Spatial output of average annual surface runoff at Two Streams

The spatial sediment yield at Two Streams (Figure 6.43) shows that, in contrast to the surface runoff, the plantation areas exhibit more runoff than the sugarcane. However, these differences are slight. The plot measurements showed that sediment loads were greater at both plot scales (1 m^2 and 10 m^2) in the plantation areas during the dry season events. During the wet season, these two landuse types yielded very similar results.

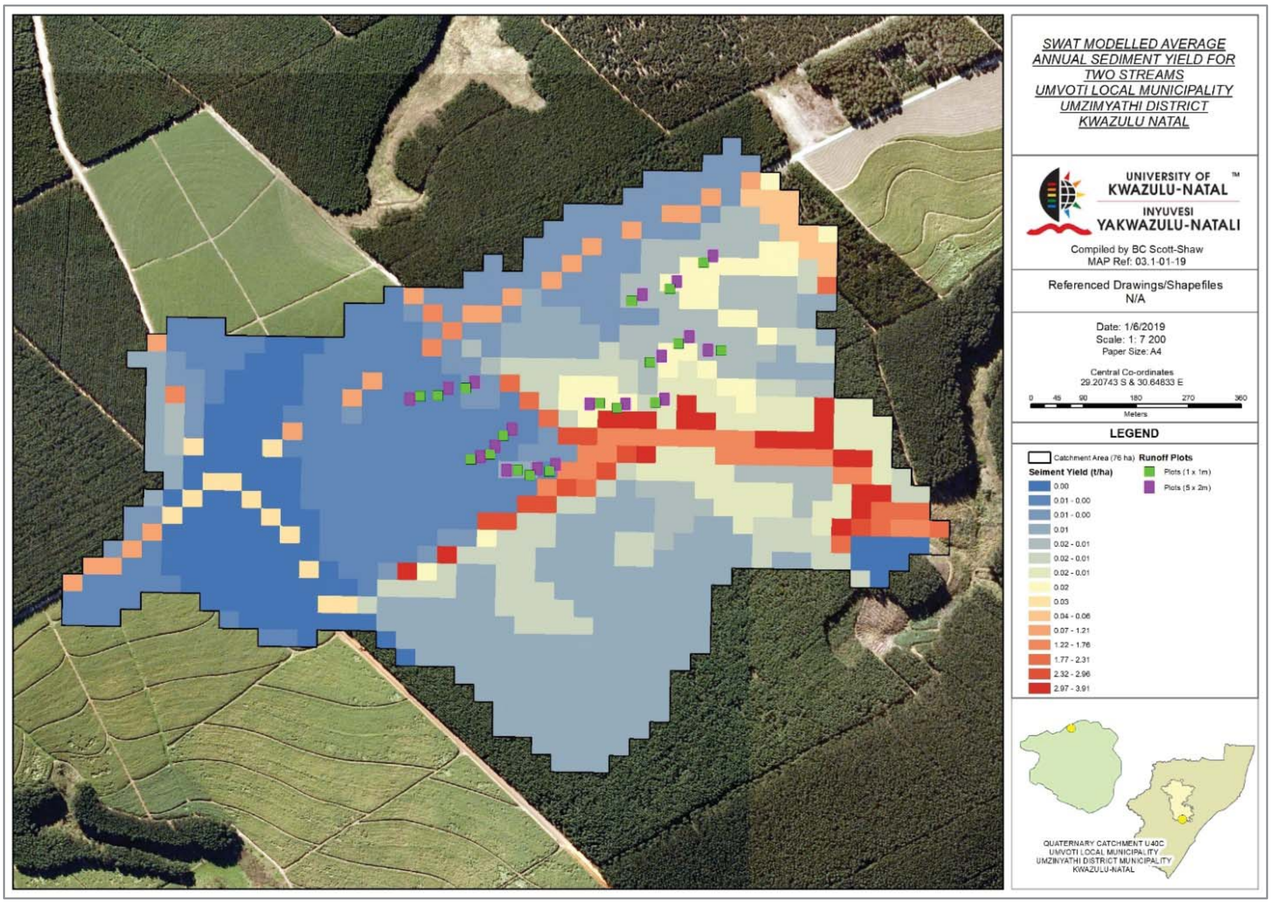

Figure 6.43 Spatial output of average annual sediment yield at Two Streams

The organic nitrogen (Figure 6.50) and organic phosphorus (Figure 6.45) at Two Streams is directly correlated to the sediment yield amount. The results show that up to 19 kg/ha could be lost during a one-year period. Up to 1.8 kg/ha of phosphorus could be lost over the same period. The results show that the plantations and sugarcane fields are not the highest areas of loss. However, the only areas that are not commercially planted are gravel road surfaces and very steep slopes that would naturally yield high amounts of sediment due to a high runoff generation.

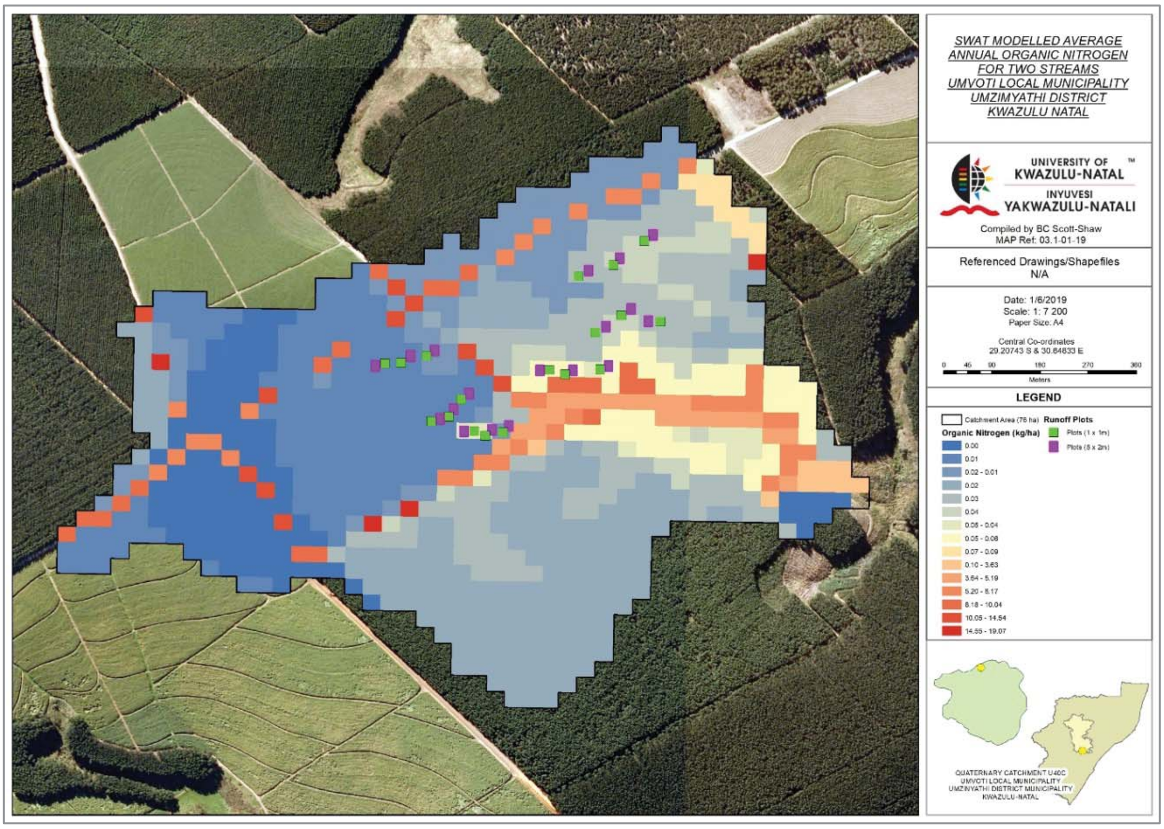

Figure 6.44 Spatial output of average annual organic nitrogen at Two Streams

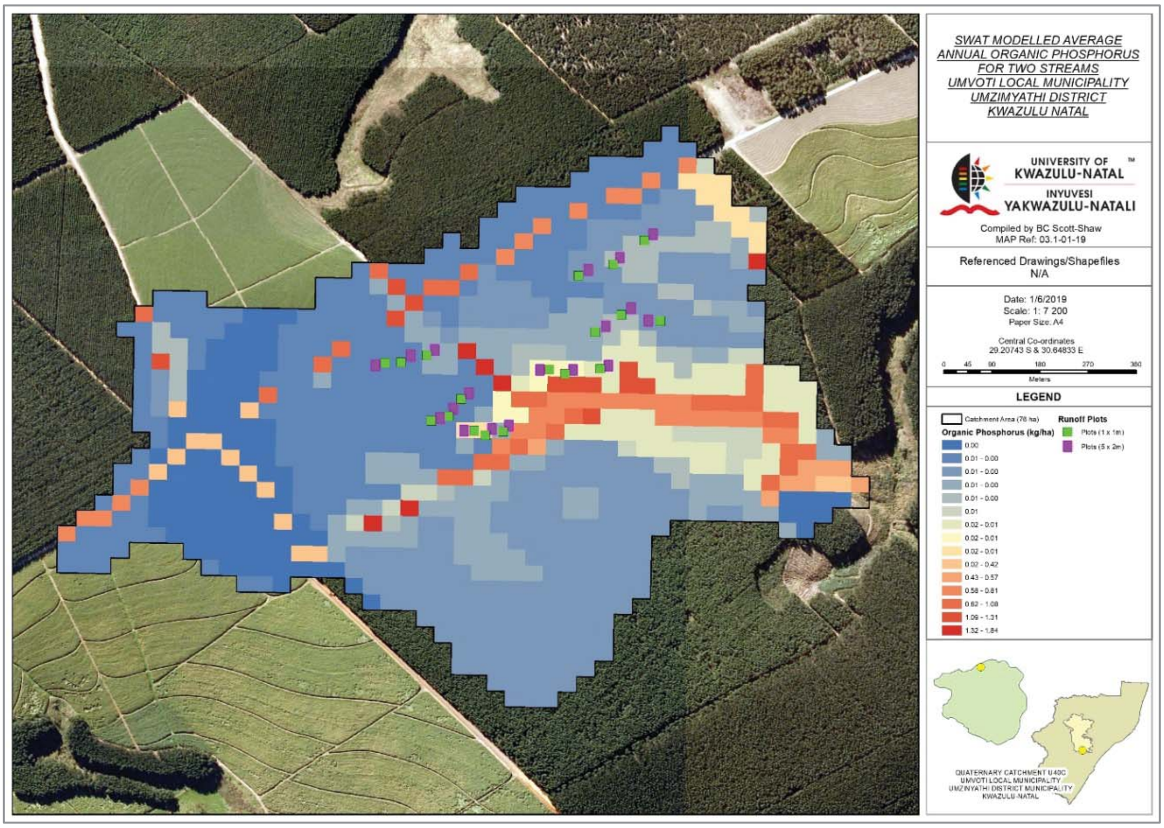

Figure 6.45 Spatial output of average annual organic phosphorus at Two Streams

Surface runoff at FHE was greatest along road surfaces and the urban impervious surfaces of Wartburg. More runoff was generated under the maize fields compared to the plantation areas (Figure 6.46). This finding is as a result of land management and vegetation type (e.g. more interception from the plantation areas). Within the observation areas, there was a generally low generation of surface runoff. The pasture areas had a slightly higher runoff amount due to a greater slope.

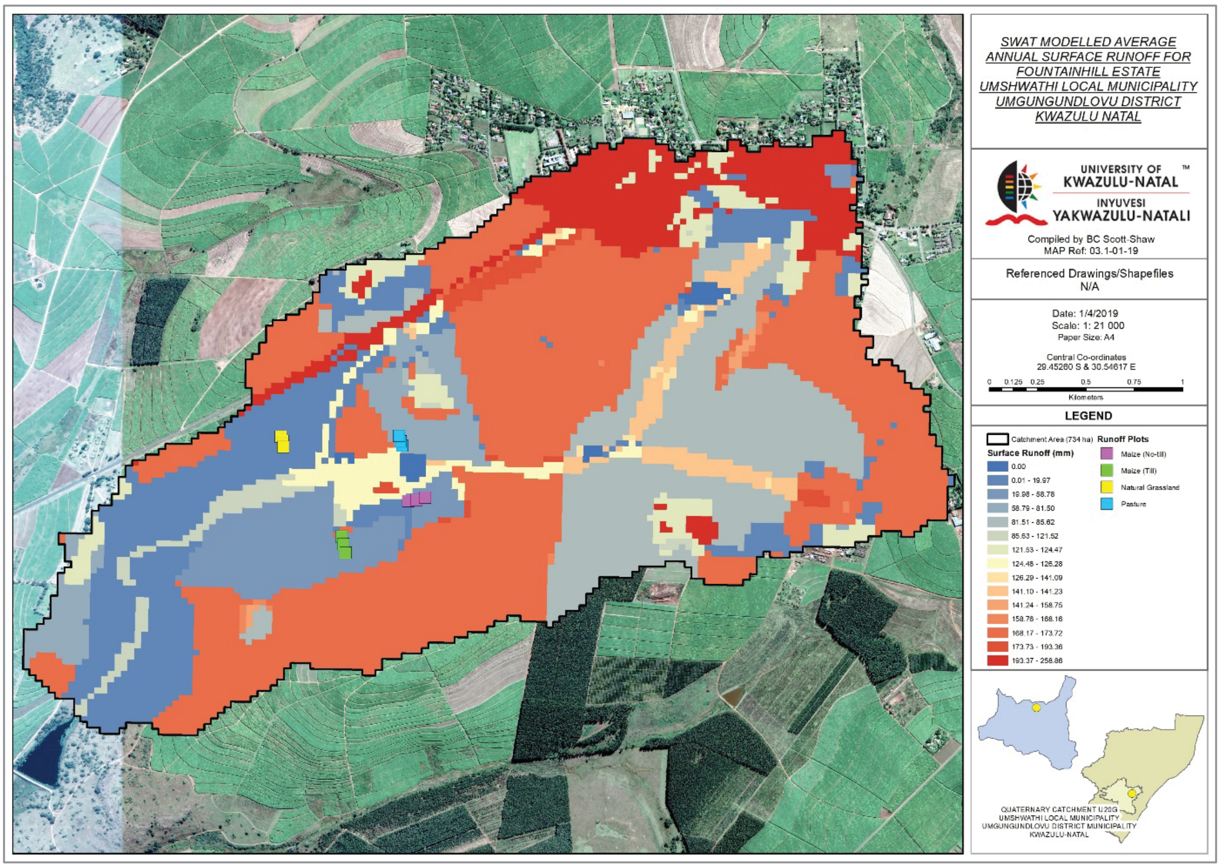

Figure 6.46 Spatial output of average annual surface runoff at Fountainhill Estate

The spatial sediment yield at FHE (Figure 6.47) shows that, in contrast to the surface runoff, the plantation areas exhibit more sediment loads than the maize. The area under pastures had a particularly low sediment yield, similar to the natural grassland areas. The two maize treatments had high amounts of sediment yield, with the till treatment exhibiting the greatest amount of sediment yield.

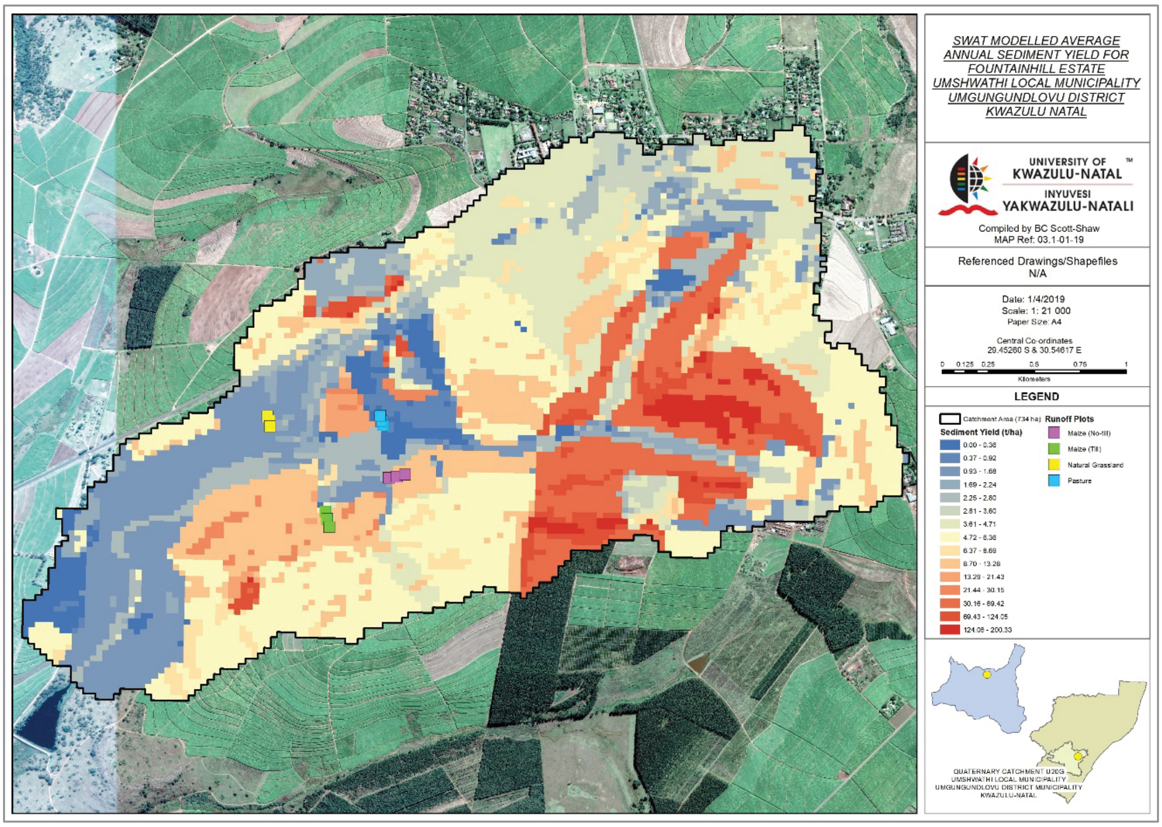

Figure 6.47 Spatial output of average annual sediment yield at Fountainhill Estate

The organic nitrogen (Figure 6.48) and organic phosphorus (Figure 6.49) at FHE is directly correlated to the sediment yield amount. The results show that up to 40 kg/ha could be lost during a one-year period. Up to 5.5 kg/ha of phosphorus could be lost over the same period. The results show that both maize treatments resulted in a high loss of organic nitrogen and organic phosphorus. This not only provides a quantification of the losses but also provides a spatial distribution of where problematic areas are and how the loads would change under fictitious management scenarios.

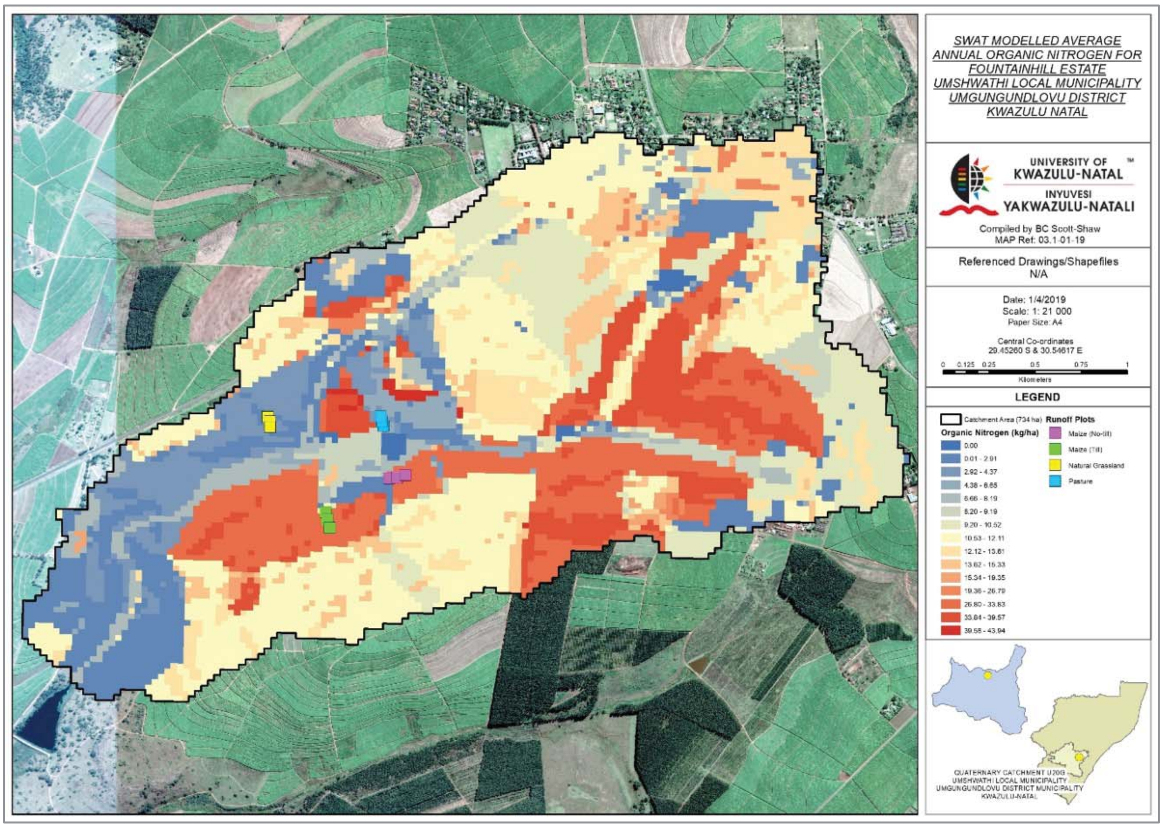

Figure 6.48 Spatial output of average annual organic nitrogen at Fountainhill Estate

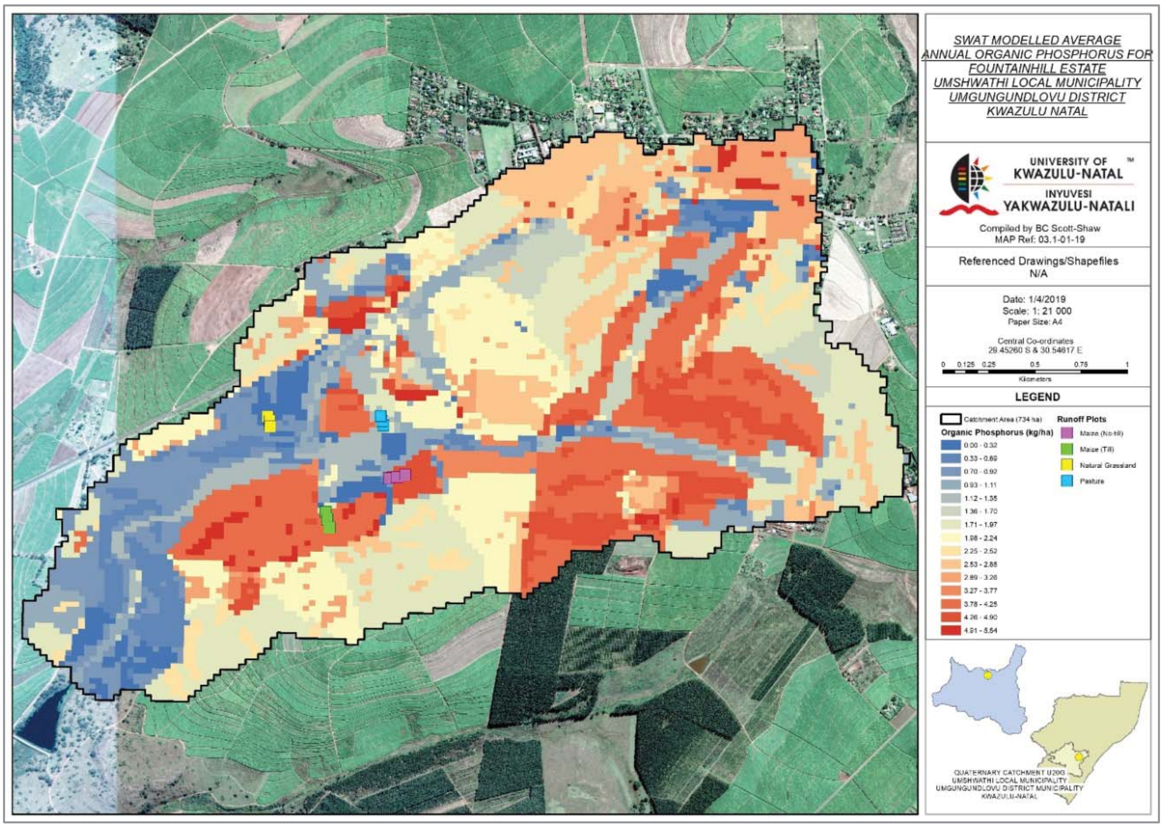

Figure 6.49 Spatial output of average annual organic phosphorus at Fountainhill Estate

6.5.5 Time Series Output

Output parameters such as streamflow only occurs in channelled areas. As such, these data cannot be viewed by HRUs. The sediment yield at the outlet of Two Streams is displayed in Figure 6.50. Between landuses, it is clear that impervious surfaces generate the greatest amount of sediments. Like it only true for gravel areas. *Eucalyptus* areas yielded higher amounts of sediment, followed by *Acacia* and the sugarcane which were similar.

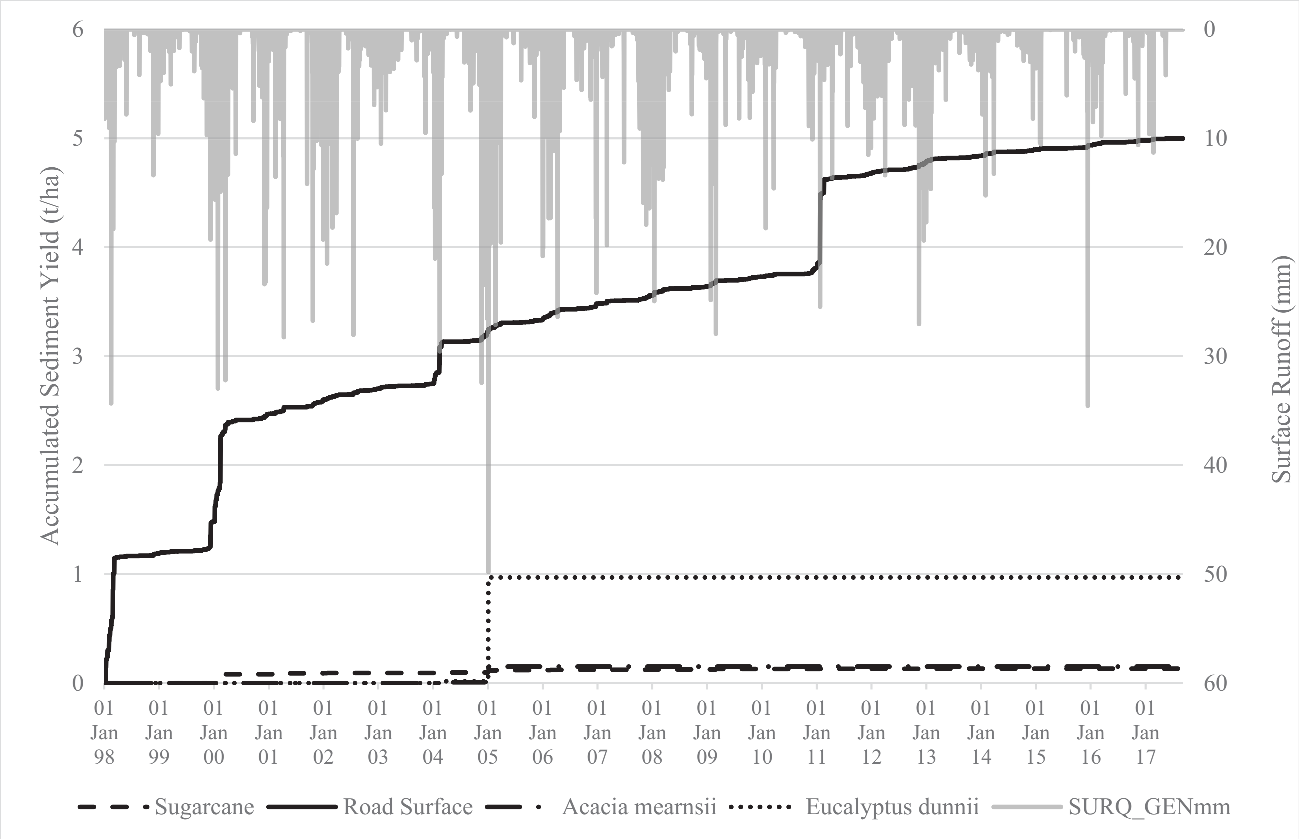

Figure 6.50 Simulated accumulated sediment yield within the monitored and modelled HRUs at Mistley Canema Estate

At FHE, tilled maize yielded the highest amount of sediments followed by maize with no tillage, then pasture and natural grasslands (Figure 6.51). As the FHE site is a recent and ongoing project, observations have not been processed for comparison. As such, the comparison and calibration at this site forms part of the future research component.

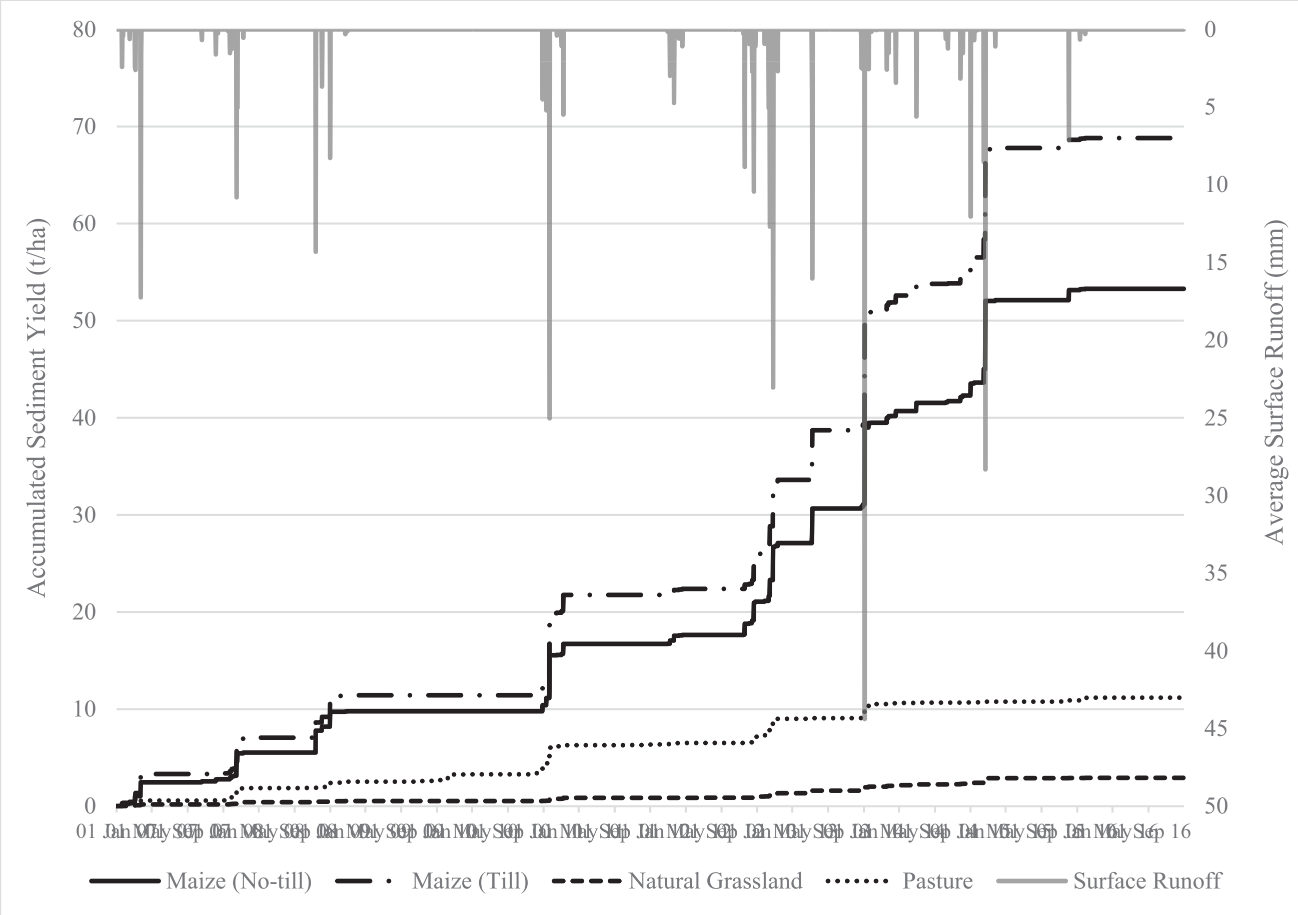

Figure 6.51 Simulated accumulated sediment yield within the monitored HRUs at Fountainhill Estate

7: CONCLUSION

Climate change is likely to affect soil erosion through its effects on rainfall intensity, soil erodibility, vegetative cover and patterns of land use (Nearing *et al.*, 2005). With the possible threat of climate change leading to high intensity rainfall, leading to increased soil erosion it is important to be proactive and protect the soil. There are large areas of KwaZulu-Natal with high potential risk of future erosion especially areas with hill sand steep terrain (Le Roux *et al.*, 2008). "Approximately 50% (61 million ha) of South Africa has a moderate to severe erosion potential (>12 t/ha/yr), whereas approximately 20% (26 million ha) of land is classified as having a moderate to severe actual erosion risk" (Le Roux *et al.*, 2008, pg 312). The results from this study show the value that vegetation cover, in particular mature trees, sugarcane and grassland, have on reducing soil erosion through canopy cover intercepting the rainfall and the litter on the ground reducing the volume of runoff. Rain splash is a key driver of detaching soil and transporting it. It is therefore imperative to be proactive and to counter the impending threats of climate change. The author's recommendation is to target areas that are under threat of severe erosion and increase vegetation cover the understory cover by using non-invasive species that can reduce the impact of rain splash and runoff. According to Le Roux *et al.* (2008) the risk of erosion is great with over 26 million ha of South African land at risk of high erosion due to the lack of maintenance of the current vegetation cover. The main issue to note is the increasing intensity of events leading to increased soil erosion.

Findings from this study concur with previous studies that the key driver of soil erosion and sediment yield is rainfall. With increased rainfall one experienced increased sediment yield. Rain was seasonal with the majority of the rain falling in the summer months. The results demonstrate the lack of significance of spatial scale. Spatially, the measurements from the variables at the different sized runoff plots were similar, demonstrating the similarity of impact that rain splash and runoff has in sediment and nutrient detachment and mobilisation. The plot sizes had similar; runoff (l/m2), sediment, nutrient concentrations and particulate organic carbon yields (g/l^{-1}), which demonstrated that the different processes experienced at the different scale were providing similar results. This depends on the difference in surface/catchment area. From small to large catchments there is a decline in sediment yield due to the increase in sediment yield due to the increase of barriers and places for deposition to occur (De Vente and Poesen, 2005). Temporally, high intensity rainfall events led to significant sediment and particulate organic carbon loss. Phosphate, nitrate and dissolved organic carbon concentrations were low for high rainfall events and high for low rainfall event this seems to infer the process of dilution which is the loss/extraction of nutrients caused by the higher volumes of runoff but, a larger rainfall event caused more nutrient loss as increased runoff caused more nutrients were detached and mobilised but diluted by the increased volume of water in the collection tank.

Compared to other land uses, commercial forestry that is not influenced by human impact (harvesting), has a low rate of soil erosion, due to the aerial, litter and grass cover protecting the soil from the impacts of rain splash and runoff. Agriculture and land that is overgrazed has much higher rates of erosion, emphasizing the importance that land use has on the rate of erosion and considerations must be given to this for future planners and managers. At Two Streams the nutrient measurements taken from the weir were all of an acceptable concentration, so the concentrations recorded at the plot scale were not influencing the concentrations at the weir, suggesting that the nutrients stayed in the system and did not reach the river.

The data from the study were used to model (ArcSWAT and MIKE SHE) the soil and nutrient loss and help inform the impacts that climate change will have on the catchment. The current land use has been effective in reducing the impact of rain splash, due to the effect that the tree canopy and litter has on intercepting the rainfall and subsequent runoff. As commercial forestry is a major contributor to South Africa's GDP, the environmental impacts have to be accepted. This study found that a commercial forest pre-harvest has acceptable soil erosion rates however when the harvesting process occurs, not only will heavy machinery increase soil erosion, the loss of canopy cover and litter will increase bare soil and subsequently soil erosion in the catchment until the new crop has reached the same mature stage as the present study. In that time the amount of soil erosion that would have occurred will be significant and post-harvest measurements need to be done to quantify the effects of harvesting.

It can be concluded that sugarcane and black wattle significantly reduce soil erosion rates due to the vegetation cover. Due to the canopy cover being greater than 60% and a high litter content, erosion from runoff was significantly reduced. Overall low sediment concentrations were recorded in the runoff samples from both land-uses. However, high nutrient concentrations such as P, N and DOC entrained in runoff was recorded which is a concern as this can pollute receiving waters downstream, decreasing water quality and worsening water scarcity. At present, nutrient concentrations at the catchment outlet remain low due to the presence of sinks and litter cover slowing runoff velocity infield. Spatial and temporal variations play an important role as rain splash was the dominant erosion process.
It is hypothesized that runoff and soil loss rates will increase due to harvesting. Harvesting will reduce the vegetation cover which protects the soil, vehicular traffic will increase bulk density of the soil, ploughing will disturb the soil and accelerate the mineralization process of nutrients and carbon, and burning of the sugarcane will negatively alter the soil physical properties. Therefore, more research will be needed into the effects of management operations affecting soil erosion and water quality on agricultural land-use pre- and post-harvest. Time was a limitation due to the nature of the study. Therefore, research with data collection over longer time periods encompassing more wet and dry seasons is needed, to accurately reflect erosion response to agriculture practices in South Africa.

7.1 Erosion and Soil Loss at Two Streams

Rainfall was, as expected, found to be seasonal, high during the summer months and low in the winter months, which impacted upon runoff, sediment and nutrient loss during the study. The canopy cover had an impact in intercepting the rainfall and reducing the amount of rainfall reaching the surface. The rain gauges set up in the catchment generally all had low variation between plots and had a constant interception offset against the AWS. The slope, soil characteristics and vegetation were measured and described in the catchment to aid in understanding soil erosion processes.

Rainfall is a key variable and high rainfall led to high runoff which led to high volumes of sediment and particulate organic carbon yield. There was minimal variation between the plots in terms of runoff, sediment yield and nutrient concentrations (Table 7.1). In terms of sediment loss and particulate organic carbon, there was similar amount of sediment and POC leaving the different plot sizes (gl^{-1}), but due to the 10 m^2 plots having greater cumulative runoff, there was a greater cumulative sediment yield/POC coming from the 34 ha catchment followed by the 10 m^2 plots and the 1 m^2 plots. The results highlighted the impact of an intense rainfall event such as the one experienced on the 18th of December 2015 can have in terms of significantly increasing the sediment and POC yield. The results from the 1 m^2 and 10 m^2 plots were similar, with only a small degree of variation in the measurements. Only the phosphate measurements had significant variation in plot sizes. This highlights that rain splash and runoff were similarly as effective in detaching and transporting sediment and nutrients. The results from this study shows that an increase in spatial scale does not have a significant impact on sediment yield (g/m^2) as the processes at the 1 m^2 plots (rain splash) are providing similar results as the 10 m^2 plot size (runoff). High rainfall led, in some instances, to low nutrient concentrations, with nutrients being diluted due to the increased runoff volume. Stream flow was measured during the study and was subject to rainfall, with intense rainfall leading to greater velocity stream flows.

On average, the highest runoff and P were recorded from the bottom slope position and the highest average sediment, NO^{3-}, DOC and POC measurements from middle slope position. The 10 m^2 plots on average recorded higher values in the measurements besides runoff (sediment, P, NO^{3-}, DOC and POC) compared to the 1 m^2 plots (Table 7.1). Rain-splash was the main contributor to sediment loss, with the 10 m^2 and 1 m^2 plots recording similar amounts. Dilution was present, with high rainfall events leading to low nutrient concentrations and low rainfall events leading to high nutrient concentrations. Besides phosphate, the nutrient and sediments concentrations recorded at the different plot sizes were similar.

Table 7.1 Summary table of the average measurements taken at the different spatial scales for the study duration

	Top		Mid		Bot	
	10 m^2	1 m^2	10 m^2	1 m^2	10 m^2	1 m^2
Runoff	9.780 l/m^2	8.870 l/m^2	6.480 l/m^2	7.490 l/m^2	10.460 l/m^2	13.490 l/m^2
Sediment	0.837 gl^{-1}	0.834 gl^{-1}	0.909 gl^{-1}	0.804 gl^{-1}	0.897 gl^{-1}	0.790 gl^{-1}
P	0.510 mgl^{-1}	0.250 mgl^{-1}	0.390 mgl^{-1}	0.140 mgl^{-1}	0.720 mgl^{-1}	0.330 mgl^{-1}
NO_3^-	4.870 mgl^{-1}	2.246 mgl^{-1}	4.470 mgl^{-1}	4.155 mgl^{-1}	3.760 mgl^{-1}	3.560 mgl^{-1}
DOC	19.250 mgl^{-1}	17.380 mgl^{-1}	23.390 mgl^{-1}	22.120 mgl^{-1}	16.920 mgl^{-1}	18.050 mgl^{-1}
POC	0.104 gl^{-1}	0.094 gl^{-1}	0.116 gl^{-1}	0.092 gl^{-1}	0.076 gl^{-1}	0.074 gl^{-1}

7.2 Rainfall Simulation at Okhombe

Land degradation is a major global issue threatening arable land, grazing, food security and water security. As described by Le Roux *et al* (2007) approximately 70% of South Africa has been affected by land degradation, emphasising the need to understand land degradation drivers and implement correct, appropriate mitigation and rehabilitation techniques. It is imperative that the land degradation found in communal areas is mitigated or rehabilitated as a large portion of the degraded land is communal areas which are necessary for sustained livelihoods. There needs to be a combination of scientific techniques and studies combined with local knowledge and resources available to community members to mitigate and rehabilitate land degradation in communal areas.

It is often difficult to explain scientific knowledge to community members; rainfall simulation provides a tool that can be used for both scientific data collection and a demonstrative tool of erosion processes to community members. The rainfall simulation was used in the Okhombe valley to study cattle path erosion and in a workshop held in the area for the community members. The community members quickly gained the concepts of slope gradient and basal cover from the rainfall demonstrations. The community could see the outcome of low basal cover and steep slope gradient against high basal cover and gentle slope gradient. The community then began to understand why mitigation measures worked and to identify sites where various mitigation techniques would work more effectively than other techniques. The understanding of the driving factors of land degradation provide the community with an applied understanding of the problem faced by the area and renewed energy and ideas to combat land degradation.

7.3 Soil Erosion and Sediment Yield Modelling

7.3.1 MIKE SHE

The hydrological characteristics of the Two Streams sub-catchment were modelled using MIKE SHE, following which the hydrological outputs were then used to deduce differences in hydrology with differences in land cover and a change in land cover. The model set-up showed the capability of the MIKE SHE model for use in the Two Streams sub-catchment and highlighted the key advantages and limitations or using the MIKE SHE model for the study site.

The MIKE SHE set-up for the study site, is to date the most exhaustive and holistic hydrological modelling approach taken for the Two Streams sub-catchment, supplying insight into the dominant hydrological processes in operation and the overall water use of the hydrological system. The capabilities of the MIKE

SHE software to incorporate detailed spatial and temporal datasets is a hugely beneficial attribute in small study sites, like the Two Streams sub-catchment, allowing for greater precision and heterogeneous expression of hydrological variables.

A key finding in the study was, due to the limited spatially explicit data inputs, specifically rainfall and geology, the vegetation classes considered did not have as big a difference in their water balance outputs as observed in literature (Calder, 1997; Vertessy, 2001; Raz-Yaseef *et al*., 2010, 2012; Warburton *et al*., 2012), bringing into question the need to use such a physically-based, data intensive model, where instead a more simplified, lumped conceptual model may be able to perform the same function (Merritt *et al.*, 2003; Devi *et al*., 2015). The study site, however is recognised for the extensive hydrological research conducted on-site and provides a great opportunity for future hydrological research, and thus using a more simplified model may be less time consuming and yield similar results, but addressing some of the key hydrological data limitations that would increase spatial heterogeneity would allow for a more accurate depiction of the Two Streams study site and be more beneficial in understanding site hydrologic physical processes.

A major challenge faced in this study was acquiring data from past research studies on-site. The Two Streams site has for many decades been run as a hydrological research catchment and should thus have a plethora of data available for hydrological modelling, however, access limitations to this data meant that the model could only be run for a ten-year period and calibration and validation were restricted to single datasets. In addition, data limitations for the period modelled for this study included: smaller temporal intervals of rainfall, the need for verification and greater consistency in capturing of the streamflow record, LAI and RD of the riparian and sugarcane vegetation classes, spatial mapping of geological layers, hydraulic conductivity of geological layers, specific yield and specific storage of geological layers, borehole data for water table mapping and macropore flow or preferential flow paths. Addressing these data limitations will improve spatial heterogeneity of the modelled system, improve model accuracy and allow for the effective re-evaluation of the benefits in relation to the work effort expended in setting up, running and calibrating the MIKE SHE model for the Two Streams sub-catchment.

Limitations with using MIKE SHE was that canopy litter interception was not captured by the model despite being a significant process in forestry ecosystems, where plant litter on the canopy floor can intercept as much as 6.6% in *Acacia mearnsii* plantations (Bulcock and Jewitt, 2012). Another limitation is that LAI is the only vegetation indices used to define vegetation canopy characteristics, as different tree species may have the same LAI but have very different canopy storage capacities depending on their specific leaf and canopy characteristics (Bulcock and Jewitt, 2012; Klamerus-Iwan, 2014). Other limitations included model uncertainty, long model run time and in-depth data requirements.

Key findings from the study included that the calibration and validation processes undertaken resulted in both the streamflow and ET records (observed and modelled) having good linear correlation to one another. Both plantation forests (*Acacia mearnsii* and *Eucalyptus dunnii*) had total ET rates that exceeded total rainfall and this was only the case during the winter months when deeper roots allowed for greater access to deeper soil water reserves and were not only dependent on rainfall for water input. The black wattle class was a greater water user in comparison to the sugarcane and riparian vegetation classes (based on ET rates and subsurface storage losses), whilst *E. dunnii* was a greater water user in relation to black wattle in terms of ET and subsurface storage losses. The ET rates between the vegetation classes of the current scenario where statistically different whilst those of the future scenario were not. I_{UZ} rates were high for all vegetation classes and showed no statistical differences between vegetation classes or between soil types. All annual I_{UZ} records showed strong linear correlations to rainfall. The soil types for the site have high soil water retentions and high hydraulic conductivities allowing for fast water movement through the soil increasing the rates of I_{UZ}. GR did not show distinct monthly or seasonal differences with no statistical differences between the winter and summer seasons for the black wattle, sugarcane and riparian vegetation classes. GR also did not correlate well to rainfall. The total rates of CIS, depth of OL and streamflow were all very low for every vegetation class considered.

Research going forward should concentrate on addressing the data limitations discussed above, as this would greatly improve the hydrological modelling of the Two Streams sub-catchment. Given that South Africa is a water scarce country, stresses the importance of reducing water use and preventing degradation of water resources, as such research should focus on improving water use efficiency of the Two Streams study site, through the implementation of a more holistic consideration of site hydrology and focus on improving management strategies, specifically within the riparian zone (i.e. vegetation clearance and monitoring).

As part of achieving a more holistic model for the site, studies should also incorporate soil erosion, given that studies on Two Streams are now starting to consider soil erosion through sediment plot studies. Soil erosion is influenced largely by and dependent on hydrological processes (Le Roux, 2012), thus having a well-developed physically based knowledge of hydrology on-site can greatly aid in understanding soil erosion processes. Studies on MIKE SHE has linked to external sediment erosion software to model sediment erosion. For example, studies have used SHESED, which is a physically based, spatially distributed erosion and sediment yield component of MIKES SHE (Wicks and Bathurst, 1996). The incorporation of a soil erosion extension within the MIKE SHE model was out of the scope of this dissertation as it would require significant programming knowledge to incorporate this extension, as this is not a readily available software package from DHI. However, a soil erosion extension such as SHESED or other extensions – RUSLE has also been incorporated into MIKE SHE in a previous study (DHI, unknown) – would be a good focus for future research on the Two Streams catchment.

7.3.2 SWAT

The SWAT modelling exercise demonstrated that the ArcSWAT model can be used effectively in South Africa, particularly eroded areas of KwaZulu-Natal. The results were compared to previous model simulations undertaken by other models where it could be seen that the SWAT model simulated flows well and with greater complexity. In addition, the management component in SWAT is very detailed and relevant to the Two Streams site. Although much time was spent on correcting input errors and translating data, if this model is used extensively it would lead to much more accurate and internationally recognized modelling going forward. A limitation is that there is no South African SWAT database for soils, land use and climate. However, the data are available and would be needed to be populated into a SWAT friendly format. More observations are needed to validate the sub-routines of SWAT such as sediment, nutrient and physiological properties of vegetation.

The spatial sediment yield at Two Streams shows that, in contrast to the surface runoff, the plantation areas exhibit more runoff than the sugarcane. However, these differences are slight. The plot measurements showed that sediment loads were greater at both plot scales (1 m^2 and 10 m^2) in the plantation areas during the dry season events. During the wet season, these two landuse types yielded very similar results. The spatial sediment yield at FHE shows that, in contrast to the surface runoff, the plantation areas exhibit more sediment loads than the maize. The area under pastures had a particularly low sediment yield, similar to the natural grassland areas. The two maize treatments had high amounts of sediment yield, with the till treatment exhibiting the greatest amount of sediment yield.

A similar and relevant study on the Makhabela catchment (Görgens *et al*., 2012) established an improved field-scale model for simulation of agricultural NPS pollution loadings for phosphorus, nitrogen, selected pesticides and sediments, as well as for simulating the beneficial impacts on nearby receiving waters of on-farm NPS pollution control measures. Through this research, it was recommended that continued research and monitoring work is needed to collect nutrient export data from agricultural systems, leading to improved model calibration and refinement of the algorithms used in the various models (Görgens *et al*., 2012). The use of land type and hydropedological surveys to estimate model parameters for water, sediment and nutrient simulation are needed for future research. Additionally, the evaluation of sensitivity of simulated sediment and nutrient loading to disaggregation versus lumping of land segments (Görgens *et al*., 2012). The approach undertaken in this research addresses some of the future requirements of this research, while providing a platform to address more detailed research questions.

It is clear from the results that the SWAT model is a suitable hydrological model for examining the impacts of different land-uses in catchments in South Africa and can provide high resolution temporal and spatial output data. The SWAT-CUP calibration interface provides a useful tool to determine the sensitivity of input parameters, improve the simulation efficiency and provide an indication of the model uncertainty.

7.4 Recommendations

Soil erosion is one of the greatest environmental problems facing South Africa (Meadows, 2003). Erosion is considered site specific and is dependent on soil type, management factors and rainfall regimes. Seventy percent of South Africa is affected by different intensities of soil erosion (Le Roux, 2011). To accurately predict areas at high risk of erosion, erosion models should be developed based on site specific conditions and soil types in South Africa. Despite the limitations of the study, the data can be used to inform, update and develop erosion models in a South African context which will help guide mitigation management measures. Furthermore, farmers can use the available information to inform mitigation measures implemented in-field to reduce on and off-site consequences of runoff and soil erosion. Strip cropping, green harvesting, mulching, minimum tillage and buffer crops are examples of mitigation measures farmers can implement in this specific context. South Africa is a less economically developed country, which relates to economy taking precedence over the environment. It is important that the environment be considered when developing policy and best management practice as humans derive various services from ecosystems such as fresh water for drinking and fertile top soil for growing crops. Further research and data collection are needed in a South African context to develop robust and accurate erosion models to improve management techniques and prediction of erosion in catchments with commercial crop plantations.

At the completion of any research project there are, one hopes, many unanswered new research questions that have arisen as a consequence of a particular project. This project is certainly no exception as new field-, laboratory- and model-based questions / ideas arose as the work was carried out. The use of plots to collect sediment for analysis and, although we made a few minor refinements in the field, they are well versed and recognised, and allow comparison across projects. At the initiation of the project the primary concern was identifying suitable sites for measurements. We feel there could be a stronger role for historical aerial photography and the use of remote sensing techniques. One of the students (Nosipho Machaya, MSc, Environmental Science) developed a GIS mapping approach to identifying potential erosion sites which were then groundtruthed and Bangani Dube (MSc, Soil Science) incorporating (with Lyndon Riddle, PhD student the use of drone technology. This resulted in a methodological paper which Mr Riddle intends to develop. We accept the drone technology is still very much a new innovation however, on a large scale, we can certainly perceive a mapping function for the technology. A similar argument can be made for the rainfall simulation experiment – for demonstration purposes and to start a discussion / workshop / community engagement / raining exercise it worked extremely well. However, as a field-based approach, although it has been cited and extensively used, we felt that under South African conditions and if for no other reason the amount of fresh water that was required to adhere correctly to the recognised international standards of methodology to allow for comparison, it was too environmentally costly. By way of example we used the simulator to demonstrate, to a community group, surface runoff on grassed versus cattle paths. We had to 'import' clean drinking water from a local conservation area to run the simulator and it was commented that the community members would rather than took to water home than we 'threw it' on the ground!

7.5 Future Research and Way Forward

One of the main motivating points for working at the selected sites was the ability to use existing research infrastructure and work at sites that had long-term data sets – this is crucial in any modelling project. It is imperative that these sites continue to be monitored. We lack many long-term research sites in South Africa and with the ever increasing difficulty of sourcing funds it will be increasingly difficult to maintain

long-term sites. Few funders are prepared to fund for an extended time period and it has to be the role of the South African Observation Network (SAEON) or Universities to commit to maintaining certain sites, after funds for the initial project have ceased. This is a difficult situation, Universities do not have the funding, external funders seek short-term projects and we have a transient population of post-graduate students. However, we do need these long-term sites and, included in this discussion, must the continuation and maintenance of long-term climatic records and, where possible, instillation of new long-term automatic weather-stations. Furthermore, these data must be access able to all researchers – surely there is way to manage this process!
Throughout this project this point has been raised and we have been aware of the need to ensure that whatever approach we adopt, can continue after the funding phrase and, if for no other reason, to monitor for a full life-cycle of a plantation to be able to monitor from harvesting, post-harvest treatment, re-planting, growth and harvest.

Through working with MONDI and the Fountain Hill Trust, we have developed a relationship that will continue beyond the life of this existing project, we will continue to monitor the sites and the idea is to use the site as field-based laboratories for generations of students. As educators this is an important outcome for us and will continue the good work already carried out in multiple WRC reports in the region and maintain the existing strong relationships with local industry and farming communities.

With regards to the modelling aspect, two areas of development arise for us. The first is to obtain the necessary environmental parameters to allow ArcSWAT to be more user-friendly. The model is a good one and has been used successfully in this project however it has taken more time than anticipated as many of the default variables/values/measurements are not set of South Africa conditions. One of the reasons for choosing this model is the software allows one to input site specific environmental information. What we require is databases that have SA scenarios and we can then choose the necessary values from a dropdown menu that has been set-up for SA conditions. This is a long-term objecting and although it is doubtful it would be considered as a single research project there should be some co-ordination between projects and site-specific environmental data inputted into a central file (custodianship unknown) to develop these data files. A similar scenario exists for MIKE SHE, however this is more complex as it requires software development as plug-ins to the existing model framework.

Encompassing all these ideas we must sound a note of caution. Yes, we make a call from research and training sites and the necessity that they continue, however the research must be relevant and necessary (not always easy to define this we appreciate!) training sites, research and must not become a researchers 'play-ground' and attempt new technologies merely for the sake of it – thus, we need to ensure the research questions are relevant to the needs of the disciplines? The role and integrity of the reviewing process must be maintained as must the role of the reference committees which, we have experienced in this and other WRC funded projects, is dwindling due to competing demands on expert's time.

8: REFERENCES

Abagale, K.F, Coffie, J., Nyadzi, E., 2012. Quantification and nutrient levels of eroded soil of farmlands in northern Ghana. *International Journal of Forest, Soil and Erosion*, 2(4). 192-194.

Akbarimehr, M., Naghdi, R., 2012. Reducing erosion from forest roads and skid trails by management practices. *Journal of Forest Science*, 58(4), 165–169.

Aksoy, H., Kavass, L., 2005. A review of hillslope and watershed scale erosion and sediment transport models, *Catena*, 64, 247–271.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. *Crop evapotranspiration. guidelines for computing crop water requirements, Irrigation and Drainage Paper No. 56,* Food and Agriculture Organization of the United Nations, Italy.

Arheimer, B., Olsson, J., 2003. *Integration and coupling of hydrological models with water quality models*. Applications in Europe, Report of the Swedish Meteorological and Hydrological Institute, Norrkoping Sweden.

Arnold, J.G., Fohrer, N., 2005. SWAT2000. current capabilities and research opportunities in applied watershed modelling. *Hydrological Processes*, 19(3), 563-572.

Bagarello, V., Ferro, V., 2004. Plot scale measurement of soil erosion at the experimental area of Sparacia (southern Italy). *Hydrological Processes*, 18(1), 141-157.

Bartley, R., Roth, C.H., Ludwig, J., McJannet, D., Liedloff, A., Corfield, J., Hawdon, A., Abbott, B., 2006. Runoff and erosion from Australia's tropical semi-arid rangelands. Influence of ground cover for differing space and time scales. *Hydrological Processes*, 20(15), 3317-3333

Bathurst, J.C., 1986. Physically-based distributed modeling of an upland catchment using the Systeme Hydrologique Europeen, *Journal of Hydrology*, 79, 79-102.

Bautista, S., Mayor, A.G., Bourakhouadar, J., Bellot, J., 2007. Plant spatial pattern predicts hillslope runoff and erosion in a semiarid Mediterranean landscape. *Ecosystems*, 10(6), 987-998.

Bechmann, M.E., Berge, D., Eggestad, H.O., Vandsemb, S.M., 2005. Phosphorus transfer from agricultural areas and its impact on the eutrophication of lakes - two long-term integrated studies from Norway. *Journal of Hydrology*, 304(1), 238-250

Bergkamp, G., 1998. A hierarchical view of the interactions of runoff and infiltration with vegetation and microtopography in semiarid shrublands. *Catena*, 3(4), 201-220.

Bergström, S., 1992. THE HBV model- its structure and applications, *SMHI Reports Hydrology*, 1-35.

Beven, K., 1989. Changing ideas in hydrology—the case of physically-based models. *Journal of Hydrology*, 105(1-2), 157-172.

Beven, K.., Lamb, R., Quinn, P., Ronanwvie, R., Freer, J., 1995. TOPMODEL, in V.P. Singh (ed.), *Computer models of hydrology*, Water Resources Publications, Highlands Ranch, CO, 627.

Beven, K., 1997. TOPMODEL. A critique, *Hydrological Processes*, 11, 1069-1085.

Binkley, D., Brown, T.C., 1993. Forest practices as nonpoint sources of pollution in North America. *America Water Resources Bulletin*, 29(5), 729-740.

Bissonnais, Y.L., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. *European Journal of Soil Science*, 47(4), 425-437.

Blackburn, F., 1984. *Sugarcane (Tropical agriculture series).* New York Edn Longman House, Burnt Mill, Harlow, Essex, UK.

Boardman, J., 2006. Soil erosion science. Reflections on the limitations of current approaches. *Catena*, 68, (2), 73-86.

Boix-Fayos, C., Martínez-Mena, M., Arnau-Rosalén, E., Calvo-Cases, A., Castillo, V., Albaladejo, J., 2006. Measuring soil erosion by field plots. understanding the sources of variation. *Earth-Science Reviews*, 78(3), 267-285.

Brinkman, R., Sombroek, W.G., 1996. The effects of global change on soil conditions in relation to plant growth and food production*. Global Climate Change and Agricultural Production*, 49-63.

Bulcock, H.H., Jewitt, G.P.W., 2010. Spatial mapping of leaf area index using hyperspectral remote sensing for hydrological applications with a particular focus on interception, *Hydrology and Earth System Sciences*, 14, 383-392.

Bulcock, H.H., Jewitt, G.P.W., 2012. Field data collection and analysis of canopy and litter interception in commercial forest plantations in the KwaZulu-Natal Midlands, South Africa, *Hydrology and Earth Systems Sciences*, 16, 3717-3728.

Butts, M. B., Overgaard, J., Viaene, P., Dubicki, A., Strońska, K., Szalinska, W., 2005. *Flexible process-based hydrological modelling framework for flood forecasting–MIKE SHE*. In Proceedings of the International Conference Innovation, Advances and Implementation of Flood Forecasting Technology, Tromsø, Norway (pp. 17-19).

Cabral, J.P.S., 2010. Water Microbiology, Bacterial Pathogens and Water. International Journal of Environmental Research and Public Health, 7 (10), 3657-3703.

Calder, I.R., 1990. *Evaporation in the uplands*, John Wiley and Sons Ltd., Chichester, UK.

Cammeraat, E.L.H., 2004. Scale dependent thresholds in hydrological and erosion response of a semi-arid catchment in southeast Spain. *Agriculture, Ecosystems & Environment*, 104, 317-332.

Campbell, I.C., Doeg, T.J., 1989. Impact of timber harvesting and production on streams. a review. *Marine and Freshwater Research*, 40(5), 519-539.

Casenave, A., Valentin, C., 1992. A runoff capability classification system based on surface features criteria in semi-arid areas of West Africa. *Journal of Hydrology,* 130, 231-249.

Cerdan, O., Govers, G., Le Bissonnais, Y., Van Oost, K., Poesen, J., Saby, N., Gobin, A., Vacca, A., Quinton, J., Auerswald, K., Klik, A., 2010. Rates and spatial variations of soil erosion in Europe. a study based on erosion plot data. *Geomorphology*, 122*,* (1), 167-177.

Chaplot, V.A., Le Bissonnais, Y., 2003. Runoff features for interrill erosion at different rainfall intensities, slope lengths, and gradients in an agricultural loessial hillslope. *Soil Science Society of America Journal*, 67(3), 844-851.

Christiaens, K., Feyen, J., 2001. Analysis of uncertainties associated with different with different methods to determine soil hydraulic properties and their propogation in the distributed hydrological MIKE SHE model, *Journal of Hydrology*, 246, 63-81.

Clulow, A.D., 2007. *The long-term measurement of total evaporation over Acacia mearnsii using large aperture scintillometry*. Unpublished Thesis (MSc), University of KwaZulu-Natal, Pietermaritzburg, RSA.

Clulow, A.D., Everson, C.S., Gush, M.B., 2011. The long-term impact of *Acacia mearnsii* trees on evaporation, streamflow and groundwater resources, WRC Report No. TT 505/11, University of KwaZulu-Natal, Pietermaritzburg.

Collins, A.L., Anthony, S.G., 2008. Assessing the likelihood of catchments across England and Wales meeting 'good ecological status' due to sediment contributions from agricultural sources. *Environmental Science and Policy*, 11, 163-170.

da Silva, V.P.R., Silva, M.T., Singh, V.P., de Souza, E.P., Braga, C.C., de Holanda, R.M., Almeida, R.S.R., de Sousa, F.A.S., Braga, A.C.R., 2018. Simulation of stream flow and hydrological response to land-cover changes in a tropical river basin, *Catena*, 162, 166-176.

De Vente, J., Poesen, J., 2005. Predicting soil erosion and sediment yield at the basin scale. scale issues and semi-quantitative models. *Earth-Science Reviews*, 71, (1), 95-125.

DeFries, R., Eshleman, K.N., 2004. Land-use change and hydrologic processes. a major focus for the future, *Hydrological processes*, 18, 2183–2186.

Demaria, E.M., Nijssen, B., Wagner, T., 2007. Monte Carlo sensitivity analysis of land surface parameters using the Variable Infiltration Capacity model, *Journal of Geophysical Research*, 112, 1-15.

Demlie, M., Titus, R., 2015. Hydrogeological and hydrogeochemical characteristics of the Natal Group Sandstone, South Africa, *South African Journal of Geology*, 118 (1), 33-44.

Department of Agriculture, (DA) 2008. Annual report 2007-2008. Republic of South Africa, Pretoria.

Department of Agriculture, Fisheries and Forestry, (DAFF) 2015. *State of the forests report 2010-2012*. Republic of South Africa, Pretoria.

Department of Environmental Affairs, (DEA) 2012. *South Africa Environmental Outlook*, Republic of South Africa, Pretoria.

Department of Water Affairs and Forestry, (DWAF) 2004*. National Water Resource Strategy, First Edition*, Republic of South Africa, Pretoria.

Devi, G.K., Ganasri, B.P., Dwarakish, G.S., 2015. A review on hydrological models, *Aquatic Procedia*, 4, 1001-1007.

De Wit, M.P., Crookes, D.J., van Wilgen, B.W., 2001. Conflicts of interest in environmental management: estimating the costs and benefits of a tree invasion. *Biological Invasions*, 3, 167-178.

DHI software, 2012. *MIKE SHE user manual. Volume 1. User guide*, MIKE by DHI Edition 2012.

Dixon, R.K., Brown, S., Houghton, R.E.A., Solomon, A., Trexler, M., Wisniewski, J., 1994. Carbon pools and flux of global forest ecosystems. *Science*, 263, 185-189.

Doody, D.G., Foy, R. H., Barry, C. D., 2012. Accounting for the role of uncertainty in declining water quality in an extensively farmed grassland catchment. *Environmental Science & Policy*, 24, 15-23.

Dye, P.J., Jarmain, C., le Maitre, D., Everson, C.S., Gush, M., Clulow, A., 2008. Modeliling vegetation water use for general application in different categories of vegetation, Water Research Commission, Pretoria, Report No. 1319/1/08.

Easton, Z.M., Fuka, D.R., White, E.D., Collick, A.S., Biruk Ashagre, B., McCartney, M., Awulachew, S.B., Ahmed, A.A., Steenhuis, T.S., 2010. A multi basin SWAT model analysis of runoff and sedimentation in the Blue Nile, Ethiopia, *Hydrology and Earth System Sciences*, 14, 1827-1841.

Ekholm P., Lehtoranta, J., 2012. Does control of soil erosion inhibit aquatic eutrophication? *Journal of Environmental Management*, 93, 140-146.

Elsenbeer, H., 2001. Hydrologic flowpaths in tropical rainforest soilscapes—a review. *Hydrological Processes*, 15(10), 1751-1759.

Elvidge, C, D., Chen, Z., 1995. Comparison of broad-band and narrow-band red and near-infrared vegetation indices, *Remote Sensing of Environment*, 54(1), 38-48.

Everson, C.S., Gush, M., Moodley, M., Jarmain, C., Govender, M., Dye, P., 2006. Can effective management of the riparian zone vegetation significantly reduce the cost of catchment management and enable greater productivity of land resources, WRC Report No. K5/1284, CSIR, Pietermaritzburg.

Everson, T. M., Everson, C. S., Zuma, K. D., 2007. *Community based research on the influence of rehabilitation techniques on the management of degraded catchments.* Report to the Water Research Commission. Report Number 1316/1/07.

Everson, C.S., Clulow, A.D., Becker, M., Watson, A., Ngubo, C., Bulcock, H., Mengistu, M., Lorentz, S., Demlie, M., 2014. The long term impact of *Acacia mearnsii* trees on evaporation, streamflow, low flows and ground water resources. Phase II. Understanding the controlling environmental variables and soil water processes over a full crop rotation, WRC Report No. 2022/1/13, University of KwaZulu-Natal, Pietermaritzburg.

Ezemvelo KZN Wildlife. 2011. KwaZulu-Natal Land Cover 2008 V1.1. Unpublished GIS Coverage [Clp_KZN_2008_LC_V1_1_grid_w31.zip], Biodiversity Conservation Planning Division, Ezemvelo KZN Wildlife, P. O. Box 13053, Cascades, Pietermaritzburg, 3202.

Fey, M., 2010. *Soils of South Africa*. Cambridge University Press, Cambridge.

Fournier, A.J. (ed.), 2011. *Soil erosion. Causes, processes, and effects*. Nova Science Publishers, Hauppauge, New York.

Fryirs, K., 2013. (Dis) Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. *Earth Surface Processes and Landforms*, 38(1), 30-46.

Gao, H., Tang, Q., Shi, X., Zhu, C., Bohn, T., Su, F., Sheffield, J., Pan, M., Lettenmaier, D., Wood, E.F., 2009. Water budget record from Variable Infiltration Capacity (VIC) model, in E.F., Wood, M., Pan, J. Sheffield, R., Vinukolu, C.R. Ferguson, H. Gao, Q., Tang, X., Shi, C., Zhu, T., Bohn, F., Su, D.P., Lettenmaier, A.K., Sahoo, G.J.M., De Lannoy, P.R., Houser, R.T., Pinker, Y., Ma, C., Li, and C.D., Kummerow (eds.), *Algorithm Theoretical Basis Document for Terrestrial Water Cycle Data Records*, 120-173.

García-Ruiz, J, M., Lasanta, T., Ortigosa, L., Ruiz-Flaño, P., Marti, C., González, C., 1995. Sediment Yield under Different Land Uses in the Spanish Pyrenees. *Mountain Research and Development*, 15, (3), 229-240.

Gassman, P.W., Williams, J.R., Wang, X., Saleh, A., Osei, E., 2009. The agricultural policy environmental extender (APEX) model. An emerging tool for landscape and watershed environmental analyses, *CARD Technical Reports*, 41.

Gillham, J., 2016. Assessing the impact of erosion and sediment yield from different land uses in farming and forestry systems and their effect on water resources in selected catchments of South Africa. Unpublished MSc (Environmental Science) thesis, University of KwaZulu-Natal.

Godsmark, R., 2014. The South African forestry and forest products industry. PowerPoint presentation by Forestry South Africa to FAO workshop on forest product statistics

Görgens, A.H.M., Lorentz, S.A., van der Laan, M., Jovanovic, N.Z., Matthews, N., Annandale, J., Grové, B., le Roux, J.J., 2012. Modelling Agricultural Non-Point Source Pollution and Economic-Environmental Trade-Offs of Pollution Control Measures: A Project Overview. WRC Report No. TT 516/12.

Govender, M., Everson, C.S., 2005. Modelling streamflow from two small South African experimental catchments using the SWAT model, *Hydrological Processes*, 19, 683–692.

Govers, G., Poesen, J., 1988. Assessment of the interrill and rill contributions to total soil loss from an upland field plot. *Geomorphology*, 1(4), 343-354.

Graham, D.N., Butts, M.B., 2005. Flexible, integrated watershed modelling with MIKE SHE, in V.P. Singh and D.K. Frevert (eds.), *Watershed Models*, CRC Press, Florida, USA, 245-272.

Griffiths, P., Hereford, R., Webb, R., 2006. Sediment yield and runoff frequency of small drainage basins in the Mojave Desert, California and Nevada [online]. *USGS*, http://pubs.usgs.gov/fs/2006/3007/. (Accessed 25 January 2016).

Gush, M.B., Scott, D.F., Jewitt, G.P.W., Schulze, R.E., Lumsden, T.G., Hallowes, L.A., Görgens, A.H.M., 2002. Estimation of streamflow reductions resulting from commercial afforestation in South Africa, Water Research Commission Report No. TT173/02.

Harlow, J., 2018. Assessing spatial and temporal patterns of groundwater recharge on Catalina Island, California, from soil water balance modelling, Masters of Science in Geology, California State University, Long Beach.

Hartanto, H., Prabhu, R., Widayat, A.S., Asdak, C., 2003. Factors affecting runoff and soil erosion. plot-level soil loss monitoring for assessing sustainability of forest management. *Forest Ecology and Management*, 180, (1), 361-374.

Hasenmueller, E.A., Criss, R.E., 2013. Water balance estimates of evapotranspiration rates in areas with varying land use, in S.G. Alexandris (ed.), *Evapotranspiration - An overview*, Intech, 1-21

Hendriks, M.R., 2010. *Introduction to physical hydrology*, Oxford University Press, Oxford, UK.

Hernandez, T, Nachabe, M, Ross, M., Obeysekera, J., 2003. Modelling runoff from variable source areas in humid, shallow water table environments. *Journal of American Water Resources Association*, 39, 75-85.

Hewlett, J.D., Hibbert, A.R., 1967. *Factors affecting the response of small catchment to precipitation in humid areas. In Forest Hydrology*, Supper WE (ed). Pergamon. New York, 275–290.

Hoffman, T., Ashwell, D.N., 2001. *Nature divided. Land degradation in South Africa*. University of Cape Town Press. Cape Town

Holmes, P.M., Esler, K.J., Richardson, D.M., Witkowski, E.T.F., 2008. Guidelines for improved management of riparian zones invaded by alien plants in South Africa. *South African Journal of Botany*, 74(3), 538-552.

Hörmann, K., Floater, M.S., 2006. Mean value coordinates for arbitrary planar polygons, *ACM Transactions on Graphics*, 25(4), 1424-1441.

Horton, R.E., 1933. The role of infiltration in the hydrologic cycle. *Transactions of American Geophysical Union*, 14, 446–460.

Hughes, J.D., Liu, J., 2008. MIKE SHE. Software for integrated surface water/ground water modeling, *Groundwater*, 46 (6), 797-802.

Ighodaro, I.D, Lategan, F.S., Yusuf, S.F.G, 2013. The impact of soil erosion on agricultural potential and performance of Sheshegu community farmers in the Eastern Cape of South Africa. *Journal of Agricultural Science*, 5(5), 140-147.

Im, S., Kim, H., Kim, C., Jang, C., 2009. Assessing the impacts of land use changes on watershed hydrology using MIKE SHE, *Environmental Geology*, 57, 231-239.

Isik, S., Kalin, L., Schoonover, J.E., Srivastava, P., Lockaby, B.G., 2013. Modeling effects of changing land use/cover on daily streamflow. an Artificial Neural Network and curve number based hybrid approach, *Journal of Hydrology*, 485, 103–112.

Jonckheere, I., Fleck, S., Nackaerts, K., Muys, B., Coppin, P., Weiss, M., Baret, F., 2004. Review of methods for *in situ* leaf area index determination: Part I. Theories, sensors and hemispherical photography. *Agricultural and Forest Meteorology*, 121 (1-2), 19-35.

Jyrkama, M.I., Sykes, J.F., 2007. The impact of climate change on spatially varying groundwater recharge in the Grand River watershed (Ontario), Journal of Hydrology, 338, 237– 250.

Klamerus-Iwan, A., 2014. Different views on tree interception process and its determinants, *Forest Research Papers,* 75 (3), 291-300.

Kose, C., 1998. *Determining of P Factor for Contour Tillage Using Simulator under Field Condition in Aegean Region*. Unpublished Ph.D. Thesis, Department of Soil, Ege University, Izmir.

Kuenene, B., 2013. Hillslope hydropedology of the Two Streams catchment in KwaZulu-Natal, Doctor of Philosophy (PhD) dissertation, University of the Free State, Bloemfontein.

Kuenene, B. T., Van Huyssteen, C. W., Le Roux, P. A. L., Hensley, M., Everson, C. S., 2011. Facilitating interpretation of the Cathedral Peak VI catchment hydrograph using soil drainage curves. *South African Journal of Geology*, 114(3-4), 525-534.

Laker, M.C., 2004. Advances in soil erosion, soil conservation, land suitability evaluation and land use planning research in South Africa, 1978-2003. *South African Journal of Plant and Soil*, 21(5), 345-368.

Lal, R., 2005. Forest soils and carbon sequestration. *Forest Ecology and Management*, 220, 242–258.

Lane, L., Hernandez, M., Nichols, M., 1997. Processes controlling sediment yield from watersheds as a function of spatial scale. *Environmental Modelling and Software*, 12, (4), 355-369.

Laznik, M., Stålnacke, P., Grimvall, A., Wittgren, H.B., 1999. Riverine input of nutrients to the Gulf of Riga—temporal and spatial variation. *Journal of Marine Systems*, 23(1), 11-25.

Le, T.P.Q., Ho, C.T., Duong, T.T., Rochelle-Newell, E., Dang, D.K., Hoang, T.S., 2014. Nutrient budgets (N and P) for the Nui Coc reservoir catchment (North Vietnam). *Agricultural Water Management,* 142, 152-161.

Le Bissonnais, Y., Singer, M.J., 1993. Seal formation and interrill erosion from seventeen California Soils. *Soil Science Society of American Journal*, 57, 224-229.

Le Bissonnais, Y., Fox, D., Bresson, L.M., 1998. Incorporating crusting processes in erosion models. In *Modelling soil erosion by water*, Boardman J, Favis-Motlock D, (eds). NATO ASI series, Vol. 155, Springer, Berlin, 237-246.

Le Maitre, D.C., van Wilgen, B.W., Gelderblom, C.M., Bailey, C., Chapman, R.A., Nel, J.A., 2002. Invasive alien trees and water resources in South Africa. Case studies of the costs and benefits of management, *Forest Ecology and Management*, 160, 143-159.

Le Roux, J.J., Newby T.S., Sumner, P.D., 2007. Monitoring soil erosion in South Africa at a regional scale. review and recommendations, *South African Journal of Science*, 103, 329-335.

Le Roux, J.J., Morgenthal, T.L., Malherbe, J., Pretorius, D.J., Sumner, P.D., 2008. Water erosion prediction at a national scale for South Africa. *Water SA*, 34 (3), 305-314.

Le Roux, J.J., 2011. *Monitoring soil erosion in South Africa at a regional scale*. ISCW Report No. GW/A/2011/23. ARC-Institute for Soil, Climate and Water. Pretoria, South Africa

Le Roux, J.J., 2012. Water erosion risk assessment in South Africa. towards a methodological framework, PhD dissertation, University of Pretoria, Pretoria

Le Roux, J.J., Sumner, P.D., Lorentz, S.A., Germishuyse, T., 2013. Connectivity aspects in sediment migration modelling using the Soil and Water Assessment Tool. *Geosciences,* 3(1), 1-12.

Le Roux P.A.L., Hensley, M, Lorentz, S.A., van Tol, J.J., Van Zijl, G.M., Kuenene, B.T., Bouwer, D., Freese, C.S, Tinnefeld, M., Jacobs, C.C., 2015. *Hydrology of South African soils and hillslopes.* WRC Report No. 2021/1/15.

Legesse, D., Vallet-Coulomb, C., Gasse, F., 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa. case study South Central Ethiopia, *Journal of Hydrology*, 275, 67-85.

Lindström, G., Johansson, B., Persson, Gardelin, M., Bergström, S., 1997. Development and test of the distributed HBV-96 hydrological model, *Journal of Hydrology*, 201, 272-288.

Low, A.B., Rebelo, A.G., 1996. *Vegetation of South Africa, Lesotho and Swaziland*. Department of Environmental Affairs and Tourism, Pretoria.

Ma, L., He, C., Bian, H., Sheng, L., 2016. MIKE SHE modeling of ecohydrological processes. merits, applications, and challenges, *Ecological Engineering*, 96, 137–149.

Macdonald I.A.W., Richardson D.M., 1986. Alien species in terrestrial ecosystems of the fynbos biome. In. Macdonald I.A.W, Kruger F.J, Ferrar AA, eds. *The Ecology and Management of Biological Invasions in Southern Africa*. Cape Town, South Africa. Oxford University Press, 77-91.

McGarry, D., 2011. Soil erosion. In. Assessing forest degradation, towards the development of globally applicable guidelines. *Forest Resources Assessment Working Paper 177, Food and Agricultural Organization*, 55-81.

Meadows, M.E., Hoffman, T.M., 2003. Land degradation and climate change in South Africa. *The Geographical Journal*, 169(2), 168-177.

Merritt, W.S., Letcher, R.A., Jakeman, A.J., 2003. A review of erosion and sediment transport models, *Environmental Modelling and Software*, 18, 761–799.

Miller, J., Muller, E., Roger, C., Waara, R., Atkinson, A., Whelan, K.R.T., Patterson, M., Witcher, B., 2009. Coral disease following massive bleaching in 2005 causes 60% decline in coral cover on reefs in the US Virgin Islands. *Coral Reefs*, 28, 925–937.

Mohammad, A.G., Adam, M.A., 2010. The impact of vegetative cover type on runoff and soil erosion under different land uses. *Catena*, 81(2), 97-103.

Moradkhani, H., Sorooshian, S., 2009. General review of rainfall-runoff modeling. model calibration, data assimilation, and uncertainty analysis, in S. Sorooshian, K. Hsu, E. Coppola, B. Tomassetti, M. Verdecchia, and G. Visconti (eds.), *Hydrological modelling and the water cycle. Coupling the atmospheric and hydrological models*, Springer, New York City, United State, 1-26.

Morgan, R.P.C., 1988. *Soil Erosion and Conservation*. Longman Scientific & Technical, Essex.

Morgan, R.P.C., 2005. *Soil Erosion and Conservation*, 3rd edition, Blackwell Publishing, Oxford, UK.

Morgan, R.P.C., 2009. S*oil erosion and Conservation*. John Wiley & Sons.

Mouzai, L., Bouhadef, M., 2003. Water drop erosivity: Effects on soil splash. *Journal of Hydraulic Research*, 41(1), 61-68.

Moyo, H.P.M., Dube, S., Fatunbi, A.O., 2009. Impact of the removal of black wattle (*Acacia mearnsii*) in the Tsomo Valley in Eastern Cape. /Consequences on the water recharge and soil dynamics (an ongoing study). *Grassroots. Newsletter of the Grassland Society of Southern Africa*, 9, 38-41.

Mucina, L., Adams, J.B., Knevel, I.C., Rutherford, M.C., Bolton, J.J., van der Merwe, J.H., Anderson, R.J., Bornman, T.G., le Roux, A., Powrie, L.W., 2006. Grassland biome, L. Mucina & M.C. Rutherford (eds.), *The vegetation of South Africa, Lesotho and Swaziland*, South African National Biodiversity Institute (SANBI), Pretoria.

Mucina, L., Rutherford, M.C., Powrie, L.W., 2007. *Vegetation map of South Africa, Lesotho and Swaziland, 1. 1000000*. South African National Biodiversity Institute, Pretoria

Musto, J.W., 1994. *Changes in soil physical properties and related hydraulic characteristics caused by Eucalyptus plantations*. Unpublished Thesis (MSc), Department of Agronomy, University of Natal, Pietermaritzburg, RSA.

Nearing, M.A., Govers, G., Norton, L.D., 1999. Variability in soil erosion data from replicated plots. *Soil Science Society of America Journal*, 63*,* (6), 1829-1835.

Nearing, M.A., Pruski, F.F., O'Neal, M. R., 2004. Expected climate change impacts on soil erosion rates. a review. *Journal of Soil and Water Conservation*, 59(1), 43-50.

Nearing, M.A., Jetten, V., Baffaut, C., Cerdan, O., Couturier, A., Hernandez, M., Le Bissonnais, Y., Nichols, M.H., Nunes, J.P., Renschler, C.S., Souchère, V., van Oost, K., 2005. Modeling response of soil erosion and runoff to changes in precipitation and cover. *Catena*, 61(2), 131-154.

Neave, M., Rayburg, S., 2007. A field investigation into the effects of progressive rainfall-induced soil seal and crust development on runoff and erosion rates. The impact of surface cover. *Geomorphology*, 87, 378-390.

Neitsch, S. L., Arnold, J. G., Williams, J. R., 1999. *Soil and Water Assessment Tool User's Manual*. Ver. 98.1. US Department of Agriculture-Agricultural Research Service, Grassland, Soil and Water Research Laboratory, Temple, TX.

Nel W., Sumner P.D., 2007. Intensity, energy and erosivity attributes of rainstorms in the KwaZulu-Natal Drakensberg, South Africa. *South African Journal of Science*, 103: 398–402.

Ngcobo, S.I., Lumsden, T G., Lorentz, S.A., Jewitt, G.P.W., Stuart-Hill, S., 2012. Projected impacts of climate change on water quality and implications for adaptation. *In Proc. 16th SANCIAHS National Hydrology Symposium*.

Nilsson, C., Malm-Renöfält, B., 2008. Linking Flow Regime and Water Quality in Rivers. a Challenge to Adaptive Catchment Management. *Ecology and Society*, 13(2), 18.

Ning, M., 2006. *Mathematical modelling of water soil erosion and sediment yield in large catchments*. Unpublished Thesis (MScEng), University of Stellenbosch, Stellenbosch, RSA.

Norris, C.H., 1993. *Slash Management*. ICFR Bulletin Series no. 15/1993. Institute for Commercial Forestry Research, Pietermaritzburg, RSA.

Oliveira, A.H., Silva, M.L.N., Curi, N., Avanzi, J.C., KlinkeNeto, G., Araújo, E.F., 2013. Water erosion in soils under eucalyptus forest as affected by development stages and management systems. *Ciência e Agrotecnologia*, 37(2), 159-169.

Osterkamp, W.R., Toy, T.J., 1997. Geomorphic considerations for erosion prediction. *Environmental Geology*, 29(3), 152-157.

Oyebode, O.K., 2014. Modelling streamflow response to hydro-climate variables in the upper Mkomazi River, South Africa, Master of Technology. Civil Engineering, Durban University of Technology, South Africa.

Palmer, M.A., Covich, A.P., Lake, S.A.M., Biro, P., Brooks, J.J., Cole, J., Dahm, C., Gibert, J., Goedkoop, W., Martens, K., Verhoeven, J., Van de Bind, W.J., 2000. Linkages between aquatic sediment biota and life above sediments as potential drivers of biodiversity and ecological processes. *BioScience*, 50(12), 1062-1075.

Parry, R., 1998. Agricultural phosphorus and water quality: A US Environmental Protection Agency perspective. *Journal of Environmental Quality*, 27(2), 258-261.

Phillips, D.L., White, D., Johnson B., 1993. Implications of climate change scenarios for soil erosion potential in the USA. *Land Degradation & Development*, 4(2), 61–72.

Pimentel, D., Kounang, N., 1998. Ecology of soil erosion in ecosystems. *Ecosystems*, 1, (5), 416-426.

Pimentel, D., Burgess, M., 2013. Soil erosion threatens food production. *Agriculture*, 3, 443-463.

Podwojewski, P., Janeau, J.L., Grellier, S., Valentin, C., Lorentz, S., Chaplot, V., 2011. Influence of grass soil cover on water runoff and soil detachment under rainfall simulation in a sub-humid South African degraded rangeland. *Earth Surface Processes and Landforms*, 36, 911-922.

Poesen, J.W.A., Hooke, J.M., 1997. Erosion, flooding and channel management in Mediterranean environments of southern Europe, *Progress in Physical Geography*, 21(2), 157-199.

Pohl, B., Macron, C., Monerie, P.A., 2017. Fewer rainy days and more extreme rainfall by the end of the century in Southern Africa, *Scientific Reports*, 7, 46466.

Postel, S.L., 2000. Entering an era of water scarcity. the challenges ahead. *Ecological Applications*, 10(4), 941-948.

Prasuhn, V., 2012. On-farm effects of tillage and crops on soil erosion measured over 10 years in Switzerland. *Soil & Tillage Research*, 120, 137-146.

Raz-Yaseef, N., Rotenberg, E., Yakir, D., 2010. Effects of spatial variations in soil evaporation caused by tree shading on water flux partitioning in a semi-arid pine forest, *Agricultural and Forest Meteorology*, 150, 454-462

Raz-Yaseef, N., Yakir, D., Schiller, G., Cohen, S., 2012. Dynamics of evapotranspiration partitioning in a semi-arid forest as affected by temporal rainfall patterns, *Agricultural and Forest Meteorology*, 157, 77-85.

Reichardt, K., Dourado-Neto, D., Schwantes, A.P., Timm, L.C., 2013. Soil water storage as related to water balances, International Centre for Theoretical Physics Report 2444-17.

Renschler, C.S., Harbor, J., 2002. Soil erosion assessment tools from point to regional scales-the role of geomorphologists in land management research and implementation. *Geomorphology*, 47, 189–209.

Rickson, R.J., 2014. Can control of soil erosion mitigate water pollution by sediments? *Science of the Total Environment*, (468-469), 1187–1197.

Ritter, J., 2012. *Soil erosion causes and effects, Factsheet* http.//www.omafra.gov.on.ca/english/engineer/facts/12-053.pdf (accessed. 24th August, 2014).

Salles, C., Poesen, J., 2000. Rain properties controlling soil splash detachment. *Hydrological Processes*, 14(2), 271-282.

Sanjari, G., Yu, B., Ghadiri, H., Cielsiolka, C.A.A., Rose, C.W., 2009. Effects of time controlled grazing on runoff and sediment loss*. Australian Journal of Soil Research*, 47, 796-808.

Savenije, H.H.G., 2004. The importance of interception and why we should delete the term evapotranspiration from our vocabulary, *Hydrological Processes*, 18, 1507-1511.

Saxton, K.E., Rawls, W.J., 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions, *Soil Science Society of America Journal*, 70, 1569-1578.

Scheepers, H., Wang, J., Gan, T.Y., Ruo, C.C., 2018. The impact of climate change on inland waterway transport: Effects of low water level on the Mackenzie River. *Journal of Hydrology*, 566, 285-298.

Scholl, M., Eugster, W., Burkard, R., 2010. Understanding the role of fog in forest hydrology. stable isotopes as tools for determining input and partitioning of cloud water in montane forests, *Hydrological Processes*, 25, 353-366.

Schulze, R. E., 1995. *Hydrology and agrohydrology. A text to accompany the ACRU 3.00 agrohydrological modelling system*. Water Research Commission Report No. TT69/95, Pretoria, South Africa.

Schulze, R.E., 2007. Hydrological Modelling: Concepts and Practice. School of Bioresources Engineering and Environmental Hydrology. University of KwaZulu-Natal, Pietermaritzburg, RSA.

Schulze, R.E., Maharaj M., Lynch, S.D., Howe, B.J., Melvill-Thomson, B. 1997. *South African Atlas of Agrohydrology and -climatology*, Report TT 82-96, Water Research Commission Report. 276 pp.

Scott, D.F., Van Wyk, D.B., 1990. The effects of wildfire on soil wettability and hydrological behaviour of an afforested catchment. *Journal of Hydrology*, 121(1–4), 239–256.

Scott, D., Versfeld, D., Lesch, W., 1998. Erosion and sediment yield in relation to afforestation and fire in the mountains of the Western Cape Province, South Africa. *South African Geographical Journal,* 80(1), 52-59.

Sen, S, Srivastava, P, Dane, J.H., Yoo, K.H., Shaw, J.N., 2010. Spatial - temporal variability and hydrologic connectivity of runoff generation areas in a North Alabama pasture - implications for phosphorus transport*. Hydrological Processes*, 24(3), 342–356.

Sharpley, A N., Menzel, R.G., Smith, S.J., Rhoades, E.D., Olness, A.E., 1981. The sorption of soluble P by soil material during transport in runoff from cropped and grassed watersheds. *Journal of Environmental Quality*, 10, 211-215.

Sherry, S.P., 1954. The effect of different methods of brushwood disposal upon site conditions in wattle plantations. II. A study of run-off and erosion during the first two years after clear-felling and regeneration. *Report – Wattle Research Institute*, (54), 27–36.

Sherry, S.P., 1961. The effect of different methods of brushwood disposal upon site conditions in wattle plantations. III. Run-off behaviour over a nine-year rotation. *Report – Wattle Research Institute*, (61), 32–40.

Sherry S.P., 1964. The effect of different methods of brushwood disposal upon site conditions in wattle plantations. IV. A study of run-off and erosion during the first two rainy seasons of the second crop cycle of the experiment. *Report – Wattle Research Institute*, (64), 41–50.

Singh, S.K., Ibbitt, R., Srinivasan, M.S., Shankar, U., 2017. Inter-comparison of experimental catchment data and hydrological modelling, *Journal of Hydrology*, 550, 1–11.

Siriwardena, L., Finlayson, B.L., McMahon, T.A., 2006. The impact of land use change on catchment hydrology in large catchments. The Comet River, Central Queensland, Australia, *Journal of Hydrology*, 326, 199–214.

Smithers, J., Schulze, R., 1995. ACRU Agrohydrological Modelling System, User Manual Version 3.00, Water Research Commission, Pretoria, Report TT70/95.

Soil Classification Working Group, 1991. Soil classification: a taxonomic system for South Africa. Pretoria: Department of Agricultural Development.

Sonnenborg, T.O., Christiansen, J.R., Pand, B., Bruge, A., Stisen, S., Gundersen, P., 2017. Analyzing the hydrological impact of afforestation and tree species in two catchments with contrasting soil properties using the spatially distributed model MIKE SHE SWET, *Agricultural and Forest Meteorology*, 239, 118–133.

Sumner, P.D., 1995. *Rates and controls of footpath erosion in Giants Castle game reserve, KwaZulu-Natal Drakensberg*. Unpublished Thesis (MSc), Department of Geography, University of Natal, Pietermaritzburg, RSA.

Sun, W., Shao, Q., Liu, J., Zhai, J., 2014. Assessing the effects of land use and topography on soil erosion on the Loess Plateau in China. *Catena*, 121, 151-163.

Swank, W.T., Johnson, C.E., 1994. Small catchment research in the evaluation and development of forest management practices. In. Moldan, B., Černý, J. (eds.) *Biogeochemistry of small catchments. A tool for environmental research*. Wiley, Chichester.

Tang, J.L., Zhang, B., Gao, C., Zepp, H., 2008. Hydrological pathway and source area of nutrient losses identified by a multi-scale monitoring in an agricultural catchment. *Catena*, 72(3), 374-385.

Teutschbein, C., Seibert, J., 2010. Regional climate models for hydrological impact studies at the catchment scale. a review of recent modeling strategies, *Geography Compass*, 4(7), 834–860.

Teutschbein, C., Seibert, J., 2012. Bias correction of regional climate model simulations for hydrological climate-change impact studies. Review and evaluation of different methods, *Journal of Hydrology*, 456–457, 12–29.

Thornley, J.H.M., 1998. *Grassland dynamics: an ecosystem simulation model*. CAB International.

Thornthwaite, C.W., Mather, J.R., 1957. Instructions and tables for computing potential evapotranspiration and the water balance, *Publications in Climatology*, 10(3), 185-311.

Ticehurst, J. L., Newham, L. T., Rissik, D., Letcher, R. A., Jakeman, A. J., 2007. A Bayesian network approach for assessing the sustainability of coastal lakes in New South Wales, Australia. *Environmental Modelling & Software*, 22(8), 1129-1139.

Tolosa, D., 2015. Modeling Sediment Yield using ArcSwat and Analyzing the Most Prominent Remedial Measures: Cases of Melka Wakena Reservoir, Ethiopia. Addis Ababa University Addis Ababa Institute of Technology, School of Graduate Studies.

Toohey, R.C., Boll, J., Brooks, E.S., Jones, J.R., 2018. Effects of land use on soil properties and hydrological processes at the point, plot, and catchment scale in volcanic soils near Turrialba, Costa Rica, *Geoderma*, 315, 138-148.

Toy, T.J., Foster, G.R., Renard, K.G., 2002. *Soil erosion. processes, prediction, measurement, and control*. John Wiley & Sons.

Turner, D.P., 2000. Soils of KwaZulu-Natal and Mpumalanga: recognition of natural soil bodies. Unpublished PhD thesis, University of Pretoria.

Turpie, J.K., Marais, C., Blignaut, J.N., 2008. The working for water programme. Evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. *Ecological Economics*, 65(4), 788-798

Valentin, C., Bresson, L.M., 1998. Soil crusting. In. Lal, R., Blum, W. E. H., Valentin, C., Stewart, B. A. (eds) *Methodology for assessment of soil degradation*. Advances in Soil Science, CRC, Lewis Publishers, Boca Rato,

Van de Giesen, N., Stomph, T. J., Ajayi, A. E., Bagayoko, F., 2011. Scale effects in Hortonian surface runoff on agricultural slopes in West Africa. Field data and models. Agriculture. *Ecosystems & Environment*, 142(1), 95-101.

Van der Watt, H.V.H., Van Rooyen, T.H., 1995. *A Glossary of Soil Science*, 2nd edn, The Soil Science society of South Africa, Pretoria

van Dijk, A.I.J.M., Keenan, R.J., 2008. Planted forests and water in perspective, *Forest Ecology and Management*, 251(1-2), 1-9.

van Noordwijk, M., Poulsen, J., Ericksen, P., 2004. Filters, flows and fallacies. quantifying off-site effects of land use change. *Agriculture, Ecosystems and Environment*, 104,19-34.

Van Oost, K., Govers, G., Desmet, P., 2000. Evaluating the effects of changes in landscape structure on soil erosion water and tillage. *Landscape Ecology*, 15, 577-589.

van Tol JJ, Le Roux PAL, Hensley M. 2011. Soil indicators of hillslope hydrology. In: Gungor BO, Mayis O (eds), Principles, application and assessments in soil science. Rijeka: InTech.

Van Zyl, J., Kirsten, J.F., Binswanger, H.P., 1996. *Agricultural land reform in South Africa. Policies, markets and mechanisms*. Oxford University Press, Cape Town Van Zyl, A., Lorentz, S.A., 2004. *Predicting the impact of farming systems on sediment yield in the context of integrated catchment management*. Water Research Commission. Research Report No.1059/1/03.

Vanclay, J.K., 2009. Managing water use from forest plantations, *Forest Ecology and Management*, 257, 385-389.

Verbist, B., Poesen, J., van Noordwijk, M., Suprayogo, D., Agus, F., Deckers, J., 2010. Factors affecting soil loss at plot scale and sediment yield at catchment scale in a tropical volcanic agroforestry landscape. *Catena*, 80, (1), 34-46.

Verster, P.S.J., 1998. Geological map of Harrismith (2828). Council for Geoscience, Pretoria.

Vertessy, R.A., 2001. Impacts of plantation forestry on catchment runoff, in E.K.S., Nambiar and A.G., Brown (eds.), *Plantations, farm forestry and water. Proceedings of a National Workshop, Melbourne, 21-22 July*, 2000, RIRDC Report No. 01.20, Rural Industries Research Development Corporation Report, Canberra, 9-19.

Von Maltitz, G., 1998. Communal rangeland management options for the Okhombe community. In Communal rangelands in southern Africa: a synthesis of knowledge, Proceedings of a symposium on policy-making for the sustainable use of southern Africa communal rangelands, University of Fort Hare, South Africa

Vrieling A., Hoedjes, J.C.B., van der Velde, M. 2014. Towards large-scale monitoring of soil erosion in Africa. Accounting for the dynamics of rainfall erosivity. *Global and Planetary Change*, 115, 33-43. 38.

Wakindiki, I.I.C., & Ben-Hur, M., 2002. Soil mineralogy and texture effects on crust micromorphology, infiltration and erosion. *Soil Science Society of American Journal*, 66, 897-905.

Walling, D.E., 1983. The sediment delivery problem. *Journal of Hydrology*, 65, (1), 209-237.

Wang, X., Williams, J.R., Gassman, P.W., Baffaut, C., Izaurralde, R.C., Jeong, J., Kiniry, J.R., 2012. EPIC and APEX. Model use, calibration and validation, *American Society of Agricultural and Biological Engineers*, 55 (4), 1447-1462.

Warburton, M.L., Schulze, R.E., Jewitt, G.P.W., 2012. Hydrological impacts of land use change in three diverse South African catchments, *Journal of Hydrology*, 414–415, 118–135.

Wicks, J.M., Bathurst, J.C., 1996. SHESED. a physically based, distributed erosion and sediment yield component for the SHE hydrological modelling system, *Journal of Hydrology*, 175, 213-238.

Winchell, M., Srinivasan, R., Di Luzio, M., Arnold, J. G., 2010. ArcSWAT Interface For SWAT 2009: User's Guide, Texas Agricultural Experiment Station (Texas) and USDA Agricultural Research Service (Texas), Temple (Texas).

World Wildlife Fund (WWF), 2009. *Agriculture. Facts and Trends South Africa*. World Wildlife Fund, Cape Town.

Xu, C.Y., Singh, V.P., 2004. Review on Regional Water Resources Assessment models under stationary and changing climate, *Water Resources Management* 18, 591–612.

Xu, Z.X., Pang, J.P., Liu, C.M., Li, J.Y., 2009. Assessment of runoff and sediment yield in the Miyun Reservoir catchment by using SWAT model, *Hydrological Processes*, 23, 3619–3630.

Yates, S.R., van Genuchten, M.T., Leij, F.J., 1989. Analysis of predicted hydraulic conductivities using RETC computer program, *Soil Science Society of America Journal*, 56, 347-354.

Zhang, L., Dawes, W.R., Walker, G.R., 1999. Predicting the effect of vegetation changes on catchment average water balance, Cooperative research centre for catchment hydrology, Technical Report 99/12.

Zhang, Z., Wang, S., Sun, G., McNulty, S.G., Zhang, H., Li, J., Zhang, M., Klaghofer, E., Strauss, P., 2008. Evaluation of the MIKE SHE model for application in the Loess Plateau, China, *Journal of the American Water Resources Association*, 44(5), 1108-1120.

Zotarelli, L., Dukes, M.D., Romero, C.C., Migliaccio, K.W., Morgan, K.T., 2015. Step by step calculation of the Penman-Monteith evapotranspiration (FAO-56 method), Agricultural and Biological Engineering Department, Uf/IFAS Extension, University of Florida.

9: APPENDICES

9.1 Capacity Building

9.1.1 Capacity Building

Over the last few years I have been involved in a number of WRC projects and have watched, with interest, when the topic of 'capacity building' comes up. It is usually responded to by stating that the project has X number of Masters or PhD students involved. At Universities, there is an annual scramble to obtain students to fill these scholarship / research positions. The funding is good and so most are filled, however my concern has been the lack of 'follow-up' or true pro-active engagement with these students during the project. By way of example, as opposed to merely providing funding and yes supervision, actually engaging with a cohort of WRC funded students and go supervisory role to some extent.

Thus, in this project we began to attempt this ideal and developed a number of 'Mastering the Masters' workshops that were carried out over a few days / weeks and involved a number of experts outside of the project with regards language, how to write a research proposal, data collecting, writing up of thesis and grant applications. We appreciate this is not completely within the ambit of a WRC funded project, however we felt it formed a strong addition within the capacity building component. The workshops were well received and we hope it produced stronger students.

A note of caution. Even within this idea of developing a cohort of students we still had a number of students leave the project prior to completing their students. There are a number of reasons for this however we do believe it is something that WRC should engage with and seek ways, in collaboration with the hosting Universities, to prevent as best we can (of course there will always be situations that we cannot control) students leaving before completion. Simple issues such as scholarships and should students have to pay back monies, can one realistically manage this? Consider the monies beyond scholarships used to purchase equipment, travel and subsistence cost and cost of supervisors – these cannot be recouped. This is complex situation as often our students are offered internships or full-time employment and in today's job market it is difficult to turn down such an opportunity. We have been able, in most cases, to persuade the student to change to part-time registration and attempt to complete their studies – however this delays obtaining data and why so many of our students are only 'under examination/ or 'on-going' at the completion of the project.

A further cost that we noticed during this project was travel cost to field sites. Many of our post-graduate students now either do not own cars or cannot drive – this really does hinder opportunities to be involved in essentially field based research. We do not provide a solution only note it based on experience of this project.

A final consideration for WRC, is to run a tracer study of what happens to these students - how many graduate, how many produce papers / begin completing for their own grants on completion, or do they join the water / research / university sector. Our observation of all these questions is rather negative.

Thus, in this project we took a conscience decision to be considered as educators first and researcher second. The notion was to develop a cohort of Masters students (3 to 5 individuals across participating Universities / Institutes) that follow a more coherent and structured pathway to completion of their degree, write academic peer reviewed papers and possibly towards grant writing and submission. WE have had two post-doctorate students that have acted as mentors for the MSc students. WE have been very fortunate in that both post-doc students spent considerable time in the field, helping with laboratory work and engaging with the MSc students in their thesis write-ups. The idea is not much different to what is purported to occur at present, however we do not perceive that many reach these laudable ideals. Within this project we have nurtured a cohort of research Masters students through a two-year degree, so not a course work Masters, however provide a more structured programme than is normally the case at Research Masers level. So, for example, we held formal classes to help in proposal writing, design research methodologies, joint field components, short courses (three days that draws in local and regional experts) that develop the necessary skills to facilitate data collection, management and analysis. Furthermore, design or include short courses to help in academic paper writing and grant applications.

Many of the Masters students joining these funded projects are often under-prepared and I think we need to take cognisance of this and develop the necessary skills to allow these research projects a better chance of being successful. Furthermore, if we nurture these students, help / coerce them through the degree, install respect for the research genre and move them beyond just degree complete, I think we will have a better chance of keeping them in the Water / Research sector than is evidently the present situation.

Please see table below of post-graduate students that have been an integral part of this project.

Student name and surname	Gender	Race	Degree	University	Country of Origin	Progress
Jarryd Gillham	Male	White	MSc (Env Sci)	UKZN	South Africa	Graduated
Chris Birkett	Male	White	MSc (Env Sci)	UKZN	South Africa	Left Project
Gaby Duncan	Female	White	MSc (Geography)	WITS	South Africa	Graduated
Nosipho Makaya	Female	Black	MSc (Env Sci)	UKZN	South Africa	Graduated, with distinction
Ashleigh van Wyk	Female	Coloured	MSc (Env Sci)	UKZN	South Africa	Graduated
Matthew Dickey	Male	White	MSc (Env Sci)	UKZN	South Africa	Thesis under examination
Megan Grewcock	Female	White	MSc (Env Sci)	UKZN	South Africa	On-going
Bangani Dube	Male	Black	MSc (Soil Science)	UKZN	South Africa	Graduated
Gugu Tshabalala	Female	Black	MSc (Env Sci)	UKZN	South Africa	On-going
Jordon Bull	Male	White	MSc (Hydrology)	UKZN	South Africa	On-going
Lyndon Riddle	Male	White	PhD (Env Sci)	UKZN	South Africa	On-going
Nqobile Lushozi*	Male	Black	Honours (Env Sci)	UKZN	South Africa	Graduated
Mandisa Kleinbooi*	Female	Black	Honours (Env Sci)	UKZN	South Africa	Graduated
Dr Khatab M. Abdalla	Male	Black	Post Doc	UKZN	Sudan	On-going
Dr Bruce Scott-Shaw	Male	White	Post Doc	UKZN	South Africa	On-going

Candidate: Jarryd Gillham

Degree: MSc (University of KwaZulu-Natal)

Title: Investigating the processes of erosion and sediment yield at different scales in commercial forestry. A case study at Two Streams in KwaZulu-Natal.

Abstract: Soil erosion is the detachment and transportation of soil particles from one location to another and has on- and off-site impacts which jeopardize the capacity of ecosystems to deliver environmental services. A possible off-site impact of soil erosion is eutrophication of water bodies, a major concern in water scarce South Africa. Previous studies have outlined the role that agriculture contributes to soil erosion. This study investigates the role of commercial plantations in contributing to soil erosion, which in South Africa occupy over three million hectares. This study considers the processes of erosion and sediment loss at different temporal and spatial scales in a commercial forestry land use.

The research study was undertaken in a mature *Acacia mearnsii* afforested catchment at Two Streams situated near Seven Oaks, Greytown. The first objective of the study was to set-up an appropriate experimental design by using 5x2 m^2 runoff plots (n=9) and 1x1 m^2 micro-plots (n=9) located at three landscape positions. Automatic tipping buckets were used to measure runoff intensity. Runoff from 1 m^2, 10 m^2 plots and 34 ha catchment were assessed from January 2015 to March 2016. At the catchment outlet there was a V-notch weir which measured stream flow, weir samples were taken using an ISCO automatic sampler. Runoff was measured and water samples were collected from the nested scales after selected rainfall events (n=15). The runoff samples were analysed in the laboratory to determine sediment volume, phosphate, nitrate and soil organic carbon.

Sediment loss, for the 1 m^2 and 10 m^2 plots averaged similar amounts per event (0.901 gl^{-1} and 0.809 gl^{-1} respectively) with an average of 0.793 gl^{-1} of sediment loss measured from the weir. The results highlight that the increase in spatial scale did not have an influence on the sediment and nutrient loss, with rain splash and runoff providing similar results (g/m^2). There was a low degree of spatial variation in sediment yield due to low variation in rainfall throughout the catchment and the increase in spatial scale did not have a significant influence in sediment yield. Temporally, higher intensity rainfall events led to high intensity runoff, which led to higher volumes of sediment loss. This was evident on the 18th December 2015 with an intense rainfall event (114 mm) leading to a significant increase in sediment yield compared to the study average. There was a inverse relationship between rainfall/runoff and phosphate, nitrate and dissolved organic carbon concentrations. With higher rainfall/runoff events resulting in lower nutrient volumes this due to the process of dilution compared to smaller rainfall/runoff events which resulted in higher nutrient concentrations.

The results from this study showed the link between rainfall/runoff and soil erosion and the vital role of vegetation interception in reducing the impact of rainfall and water erosion. The results suggest that the *Acacia mearnsii* catchment was effective in reducing the impact of water erosion, which demonstrates that a mature commercial forest with low human impact (harvesting) has manageable soil erosion rates. With the potential increase in the rate of soil erosion due to climate change, more research needs to be undertaken, so that mitigation measures can be designed for the future.

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Candidate: Gaby Duncan

Degree: MSc (WITS)

Title: Modelling the impact of land cover and forestry change on the hydrological characteristics of the Two Streams sub-catchment, Natal Midlands

Abstract: Understanding of the impacts of land cover and the changes thereof on water resources is essential in improving management practices and protecting water resources, particularly in water scarce countries like South Africa. In order to determine the impacts of land cover and land cover change on hydrological processes, a small sub-catchment in the Natal Midlands was modelled. The Two Streams sub-catchment was modelled for both a current (2007-2016) and future (2019-2028) scenario using MIKE SHE deterministic hydrological modelling software. The current scenario was modelled to compare the hydrological characteristics of the dominant land cover classes: sugarcane (*Saccharum officinarum*), black wattle (*Acacia mearnsii*) and riparian vegetation. The future scenario was run to determine the hydrological impact a change in plantation forestry from black wattle (*Acacia mearnsii*) to *Eucalyptus dunnii* would have. The objectives of the study were to 1) Populate the MIKE SHE current (pre-forestry change) and future (post-forestry change) models with appropriate datasets, by identifying, sourcing, collecting, gathering, measuring and generating required inputs. 2) Calibrate and validate the MIKE SHE set-up to determine how accurately the current scenario modelled the observed sub-catchment hydrology. 3) Simulate the water movement and water balance of the Two Streams sub-catchment for the current and future scenario, in order to determine the changes in hydrology experienced with different land covers. 4) Draw conclusions on the hydrological impacts. Results indicated that the MIKE SHE model was effective at modelling the Two Streams site (however, not significantly so). The black wattle plantation was found to use more water through ET and experience greater loss in subsurface water supplies in relation to sugarcane and riparian vegetation. In comparing the hydrological characteristics of black wattle and *Eucalyptus dunnii* forestry plantations, *E. dunnii* was the greater water (however not significantly so) and experienced greatest reduction in subsurface storage. Before the MIKE SHE model can be used for further modelling on-site, the limitations identified, including those pertaining to the subsurface hydrological characteristics, limited LAI data and limited *E. dunnii* research, need to addressed and overcome.

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Candidate: Nosipho Makaya

Degree: MSc (Distinction) (University of KwaZulu-Natal)

Title: Assessing the potential of Sentinel-2 MSI sensor in detecting and mapping the spatial distribution of gullies in a communal grazing landscape.

Abstract: The main aim of this study was to assess remote sensing applications for detecting and mapping the spatial distribution of gully erosion in the communal lands of Okhombe Valley, Drakensberg, South Africa. The study first sought to review the progress of remote sensing by examining its usage and users over the years. The findings showed that the application of remote sensing for soil erosion studies has significantly increased by 45% since the 1960s. Although remote sensing is becoming widely accepted by a growing number of scientific disciplines, there is paucity in African lead authors, and this call for more collaborative research and knowledge transfer. Literature further shows that Landsat series data is a popular remote sensing system used for soil erosion monitoring and mapping, mainly due to its multispectral bands and archival data. Although, commercial high-resolution satellites have been demonstrated to accurately map small soil erosion features; their high acquisition costs remain a challenge, especially in resource constrained regions. Therefore, this allows for the exploration of the freely available new generation sensors for gully erosion mapping at regional scales. The second objective of the study was to evaluate the potential of the Sentinel-2 MSI sensor in detecting and mapping the spatial distribution of gullies. The study further investigated environmental variables (i.e. slope, vegetation cover, TWI and SPI) that may have a potential influence on gully initiation and development. The study evaluated the effectiveness of the Sentinel-2 spectral bands in discriminating gullies from other land cover types using the Support Vector Machine. The overall classification accuracy achieved for gully discrimination was 77% and all 10 Sentinel-2 spectral bands were selected as the ideal variables for discriminating gullies from other land cover types. Additionally, the findings of the study indicated that there is no significant difference between the environmental variables across different gully volumes and that all the measured variables have a weak influence on the volume of soil loss (i.e. Slope (R2 = 0.02); Vegetation cover (R2 = 0.01); TWI (R2 = 0.11) and SPI (R2 =0.02) despite an observable trend of influence. Overall, Sentinel-2 has demonstrated its usefulness in detecting and mapping gullies and it is therefore recommended that future studies explore the use of the freely available sensor in monitoring mapping soil erosion at regional scales.

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Candidate: Ashleigh van Wyk

Degree: MSc (University of KwaZulu-Natal)

Title: Investigating the impact of cattle path erosion on soil organic carbon and nitrogen, Okhombe Valley, KwaZulu-Natal Drakensburg, South Africa.

Abstract: While soil erosion is a natural geologic phenomenon its' exacerbation, as a consequence of socio-economic and political factors, threaten rural sustainability and livelihoods. Smallholder rural farmers within the KwaZulu-Natal Drakensburg region of South Africa are reliant on the surrounding grasslands for livestock grazing. Poor land management through overgrazing, overstocking and livestock trampling have led to cattle path formation and resultant soil erosion, which negatively affects these montane grasslands. Community members have identified cattle path formation as a grave concern as the loss of land, through excessive erosion, leads to gully formation and presents a safety hazard to residents and livestock. This study investigates the impact of cattle path erosion on soil properties, in particular soil organic carbon (SOC) and nitrogen (N) along a degraded slope profile. For this purpose four positions (reference site, top-slope, mid-slope and lower-slope) were identified and sampled at three soil depths (0-5 cm, 5-15 cm and 15-30 cm) along a degraded slope at Okhombe, Drakensburg region South Africa. Soil properties, soil nutrients, SOC and N were measured and physical soil fractionation were completed to determine carbon (C) and N protection within soil aggregates. To understand SOC and N distribution, areas of erosion and deposition were determined by measuring fallout radionuclides caesium-137 (^{137}Cs) and excess lead-210 ($^{210}Pb_{ex}$). Soil property measurements revealed that the undisturbed reference site contained higher nutrient content and greater C and N protection within soil aggregates compared to the degraded slope profile. This suggests that nutrient loss has occurred on the degraded slope, possibly as a result of cattle path erosion. Due to the low activity of the samples, count times for $^{210}Pb_{ex}$ and ^{137}Cs ranged from 24- 48 hours, using detection limits of 0.3 dpm g^{-1} for $^{210}Pb_{ex}$ and 0.05 dpm g^{-1} for ^{137}Cs. The analysis of ^{137}Cs showed low activity, with 75% of the samples (n=36) having activities below the detection limit. Thus, the use of ^{137}Cs as an indicator for soil erosion could not be determined. Excess lead-210 indicated significant post-depositional movement and that this movement is spatially heterogeneous and temporally variable. As such, determining sedimentation rates within the study area was not possible, as $^{210}Pb_{ex}$ did not decline with depth at a consistent rate. Excess lead-210 did however show that at areas of soil erosion, SOC and N concentrations are low, highlighting the physical removal of these soil properties with the detachment and transportation of soil particles through sheet erosion. Knowledge of soil erosion processes will aid in the design and implementation of effective soil erosion and sediment control strategies. Improved understanding of the effect of cattle paths on soil properties and soil organic matter distribution will contribute to the ongoing efforts to rehabilitate rural landscapes to ensure sustainable land use management.

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Candidate: Bangani Dube

Degree: MSc (University of KwaZulu-Natal)

Title: Analysis of global gulley characteristics and the impacts of gabions and grass on sediments and carbon storage.

Abstract: Gully erosion has immediate and long-term negative impact on the environment. Rehabilitation effectiveness depends on gully characteristics and the trapped sediments, which can help to sequester carbon (C) and mitigate climate change. The C from the sediments, if not trapped, is either eroded into the ocean or mineralized to CO_2, which accumulates into the atmosphere and contribute to global warming. The objectives of the study were to evaluate (1) the main factors that affect gully characteristics at global scale, and (2) the potential impact of gabions and grass, as gully rehabilitation techniques, on sediment retention and C sequestration. In the global analysis of permanent gullies, available literature on factors affecting characteristics of gullies was explored. Data were collected from online search engines such as Google Scholar and electronic bibliographic databases (e.g. Science Direct, Springerlink). A database on published gully channel dimensions volume (V), length (L), width (W), depth (D), W:D ratio (indicator of incision shape), top-view (A) and cross-sectional areas (Ac) for 435 permanent gullies across the world was compiled and used to analyse for the impacts of different climates (tropical, sub-tropical and temperate), land cover, terrain altitude and slope, soil texture and bulk density on the channel dimensions. Potential impact of gully rehabilitation on sediment and carbon storage was evaluated in Okhombe area near the Drankensburg mountain range in KwaZulu-Natal province, South Africa. The rehabilitation techniques used in the studied gully was a combination of stone-checks and vegetative methods. Soil samples (n= 206) were collected from the 0-5, 5-15, 15-30, 30-60, 60-90 and 90-120 cm depth of lower, mid and upper gully positions, and adjacent positions outside the gully. These soil samples were analysed for particle size distribution, total organic carbon and nitrogen content (OCC, ONC) and soil bulk density. Information on soil bulk density allowed for OC and ON stocks (OCS, ONS) to be assessed. Finally, ^{14}C activity was evaluated for informing on the origin of the stored OC. These quantitative results on the factors controlling gully morphology at global scale contribute to better understanding of gullying mechanisms, a prerequisite for modelling gully channel formation and for development of mitigation measures under different environmental conditions. The most important soil parameter was texture as sand content had the most significant influence (when it comes to gully initiation and development), while land use change was also essential (as change from natural to agriculture or residential increased the chances of gully initiation or development). The sediments from the gully under rehabilitation were sandier than soils adjacent to the gully. Sediments from the upper and mid slope positions of the gully also showed greater silt content within the 0-15 cm depth than adjacent soils outside the gully. There was a general increase of C content with depth of gully sediments, except at the mid slope position where soils from both within and outside the gully showed a decrease of C content with depth. Gully sediments were generally richer in C content than adjacent soils. However, the soils from outside the gully showed greater C within the 0-5 cm depth at the lower slope position. The greater C content of soils from the rehabilitated gully pointed to potential C sequestration. The findings of this study imply that rehabilitation of gullies with stone checks and grass results in sediment and carbon storage which helps in the sequestration of carbon, potentially mitigating global warming.

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Candidate: Matthew Dickey

Degree: Under examination MSc (University of KwaZulu-Natal)

Title: Quantification of soil erosion and sediment yield from commercial sugarcane and commercial forestry in KwaZulu-Natal, South Africa.

Abstract: Soil erosion, which is a natural occurring event, involves the detachment and transport of soil particles due to topography, climate, management practice and human activity. The topic of soil erosion has been investigated in-depth in many developing countries, however, few studies in South Africa have been conducted on run-off and soil erosion relating to commercial *Saccharum officinarum* (Sugarcane) and *Acacia mearnsii* (Black Wattle) plantations. The aim of the study is to investigate the effect of runoff and sediment yield on water quality, in a catchment consisting of commercial *Acacia mearnsii* plantations and *Saccharum officinarum* crop.

The study site was chosen based on existing infrastructure and a record of historical data. Runoff plots at different scales, namely; 10 m^2 and 1 m^2, were installed at various landscape positions in the two land uses. The 1 m^2 plot scale was chosen to represent rain splash and the 10 m^2 plots surface runoff. Nutrients, phosphate and nitrate were measured to quantify the effect of pollution due to runoff from agricultural land uses. The study site received lower than average annual rainfall for the 2016 and 2017 rainfall seasons. Rainfall affected the response of runoff, sediment yield and nutrient fluxes in the different climatic seasons. High sediment yield was observed in the 1 m^2 plots in the sugarcane (7.81g/L) and black wattle (7.33g/L). Despite lower annual rainfall experienced over the study period, high intensity storm events led to higher runoff volumes and increases in sediment yield for the black wattle and the sugarcane compared to undisturbed natural forest and grasslands. High runoff volumes were observed in the black wattle due to the soil being strongly repellent with low infiltration rates. The sugarcane provided better canopy protection while the black wattle had higher litter percentages. The sugarcane had a high interception rate of 51% due to the high canopy cover. High concentrations of nutrients and sediment were observed within the catchment, while very low nutrient and sediment concentrations were recorded in the stream.

Due to the canopy cover being greater than 60% and a high litter content, erosion from runoff was significantly reduced. Low sediment concentrations were recorded in the runoff samples from both land-uses. However, high nutrient concentrations such as P, N and DOC entrained in runoff were recorded which is a concern as this can pollute receiving downstream waters, decreasing water quality and increasing water scarcity. At present, nutrient concentrations at the catchment outlet remain low due to the presence of sinks and litter cover slowing runoff velocity. Furthermore, sediment concentrations remained low due to scale effects whereby surface runoff was low at the 10 m^2 plot scale, and rain splash was dominant at the 1 m^2 scale. Spatial and temporal variations play an important role as rain splash was the dominant erosion process.

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9.2 Technology Transfer

Technology or knowledge transfer took place as; community engagement and workshops – occurred in Okhombe Valley with community members; Farmers Association meetings – with farming community in the Greytown and Wartburg Districts; research institutes – through research days; and through academic peer reviewed papers. The various approaches were detailed in appropriate deliverables that were specific to the ideals of knowledge transfer.

The papers are:

Birkett, C.K., Hill, T.R., Zuma, K.D. & Everson, T.M., 2016: Bringing rain to the land: Rainfall simulation as a participatory teaching aid to understanding erosion. *Journal of Environmental Protection*, 7, 1305-1316.

Riddle, L., Hill, T.R. & Gijsbertsen, B. 2018: Geomorphology from 'on-high': The use of drones/UAV technology in teaching soil erosion. *Journal of Geography Education for southern Africa,* 3 (1), 10 – 22.

Abdalla, K, Dickey, M., Hill, T, & Scott-Shaw, B., Assessment of soil erosion under rainfed sugarcane in KwaZulu-Natal, South Africa. Submitted to *Natural Resource Forum*

Scott-Shaw, B.C., Hill, T.R. & Gillham, J.S. Validation of a Modelling Approach for Sediment Yield in a Wattle Plantation, KwaZulu-Natal, South Africa. Submitted to: *WaterSA* (WaterSA 3611). **Accepted with changes**

Khatab, A., Mutema, M. & Hill, T.R. Global perspective of soil and organic carbon losses from different land uses: a meta-analysis. Submitted to: *Geographical Research* (GEOR-2018-055) **Under Review**

With regards to knowledge transfer the project took a pro-active stance to ensure that the various stakeholders were informed and part of the research process, be it commercial concerns such as MONDI and commercial farmers through to the local communities, within which are sites were situated. In particular, within the rural context, the paths to development are perceived to lead through identifying problems and their causes and to then seek solutions. The South African scene is complicated by fundamental and economic realities. There have been decades of enforced discrimination, racially based inequalities and disparities in income, access to land and employment opportunities. One of the consequences has been the collapse of the rural agricultural base and creating dependence on urban sourced incomes and services. In effect, a system of functional urbanization and the process of de-agrarianisation has been placed onto rural communities.

With respect to this project, land degradation is a major global issue threatening arable land, grazing, food security and water security. Approximately 70% of South Africa has been affected by land degradation, emphasising the need to understand land degradation drivers and implement correct, appropriate mitigation and rehabilitation techniques. It is imperative that the land degradation found in communal areas is mitigated or rehabilitated as a large portion of the degraded land is communal areas which are necessary for sustained livelihoods. There needs to be a combination of scientific techniques and studies combined with local knowledge and resources available to community members to mitigate and rehabilitate land degradation in communal areas.

It is often difficult to explain scientific knowledge to community members; rainfall simulation provides a tool that can be used for both scientific data collection and a demonstrative tool of erosion processes to community members. The rainfall simulation was used in the Okhombe valley to study cattle path erosion and in a workshop held in the area for the community members. The community members quickly gained the concepts of slope gradient and basal cover from the rainfall demonstrations. The community could visualise the outcome of low basal cover and steep slope gradient verse high basal cover and gentle slope gradient. The community then began to understand why mitigation measures worked and to identify sites where various mitigation techniques would work more effectively than other techniques. The understanding of the driving factors of land degradation provides the community with an applied understanding of the problem faced by the area and renewed energy and ideas to combat land degradation. Through the rainfall demonstration a better understanding of the driving factors in the erosion process, an understanding of why particular mitigation techniques work and where such mitigation measures would be effective were identified. With the combination of scientific techniques and community knowledge and resources a step can be taken towards sustainable land degradation mitigation and rehabilitation in the communal areas of South Africa.

9.3 Data Storage and Knowledge Dissemination

All processed data have been stored at:

DISCIPLINE OF GEOGRAPHY
School of Agricultural, Earth and Environmental Sciences
University of KwaZulu-Natal
King Edward Avenue
Scottsville
Pietermaritzburg 3209
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Information / data will be stored for five years from completion of project.