RAIN EVENTS BASED HILLSLOPE HYDROLOGICAL PROCESSES AT THE LANGGEWENS EXPERIMENTAL FARM, WESTERN CAPE, SOUTH AFRICA

by

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Abstract

Hillslope hydrology represents a complex system with several interacting processes influencing the movement of water through the landscape. The Western Cape area of South Africa is expected to be impacted on by a change in climate and the importance of water management that will increase in the future. Climate, especially precipitation, is the driving factor behind the hydrological system and there are currently no predictions as to what the impact will be on the hydrological conditions. The main objective of the study is to understand the hydrological responses along a hillslope and secondly to determine the effect of climate change on the hydrology by using hydrological models.

The studied system is situated on the Langgewens Experimental Farm, north of Malmesbury in the Swartland region of the Western Cape. Six sites in a range of vegetation, land use and expected soil types along a toposequence were investigated. All sites are rain fed areas with natural vegetation, seasonal or long-term shrubs. Through monitoring different components of the hydrological cycle, including rainfall, overland flow, infiltration, soil water content, base flow and water table depth at the different sites, the movement of water through the landscape can be defined. Hillslope hydrological processes at different positions on the hillslope were investigated. The baseline data obtained during this process was used in hydrological modelling for the different positions on the hillslope to determine the accuracy of model predictions. Expected future climatic conditions were emulated in this model to determine the possible effect of a change in climate on the hydrological system.

The research confirmed the complex interaction between different processes within the hydrological system. At each point along the toposequence different components of the hydrological cycle contributed on a different scale to the hydrological system. Soil properties were the most significant factor influencing water movement through the landscape, directly impacting infiltration, overland flow, lateral water flow and deep percolation. This resulted in water table fluctuations through the seasons as the contribution of different components towards the hydrological cycle changed. By comparing soil water content measurements through the season with modelled water content levels, accurate hydrological models were created for different measuring points in the landscape. By using forecasted climate data of two different weather generators, accurate estimations of expected soil water content were possible. This indicated that droughts will occur on a regular basis in the future.

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This research made it possible to understand water movement through the landscape at hillslope level and contributed towards future water management plans by estimating future soil water content levels based on current predictions.

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Opsomming

Heuwelhang hidrologie omskryf die proses van water beweging deur die landskap en dit word deur verskeie prosesse beinvloed. Onder huidige toestande word verwag dat die Weskaap provinsie van Suid-Afrika warmer en droëer sal word in die toekoms as gevolg van klimaatsverandering. Dit sal die noodsaaklikheid van effektiewe waterbestuur verhoog in die toekoms. Klimaat, en in besonder reënval, is die dryfkrag agter die hidrologiese sisteem en huidiglik is daar geen aanduiding van wat die effek van klimaatsverandering op die hidrologiese sisteem gaan wees nie. Die eerste doel van die studie is om die heuwelhang se hidrologiese sisteem te ontleed en tweedens om die impak van klimaatsverandering op die hidrologiese sisteem te bepaal deur gebruik te maak van hidrologiese modelle.

Die studie area is geleë op die Langgewens Proefplaas, noord van Malmesbury in die Swartland distrik van die Weskaap. Ses verskillende posisies is op die heuwelhang geselekteer op grond van posisie in die landskap, plantegroei, landgebruik en verwagte grondvorms. Al die studiepunte ontvang slegs water deur reën en die landgebruik wissel ten opsigte van natuurlike plantegroei, en eenjarige- of meerjarige gewasse wat gevestig is. Deur verskillende komponente van die hidrologiese sisteem te monitor, insluitend reënval, oppervlak afloop, infiltrasie, grond water inhoud, laterale water vloei en die diepte van die watertafel, kan die beweging van water deur die landskap gedefinieër word. Die data wat versamel is gedurende die proses word gebruik om die akkuraatheid van die hidrologiese modelle se resultate te bepaal. Tesame met vooruitgeskatte klimaatdata kan die modelle gebruik word om die impak van klimaatsverandering op grondwater toestande vas te stel.

Die navorsing toon die komplekse interaksie tussen verskillende prosesse in die hidrologiese sisteem. By elke punt in die landskap dra verskillende komponente op verskillende skale by tot die hidrologiese sisteem. Grondeienskappe het die meeste invloed op die verskillende komponente van die hidrologiese sisteem en beïnvloed die infiltrasie, oppervlak afloop, laterale water vloei en diep dreinering. Soos die verskillende komponente se bydrae tot die hidrologiese sisteem verander, vind daar fluktuasies in die diepte van die water tafel plaas. Deur die vergelyking van gemete grondwaterinhoud teen hidrologiese model voorspelde grondwaterinhoude, is akkurate hidrologiese modelle opgestel vir verskillende punte in die landskap. Deur gebruik te maak van twee moontlike verwagte klimaat toestande, is gevind dat droogtes op ‘n roetine basis in die toekoms sal voorkom.

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Die navorsing maak dit moontlik om die beweging van water deur die landskap te verstaan en dra by tot die opstelling van toekomstige waterbestuur planne. Dit word moontlik gemaak deur die vooruitskatting van grondwater inhoude gebasseer op verwagte klimaatsveranderinge en huidige grondwater toestande.

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DEDICATION

Proverbs 3:5-6 – "Trust in the Lord with all your heart and lean not on your own understanding; in all your ways submit to him, and he will make direct your paths."

2 Corinthians 12:9 – "My grace is sufficient for you, for my strength is made perfect in weakness."

This thesis is dedicated firstly to the Lord God Almighty, through whom all things are possible. May Your name be glorified!

Secondly, this thesis is dedicated to my late grandfather, Nico Giliomee. Thank you for the example you were, the legacy you left behind and making me excited about agriculture.

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Contents

List of Figures

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Stellenbosch University http://scholar.sun.ac.za

List of Tables

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List of Abbreviations

BRC - Berg River Catchment

DEM - Digital Elevation Model

CCAM - Conformal-Cubic Atmospheric Model

EC - Electrical Conductivity

ET - Evapotranspiration

FAO - Food and Agricultural Organization

GCM - General Circulation Models

GIS - Geographical Information System

HRU - Hydrological Response Unit

IPCC - Intergovernmental Panel on Climate Change

LAI - Leaf Area Index

MAE - Mean Absolute Error

OM - Organic Matter

PET - Potential Evapotranspiration

RCM - Regional Climate Models

RMSE - Root Mean Square Error

VWC - Volumetric Water Content

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CHAPTER 1 GENERAL INTRODUCTION

Hillslope hydrology represents a complex system with several interacting processes influencing the movement of water through the landscape. With current climate predictions that the Western Cape will become drier and warmer in the future, it is important to determine what the change in groundwater will be and the effect thereof on agricultural management practices.

Any changes with regard to the current climate will have a significant impact on groundwater recharge. According to the Intergovernmental Panel on Climate Change (IPCC), climate is defined as “The average weather in terms of the mean and its variability over a certain time-span and a certain area”. Climate Change is when there is a significant statistical variation of the current climate conditions compared to historical conditions over a time-span of decades or longer (Singh & Kumar, 247667). Since 1861, global surface temperatures have increased by 0.6±0.2°C with a further increase over the next 100 years that can vary from 2-4°C (IPCC, 1996). The different interactions between climate, vegetation and soil properties all contribute to the hydrological system and its functioning. Any changes regarding the climate will have an impact on different aspects of the hydrological cycle. Alterations in the infiltration regime, overland flow (runoff), subsurface flow (base flow) and ultimately groundwater can be expected due to changes in rainfall, rainfall intensities and temperature.

Most studies have focused on what the impact of climate change has had on surface water and little research currently explains the effect that climate change will have on groundwater. Since groundwater conditions are a reflection of climatic variables, landscape characteristics and human activities, predicting future hydrological conditions depends on our current understanding of the hydrological cycle.

Several factors influence the movement of water through the landscape. The flow path of water through and over the soil is very important. We know that landusers aims to change soil to be able to take up all the water it receives. Land-use practices therefore aim to maximise infiltration and minimize overland flow while in most dryland situations the soil returns during the rainy season to a more compact soil with less infiltration. By investigating the different components and processes of the hydrological cycle, accurate estimations of water movement and the effect of different management practices can be determined.

1.1. PROBLEM STATEMENT

Climate is the single most important factor that has an impact on the hydrological cycle and currently there are no predictions as to what the impacts of a change in climate will be on soil water conditions and ultimately groundwater recharge. Through the understanding of the hydrological cycle, hydrological models can be used to forecast future soil water conditions in order for management recommendations to be made.

The system that we plan to research is a hillslope on the Langgewens Experimental Farm in the Swartland area of the Western Cape. Six different research plots were selected along the hillslope to form a toposequence, which includes natural vegetated areas, cultivated areas that are subjected to tillage practices, and a site with permanent or long term dryland shrubs. All of these sites are rainfed dryland areas. Through investigating the different components of water movement through the landscape, the hydrological cycle can be defined and the impact of different land management practices can be determined. This will be done through different in situ measurements, including rainfall, overland flow, infiltration, soil water content, baseflow and water table depth at the different sites.

1.2. OBJECTIVES

- Investigating the hydrological processes on a hillslope to determine the effect of seasonal weather events on site specific soil water conditions.
- Set up a one dimensional hydrological model for the study area per measurement point to assess the differences in water response.
- Assessment of the site specific hydrological response as affected by the predicted change in climate.
- Recommend management practices according to expected future soil water conditions based on modelling results.

1.3. REFERENCES

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CHAPTER 2 LITERATURE REVIEW

2.1. GENERAL INTRODUCTION OF LITERATURE OVERVIEW

Hydrological processes on any hillslope are a reflection of the interaction between different systems and components which all contribute to the complexity of the system. In the Western Cape region of South Africa, water is the most important limitation on agricultural expansion and sustainability. Currently there are no predictions of the impact that a change of climate will have on groundwater. It is important to create a model that is able to estimate future groundwater conditions to enable water management agencies to manage water resources. Another important parameter of the model is to determine what the impact of different climatic variables will be on groundwater.

Estimates indicate that by the year 2025 about 5 billion of the total expected world population of 8 billion people will be living in countries that experience water shortages, thus using up to 20 % of their total available resources (Arnell, 1999).

The low number of assessments that have been made on a global scale that are concerned with the impact that a change in climate will have on global water resources, is a major concern worldwide. This is mainly due to the complexity of the relationship between different climatic parameters and groundwater recharge (Jyrkama & Sykes, 2007). Other factors that contribute to the difficulty of temporal and spatial groundwater recharge characterization include hydrogeological heterogeneity and land-use factors such as vegetation, cultivation and landscape modifications (Lerner *et al.*, 1990).

Pressure on water resources can be divided into two sections, the supply-side and the demand-side. Factors that influence the supply-side pressure include climate change (expected changes in precipitation and evaporation) and environmental degradation, causing lower water quality and less water that is available for use. Pressures on the demand-side include an increase in the global population and concentration as well as the distribution around the globe. This will result in increasing demands for agricultural, industrial and domestic water (Arnell, 1999). Climate change will also affect the demand-side as temperature and evaporation increases.

Increases in population and water usage in the near future will cause a significant increase in the pressure on water resources. As the effect of climate change will differ between regions

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around the globe, predictions indicate that countries that are situated in the Middle East, southern Africa and the Mediterranean regions will experience the greatest impact. Southern Asia and Africa will most likely experience the sharpest pressure increase on regional water resources. Unfortunately, most of these countries are neither able nor well equipped to cope with these expected changes (Arnell, 1999).

The expected changes caused by climate change, in combination with increasing global population levels and the expected pressure that is expected on water resources, increases the need to forecast future climate conditions and the effect that it will have on water resources (Woldeamlak *et al.*, 2007). According to Allen *et al.*, (2004), many studies regarding the effect that a change in climate will have on surface water have been done worldwide. Planning different techniques/systems to mitigate the effect of a change in climate will be determined by the scale at which climate change occurs (Woldeamlak *et al.*, 2007).

Digital elevation models (DEM) are used to derive information regarding the hydrological system along with different terrain characteristics. DEM contain valuable information regarding the terrain properties, including slope, curvature, aspect, stream ordering, watershed delineation, flow accumulation, etc. DEM information can be extracted in two different ways, firstly through visualization, and secondly through quantitative analysis (Saraf *et al.*, 2004). Hydrological modelling and geographic information systems (GIS) are strongly linked. GIS is concerned with the earth's spatial features, while hydrological modelling provides data related to the flow of water, as subsurface and surface water (Saraf *et al.*, 2004).

Theory indicates that the change in climate will lead to increases on both precipitation and evaporation, resulting in the hypothesis that the intensification of the water cycle will be a major consequence. Any changes in the hydrological cycle will have a dramatic impact on water resources worldwide and will also have an impact on various populations due to the increased occurrence of extreme events (Huntington, 2006). Impact quantification is a complex problem due to the interactions between several different systems. Overland flow as well as erosion processes are sensitive to any changes in precipitation patterns, thus it is expected that these processes will be influenced by climate change. Other factors like soil water also influence these processes (Latron & Gallart, 2007). Watersheds situated in Mediterranean climate regions are expected to be severely impacted on by climate change with regard to erosion and overland flow processes (Nunes *et al.*, 2009).

Human intervention in the hydrological cycle will increase in the near future. Landscape modifications to reduce floods will impact peak flows, while increased consumption will reduce flow, and land-use changes will alter ET and ultimately influence overland flow (Huntington, 2006).

Chaplot (2007) came to the following conclusion:

- Precipitation had the greatest impact on water and soil resources, compared to changes in CO_2 levels and temperature.
- Environmental conditions determine the water and soil response to changes in the global climate.
- Over a longer period of time, the interactions between climate, CO_2 concentration, vegetation and soil feed back to the water balance.

Studies that are investigating the water balance are becoming more important as this has a major impact regarding the water yield within catchments. Groundwater recharge is a complex process (Figure 2.1) and is influenced by physical land characteristics together with the hydrological process (Jyrkama & Sykes, 2007). This is influenced by changes in the land use which are mostly due to human activities. To make accurate predictions regarding water quality and quantity, as well as the impact of possible floods and droughts, it is necessary to understand what the controlling factors such as topography, vegetation, soil and the climate have on the water balance (Jothityangkoon *et al.*, 2001; Jyrkama & Sykes, 2007).

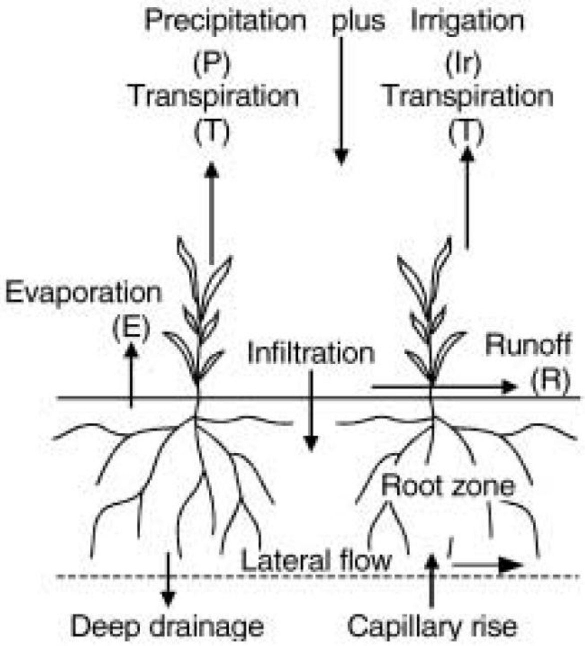

Figure 2.1: Factors contributing to the soil-water balance (Walker *et al.*, 2002).

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2.2. WATER

The level of sustainability in the agricultural sector within semi-arid regions is directly linked to the knowledge of water movement in the landscape (Figure 2.2). Two major problems experienced in agriculture are salinity and waterlogging, which are often caused where deep-rooted natural vegetation is replaced by shallow-rooting crops, resulting in the accumulation of excess water (Dunin *et al*, 1999). Hillslope hydrological models are important for land-use planning, and thus knowledge of the hydrological processes within a specific region is important.

Precipitation is the driving force behind groundwater recharge and is strongly dependent on the rainfall characteristics namely duration, intensity and temperature. The process of percolation that leads to groundwater recharge is strongly associated with rainfall intensity. Zuo (2010) found that greater percolation rates occur under high intensity and low frequency rainfall events compared to low intensity and high frequency. Under estimated climate change scenarios, this will have a great impact on groundwater recharge. Various processes like surface overland flow, evaporation and interception have an influence on groundwater recharge. Before water reaches the vadose zone after infiltration into the soil, plant roots withdraw water which is transpired back into the atmosphere. Water that moves past this zone through deep percolation reaches the saturated groundwater zone where it contributes to groundwater (Jyrkama & Sykes, 2007).

Water quality will be affected substantially by a change in climate. The quality is influenced by temperature and flow, and although the quality of some sources will improve, most will experience a deterioration regarding the quality. The quality of water is most often defined according to maximum and minimum concentrations of unfavourable and favourable chemical substances as well as physical properties like colour, sediment concentration and temperature (Arnell, 1998; Jacoby, 1990). Maximum concentrations will be applied to chemical substances like salinity and toxic chemicals, while minimum concentrations will be applied to substances like dissolved oxygen (Jacoby, 1990). Stream flow will be affected by any change in climate, causing lower flow levels and thus a rise in chemical concentration levels. This deterioration of stream quality will occur under decreasing precipitation and increasing evapotranspiration conditions, or when the increase in evapotranspiration is greater than the precipitation increase (Jacoby, 1990).

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Two major problems experienced in agriculture are salinity and waterlogging, which are often caused where deep-rooted natural vegetation is replaced by shallow-rooting crops, resulting in the accumulation of excess water (Dunin *et al.*, 1999). In arid regions, salinity is a frequent problem and will be more severe depending on the effect that climate change will have on the region. Recent floods and droughts have increased the awareness regarding global climate change and the effect that it will have on society, especially water resources (Arnell, 1998). The physical effect of climate change on water quality and quantity has an impact on water as a resource and the management thereof, with different effects having different impacts on this valuable resource (Arnell, 1998).

Watersheds that are under climatic conditions currently experiencing water stress are likely to become vulnerable as the mean climate changes and more extreme events occur. By identifying potential vulnerable watersheds, proactive decisions can be made to monitor, collect data and assess the impact of a change in climate (Hurd *et al.*, 1999).

2.2.1. Hillslope Hydrology

Variability in soil water dynamics can be attributed to several factors, including meteorological factors, total water content, water table depth, soil properties, vegetation composition and topography (Famiglietti *et al.*, 1998). All of the above factors and their interaction with one another influence water movement through the landscape on a temporal and spatial scale (Figure 2.2).

Topography

The main factor influencing water movement through the hillslope is topography. This determines the water movement in space, influences the gravity response and has an influence on the water storage capability of the hillslope (Creutzfeldt *et al.,* 2010). Within the topographical unit of a hillslope, several variations are present. Elevation in relation to the rest of the hillslope, upslope area, aspect, slope and curvature affects soil water distribution throughout the hillslope (Famiglietti *et al.,* 1998). Steep slopes compared to flatter areas are drier due to more overland flow, less infiltration and rapid drainage. According to Hill and Reynolds (1969) and Moore *et al.*, (1988) slope angle or aspect have an influence on the variability of soil water along a slope. This is due to variations in solar radiation that cause heterogeneous evapotranspiration patterns that lead to uneven soil water distribution. This was confirmed by Reid (1973).

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Soil Properties

Soil water distribution is related to several soil properties, including their interaction with one another. Pore geometry, soil texture and organic matter affect retention and transmission properties of soil water, while soil colour influences the albedo and ultimately the evapotranspiration rate (Famiglietti *et al.*, 1998). While variation due to soil texture was investigated and confirmed by Reynolds (1970) and Crave and Gascuel-Odoux (1997), Hawley *et al.*, (1983) found that the effect of soil texture under dry conditions was less noticeable than under wet conditions.

Vegetation

The effect of vegetation on soil water is determined by the vegetation composition and density which is mostly related to the season. Factors that influence the variability in soil water patterns include through fall patterns which are related to the canopy, shading which influences evapotranspiration, root activity and organic matter that affect hydrological conductivity and extraction by roots (Famiglietti *et al.*, 1998).

Total Water Content

Hills & Reynolds (1969) noted that a decrease in total water content resulted in a decrease in soil water variance. This is supported by Reynolds (1970b) who stated that the variability in soil water is the highest after a precipitation event.

Reynolds (1970b), Nyberg (1996) etc. all studied factors that influence soil water variability on a different scale. The interactions between these different factors cause alterations to expected soil water conditions. Henninger *et al.*, (1976) investigated and found that drainage properties and elevation along a hillslope were both factors contributing to variability in soil water distribution. Hawley *et al.*, (1983) investigated the effect of the combined effect of topography and vegetation on soil water. This study indicated that elevation was the most dominant factor, however its effect on soil water was diminished by vegetative cover. Another study by Moore *et al.*, (1988) examined the impact of slope, aspect, curvature and the contributing area in order to determine the combined effect on soil water. It was concluded that the combination of slope and contributing area, together with aspect, played a major role in soil water.

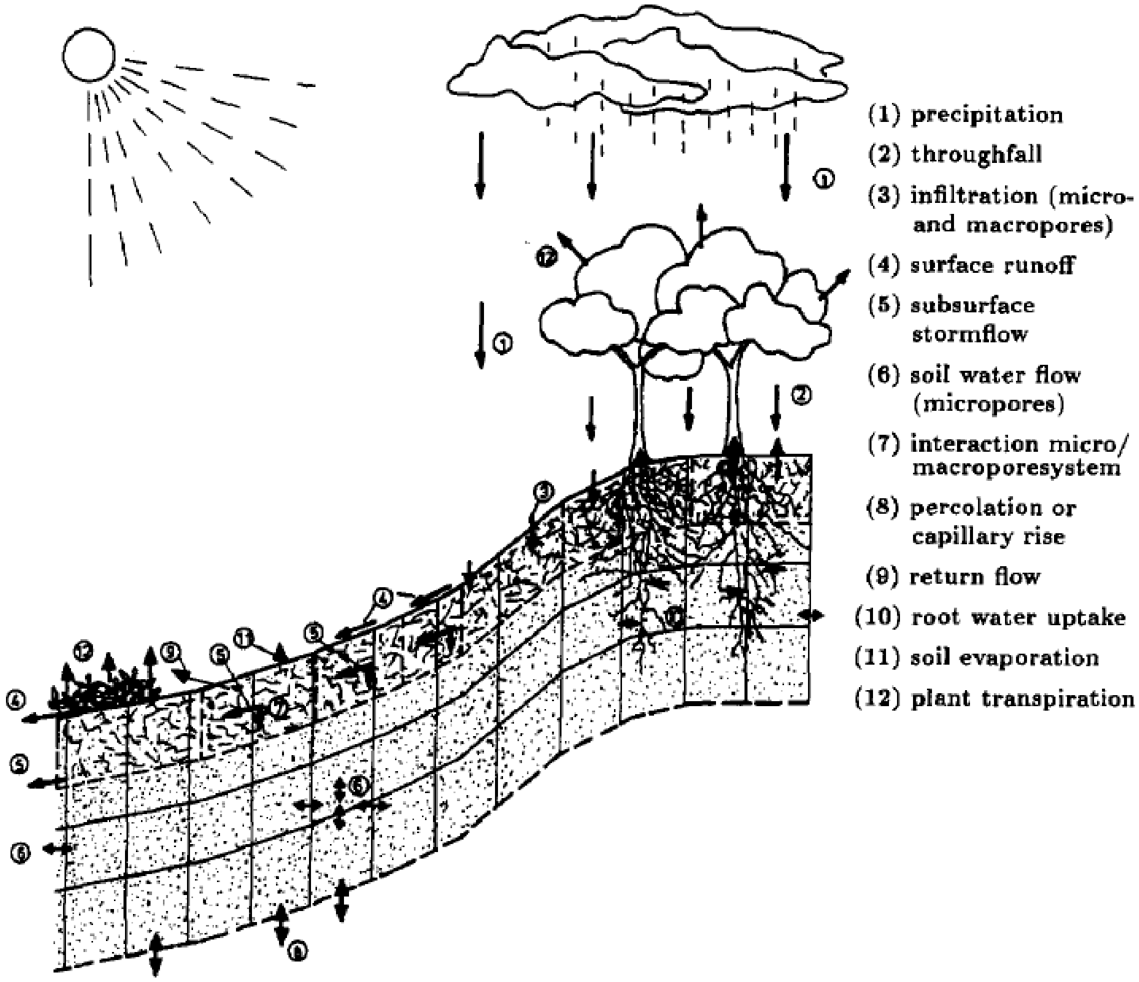

Figure 2.2: Overview of the hydrological system and water movement through a hillslope (Bronstert & Plate, 1997).

Three groundwater recharge mechanisms have been defined by Lerner *et al*., (1990):

1. Localized Recharge: intermediate recharge due to water accumulation on the surface where flow channels are absent.
2. Direct Recharge: precipitation exceeding ET and water deficit in the soil is added and percolates into the groundwater reservoir.
3. Indirect Recharge: percolation from surface water bodies towards groundwater.

2.2.2. Factors influencing Future Water Use

According to Arnell (1999), the following factors will influence water demand:

- Population growth and concentration: Higher demand for water and higher concentrations in areas like big cities could result in water shortages.

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- Industrial alteration: Increasing industrial activities, especially in developing countries, will increase the pressure on water resources. However, since water has been seen as an economic good, more efficient usage practices have been put in place.
- Irrigation developments: The expansion of agricultural activities that require irrigation has increased the water demand by the agricultural sector, but improved irrigation techniques may offset the higher demand.
- Management and efficiency: Management measures that aim to lower water usage have improved the water use efficiency levels.

Available studies that focus on groundwater discharge and recharge conditions found that it is a reflection of climatic variables, precipitation regime, landscape characteristics human impacts, which include agricultural flow regulation and drainage (Allen *et al.,* 2004).

Groundwater is a natural replenishable resource, but under hard rock terrains groundwater may be limited. In these areas groundwater occurs in weathered and fractured horizons (Saraf *et al.*, 2004). Water that enters the soil through the process of infiltration, can move through the soil profile in various ways. This includes the removal through evapotranspiration or uptake by plants, lateral movement that contributes to stream flow and percolation that will result in aquifer recharge (Nejadhashemi *et al.,* 2011). Movement of water through unsaturated soils fulfil an important role in water management and conservation, as well as agriculture and civil engineering (Touma *et al.*, 2007). Predictions regarding overland flow are difficult due to the large heterogeneity within catchment areas regarding the topography, vegetation, soils and variability in climate, all of these factors contributing to hydrological challenges (Waymira & Gupta, 1998). Infiltration is an important process within hydrological modelling. During a rainfall event, infiltration determines the amount of water that will reach the river system indirectly as subsurface flow or directly as overland flow (Bronstert & Plate, 1997).

Nunes *et al.* (2009) found that there are mainly three driving forces resulting in a change within the erosion patterns and overland flow generation system. These are the vegetation cover, soil water levels/patterns and the precipitation characteristics. Expected increases in evapotranspiration and precipitation could lead to a decrease in overland flow, as the evaporation is expected to outweigh the precipitation (Huntington, 2006). Land degradation and agricultural activity intensification have caused an increase in overland flow despite a decrease in rainfall in Sahelian, North Africa. This is directly related to surface compaction caused by the cultivation of land to transform it from natural vegetation to agricultural farmland (Mahe, 2009). Changes in land-use activities and the water requirements of the vegetation have an influence on base flow and overland flow (Zhang & Schilling, 2006).

The water table will respond to changes in the groundwater recharge, but the period depends on the length water has to move from the surface to the groundwater, as well as the directness of water movement (Le Maitre *et al.*, 1999). Groundwater depths vary significantly and are influenced by climate and the topography, elevation and rock type with regard to the valley bottom. Groundwater levels vary between the valley floor, where the level can be near the surface, and the hilltops and valley sides, where it can be as deep as 20 m (Hughes, 2010). Groundwater recharge is highly inconsistent due to evapotranspiration rates that exceed rainfall in most of South Africa (Midgley *et al.*, 1994).

With all these different factors and changes that are expected, the use of hydrological models will increase as water managers search for more accurate predictions regarding future groundwater conditions.

2.3. CLIMATE

The IPCC (2001) defines climate as “the average weather in terms of the mean and its variability over a certain timespan and a certain area”. If there is a significant variation with regard to the mean state of different parameters such as temperature and rainfall, or if there is a variability that lasts 10 years or longer, the climatic condition is described as climate change (Woldeamlak *et al.*, 2007). Future climatic changes will adjust hydrological cycles which will have a major impact on water resources with regards to quality and quantity (Gleick, 1989).

Changes in climate that occur within several decades is a concern for water managers due to the problems that it causes and the difficulty of separating these events from natural changes in the long term weather cycle (Frederick, 2002). Prior to the industrial revolution, the main source of changes regarding climate were changes in the circulation patterns of the ocean and the output levels of the sun. The industrial revolution led to large scale changes in energy usage and land-use patterns caused by human activities which affect the global climate pattern and also accelerate the rate at which these changes occur (Wigley, 1999).

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Major increases in different forms of carbon have been reported since the industrial revolution took place during the 18th and 19th century. The resulting increase in greenhouse gas concentrations has resulted in an enhanced greenhouse effect, causing an increase in the mean surface temperature of the earth (Chaplot, 2007). A report published by the IPCC (2001), stated that the surface temperature increased 0.04 °C every decade during the early stages of the last century, and the current rate is 0.17 °C every decade (Figure 2.3). The negative impact of these changes is visible all around the globe with changes in the hydrological processes, shifts in vegetation patterns, ever shrinking ice sheets and an increase in extreme weather events like droughts, floods, hurricanes and cyclones.

The first assessment by the Intergovernmental Panel on Climate Change (IPCC) during 1990, found that human activities that result in emissions are causing an increase in the concentration of greenhouse gases, and that this increase will boost the natural occurring greenhouse effect on the surface of the earth and result in additional warming. Furthermore, with an increase of the surface temperature, the water vapour content (which is the most substantial greenhouse gas) in the atmosphere will increase, causing further global warming (IPCC, 1996a).

Global warming, also known as “Enhanced greenhouse warming”, is used to refer to the projected change in climate that is expected due to human activities. The projections are based on the concentration of carbon dioxide in the atmosphere. Carbon dioxide accumulates in the atmosphere due to the burning of fossil fuels like gasoline, natural gas or coal, as well as when deforestation takes place (Trenberth, 1999).

Climate affects all phases that occur within the hydrological cycle and any change that occur regarding the climate will have an impact on water demand and supply. The relationship between groundwater and climatic variables can be subdivided into direct and indirect interaction- directly through rivers and lakes, and indirectly with regards to the process where groundwater recharge takes place (Jyrkama & Sykes, 2007). A change in any climatic parameter will affect the hydrology. Increasing air temperatures (Figure 2.3) are a result of additional heat within the atmosphere due to increased greenhouse gas concentrations. The warmer air temperatures directly affect evaporation rates, with higher temperatures resulting in increased evaporation levels. Warmer air has a higher water holding capacity and in combination with higher evaporation levels will lead to higher water levels that are present in the atmosphere (Trenberth, 1999).

As the earth is a balanced system, the increase in evaporation will greatly affect other systems and will results in a change in the atmospheric conditions. This will result in localized higher precipitation rates and increasing occurrence of flooding events. Heavy rainfall contributes to the occurrence of flooding events, but other factors such as the amount of rainfall, spatial distribution, precipitation rate as well as the nature and conditions of the terrain, are also contributing factors. Droughts are also expected to be a more common occurrence due to changes in the precipitation regimes, where infiltration and overland flow will be impacted on (Eckhardt & Ulbrich, 2003; Trenberth, 1999).

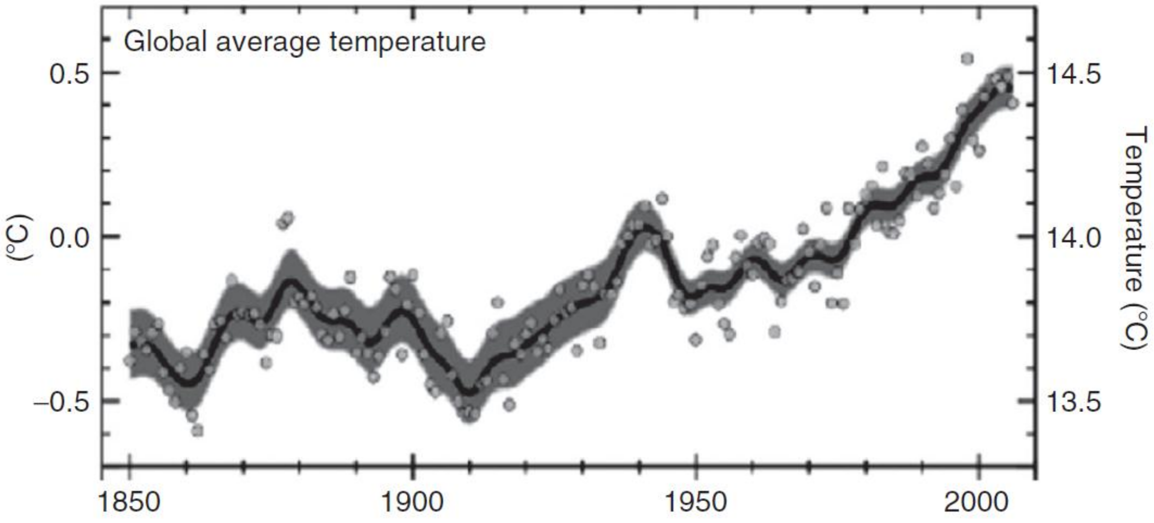

Figure 2.3: Global average temperature 1850-2005 compared to the 1961-1990 long-term average (IPCC, 2007).

Sandstrom (1995) concluded that if the temperature remains stable and the precipitation reduces by 15 %, a 40-50 % reduction in groundwater recharge can be expected. As soil water forms a major part of water resource systems in terms of transformation, formation and consumption, any changes within this system will have a major impact on forestry, agriculture and other hydrological processes (Zuo *et al.*, 2010). This indicates that a small change in precipitation can have a major impact on groundwater resources. Predictions indicate that climate change will affect overland flow and the resulting erosion process at numerous spatial scales in Mediterranean watersheds.

2.3.1. Evidence of Climate Change

The IPCC (1996a) report stated the following evidence of climate change:

- Greenhouse gas concentrations have risen significantly, causing an increase in surface temperature.
- Human activities, which include the burning of fossil fuels, agriculture and land-use changes, are mostly responsible for the significant increase in carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) levels in the atmosphere
- Temperature fluctuations occur on an annual basis, but long term changes are evident.
- Under current conditions, the surface temperature will rise 2 °C by 2100. Under the lowest emissions scenario created by the IPCC, the change will be 1°C by 2100, and 3.5 °C under the highest predicted emission scenario.
- Warmer mean surface temperatures will have a precarious effect on the hydrological cycle, increasing the occurrence of extreme events, mostly floods and/or droughts. Due to the higher evaporation rates and corresponding precipitation intensity increase, more severe rainfall events are expected.
- Between 1900 and 1990, an average global precipitation level increased by 2 %, but this varies significantly between different regions (Hulme *et al.*, 1999).

2.3.2. Possible Impacts of Climate Change

Changes in the climate will have a significant impact worldwide, especially on water resources. Water management will be affected by the changes in precipitation, overland flow and changes in land use as well as shifts in the population distribution (Frederick & Major, 1997).

The increase in surface temperature will have a major effect on the hydrological cycle, causing changes in the precipitation and overland flow, as well as the frequency and intensity of extreme weather events like droughts and floods. Greater temperatures will intensify evapotranspiration rates on the surface, resulting in changes in the soil water levels and water infiltration rates (Frederick & Major, 1997).

As there are still many uncertainties regarding the change in global temperature, the change in climate at regional scale is even more unpredictable and uncertain. Changes that will occur at watershed levels and basins are two of the most unknown aspects regarding the impact of climate change (Frederick & Major, 1997).

Greenhouse warming will have several impacts on water resources, according to working group 2 of the IPCC (1996b):

- Regional precipitation patterns will change, with a change in the timing, distribution pattern and intensity expected
- General Circulation Models (GCM) estimate that a mean temperature increase of 1.5-4.5 °C will lead to a mean precipitation increase of 3-15 %
- The effect of higher precipitation rates on overland flow will be offset by the increase in evaporation rates caused by higher global surface temperatures
- Potential Evapotranspiration (PET) will increase, caused by the increase in global temperatures, but may decrease or increase, depending on the availability of soil water
- Flood occurrence predictions vary worldwide and may decrease in some regions
- Higher evapotranspiration rates, decrease in precipitation and drier spells can increase the severity and frequency of droughts
- Semiarid and arid areas will be the most sensitive to any variations in the climate
- Water quality will become a major concern as the stream flow decreases due to higher evapotranspiration and less overland flow

2.3.3. Effect of Climate Change on Agriculture

Climate change will have a dramatic effect on the agricultural sector worldwide (Hatch *et al.,* 1999). As the climate changes, the high heterogeneity regarding the topography, soils and climate result in a wide variety of possible outcomes. Recorded changes of greenhouse gas concentrations in the atmosphere and the possible effect that it will have on the climate, is a major cause for concern for the agricultural sector worldwide (Peart *et al.*, 1995).

The effect of climate change and changing CO_2 levels on evapotranspiration, water flow and the impact on supplies is uncertain (Frederick & Major, 1997). Uneven distribution with regards to the increasing level of precipitation that is expected with a change in climate will result in precipitation declines in certain regions and increases in other regions. This will result in more floods and droughts, as well as shifts in the dry and wet season timing (Arnell, 1999).

Soil resources will be heavily impacted on through climate change, as changes in overland flow and rainfall will increase sediment transport and soil erosion within landscapes (Chaplot, 2007). Temperature changes significantly affect the precipitation regime, although it has a smaller impact on natural resources. Overland flow that occurs due to precipitation increases as the precipitation increases, but soil erosion may decrease or increase with decreasing precipitation rates (Pruski & Nearing, 2002). Precipitation is the key parameter required to generate overland flow, but it is also influenced by parameters such as land use, vegetation and other landscape characteristics. Pruski & Nearing (2002) found that stream flow followed changes in precipitation, and that the effect of climatic scenarios varied between regions. Changes involving land cover and land use leads to a change in the greenhouse gas concentration in the atmosphere (Miller, 1990). Global Circulation Models (GCM) as well as Regional Climate Models (RCM) indicates a decrease in annual precipitation and also a shift in rainfall concentration in Mediterranean regions, also leading to an increase in the rainfall intensity (Lionello *et al.*, 2002). This will directly influence future water conditions.

2.4. LAND USE AND LAND COVER

Land cover and land-use changes both have a strong influence on hydrological processes, with land cover referring to the type of vegetation that covers the land and land use referring to the human activities that are being implemented (Holko & Kostka, 2008; Keating *et al.*, 2002).

Groundwater and vegetation interact in two stages within the hydrological stages. This is in the form of interference as precipitation moves through the surface into the soil and through extraction via the plant’s root system. Vegetation cover and composition have a major influence on the quantity and distribution of precipitation that reaches the surface and also influences the water movement through the soil as it has an impact on percolation, infiltration, drainage and the water storage capacity (Le Maitre *et al.*, 1999).

Changes in climate variability, demographic trends, macroeconomic activities and national policies result in alterations in land use and land cover, which have a significant impact on the regional and basin scale hydrological systems (Legesse *et al*, 2003). Climate and land use change form a complex interaction that have an impact on the hydrology, which makes it problematic to study what the effect of each driver is. Tomer & Schilling (2009) found that climate change is the largest driver that influences the hydrology. This conclusion was made

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after changes to land use plateaued out in different agricultural regions in the Midwest of the U.S.A.

Land use is important within all watersheds and plays a significant role regarding the hydrological response (Nejadhashemi *et al.*, 2011). Land use influences surface processes and characteristics including evapotranspiration, leaf area index (Mao & Cherkauer, 2009), infiltration capacity and the soil water content (Fu *et al.,* 2000), surface roughness and recharge (Fedemma *et al.*, 2005), overland flow, base flow, subsurface and surface flow regimes. Land-use changes can also lead to soil erosion caused by the interactions between climate processes, geology, soils, terrain and vegetation. Any changes regarding land use, including deforestation and urbanization, affect surface water and groundwater interactions (Nejadhashemi *et al.*, 2011).

Vegetation participates in several processes that have an influence on the hydrological cycle, i.e. evapotranspiration, infiltration and interception. Investigating the role that vegetation plays in each of the different processes will improve our understanding of the impact that vegetation has on run off and the rest of the hydrological cycle (Holko & Kostka, 2008). Flow resistance, surface roughness and the leaf area index are the most important factors for the parameterization of land cover. Leaf area index is used to determine canopy cover and interception capabilities, while the surface roughness is used to determine the depression storage (Nunes *et al.*, 2009).

The complexity of hydrological response within a catchment is caused by the defining role that each factor plays and the intervention of each factor with another (Ceballos & Schnabel, 1998). Annual rainfall is not the only factor that influences overland flow - it also depends on the precipitation distribution throughout the year (Ceballos & Schnabel, 1998). Ceballos & Schnabel (1998) also found that there is a strong correlation between actual evapotranspiration and precipitation, as well as discharge and precipitation.

Studies related to the interaction between groundwater and vegetation in South Africa is very limited. Management of natural water resources is seriously affected by these interactions, especially in semi-arid regions (Le Maitre *et al*, 1999). Vegetation has a direct impact on groundwater, firstly by extracting water, secondly through interference as precipitation moves from the atmosphere through the vegetation and soil profile to the water table and finally through the creation of preferential flow paths and tunnels (Le Maitre *et al*, 1999). Vegetation also influences water quantity and quality and thus has an effect on the recharge of aquifers.

This occurs through the uptake of nutrients from the soil and decomposition of plant material (Le Maitre *et al*, 1999).

2.4.1. The Different Effects of Vegetation on Groundwater Recharge

Interception

Interception is described as the process by which precipitation is absorbed/retained on the plant surface, from where it evaporates back into the atmosphere. Vegetation changes will result in interception changes and ultimately groundwater recharge. Different plant species have different interception values which are influenced by their canopy structure, leaf area and the chemical/physical composition of the leaves and bark. The amounts of precipitation that are intercepted depend on rainfall intensity and duration, the surface roughness and area of the plant or litter which intercepts water (Larcher, 1983). Rainfall events with a long duration and high intensity, plants with open canopies and bark that is smooth, will result in low interception values (Le Maitre *et al*, 1999). Interception losses that vary between 15 % and 24 % have been measured in coniferous forests and corresponding plantations where the canopies are dense, leaf area is high and the bark is rough (Calder, 1992).

Stem Flow

Stem flow occurs when the plant's surface area reaches saturation, resulting in water flow from the tree canopy and branches along the stem to the base of the plant. The area around the stem can receive up to 18 times more rainfall (Navar & Ryan, 1990), depending on the mean annual rainfall, with a decrease in spatial heterogeneity as mean annual rainfall increases.

Infiltration and Percolation

Infiltration describes the movement of water from the surface into the soil profile and percolation refers to the process by which water moves through the soil profile to the underlying rock. Vegetation has numerous benefits that improve infiltration. It provides cover through its canopy to protect the soil from compaction caused by raindrops and the organic matters that it produces bind the soil particles as well as increase the soil porosity. Infiltration rates and litter are positively correlated, with infiltration at fully covered soils significantly faster than at bare soils (O'Conner, 1985). Rooting depth also influences infiltration, with a decrease experienced when Eucalypt was replaced by shallow-rooted grass (Sharma *et al*, 1987). Grazing activities increase bulk density, causing a decrease in infiltration rates. All grazing systems have different impacts on the soil and infiltration rate, with early grazing and high intensity systems having the greatest impact.

Several factors have an influence on the percolation process, of which the soil properties that influence hydraulic conditions are most important. Percolation rates are sensitive to pressure head and soil water conditions. Small changes in abovementioned can have a significant impact on the percolation rates. Water distribution in the soil is mostly non-uniform due to heterogeneous soil properties, resulting in unpredictable wetting front. Due to the instability regarding the permeability structure caused by different soil layers and hydraulic properties, flow fingering may occur (Kung, 1990; Selker *et al.*, 1992). Simmers (1990) found that preferred flow paths can exist in homogeneous soils due to unpredicted pathways caused by cracks, plant roots and biological activity (Figure 2.4).

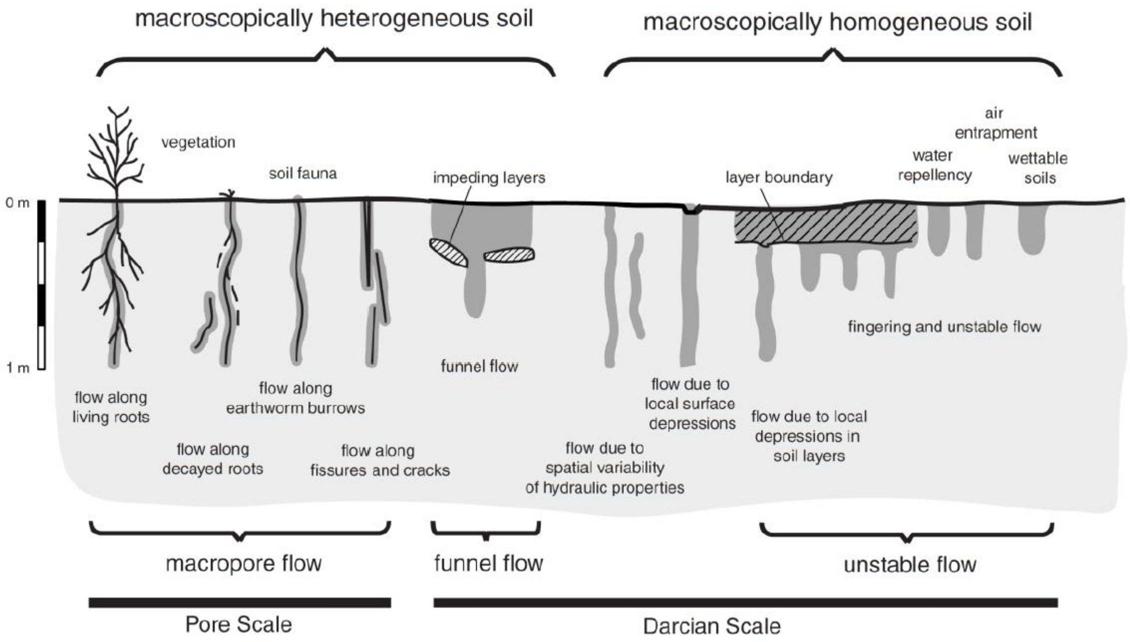

Figure 2.4: Preferential flow paths through homogeneous- and heterogeneous soils (Hendrickx & Flury, 2001).

Root channels as preferential flow paths

Preferential flow contributes significantly to hydrological systems (Schaik *et al*., 2008). Roots aid the flow of water through the soil profile, thus increasing percolation (Figure 2.4). Different plants provide different benefits, depending on their coarseness and depth of their root system. Other mechanisms of preferential flow paths include cracks and other macropores and their importance varies between soils with different textures (Le Maitre *et al.*, 1999).

Root depths, groundwater extraction and soil water

1. Different plant species have different rooting depths and these depths are mainly determined by their water requirements.
2. Root depth is limited by factors such as a water table and soil properties that are not permeable for the roots. Roots have the ability to extract water from great depths, with woody plants having a maximum root depth of 7.0 ± 1.2 m and shrubs 5.1 ± 0.8 m. Plant species in arid and semi-arid regions have a shallow and more spreading root system with a higher water storage capacity within the plant (Le Maitre *et al.*, 1999).
3. Plants decrease recharge and soil water as they transpire, removing water from the soil profile and releasing it as vapour into the atmosphere.

Agricultural activities which include terraces, tillage and contour practices, are instrumental in reducing soil erosion. These practices have a positive effect on water infiltration, since overland flow is reduced and more water is captured, contributing to groundwater recharge (Zhang & Schilling, 2006). Vegetation can have a positive effect through improved infiltration, percolation and storage capacities, but can also be detrimental caused by its interception and transpiration capabilities (Le Maitre *et al.*, 1999).

Concluding the above, it is evident that vegetation and land use changes, and any changes to their composition will have a major influence on groundwater recharge through changes in the interception capacity, overland flow, transpiration and root depth. Vegetation contributes to groundwater quantity and quality levels, thus impacting factors such as salinity.

2.5. HYDROLOGICAL MODELLING

For accurate estimation of future hillslope hydrological conditions and groundwater recharge, accurate forecasting of climatic variables is required and the modelling of their impacts on spatial variation within the landscape is essential (Jyrkama & Sykes, 2007). Hydrological models are used widely in a spread of different fields and have been part of several worldwide studies estimating the impact that climate change will have on groundwater as well as surface water (Jyrkama & Sykes, 2007).

"Hydrological modelling is concerned with the accurate prediction of the partitioning of water among the various pathways of the hydrological cycle" (Doodg, 1992). Hydrological models play an important part in the prediction of future groundwater levels (Arnold *et al.*, 1993) and the construction of hydrological models require critical understanding of the hydrological processes. This understanding will contribute and lead to improved management decisions, especially with regard to climate change and land use (Hughes, 2010).

Modelling of hydrological processes within a hillslope is important due to the fact that all hillslopes can be seen as a mosaic of different smaller hillslopes, although the application of hillslope modelling can be used at hillslope scale (Bronstert & Plate, 1997).

Hydrological models are used to examine the relationship between water resources and climatic conditions. There are a wide variety of processes that can be investigated, including seasonal and annual stream flow variations, groundwater and surface water quality and quantity as well as the timing thereof (Leavesley, 1994). The effect of a change in climate on hydrological conditions can be estimated by evaluating the model outputs as well as changes regarding input data such as temperature and precipitation regimes (Jyrkama & Sykes, 2007).

2.5.1. Models

According to the scheme of each model, models can be classified according to a criteria. The criteria can include the model structure, purpose for use of model, temporal scale, spatial scale and spatial discretion (Leavesley, 1994). One-dimensional models are preferred above two-dimensional models due to parameterisation that can be done with more accuracy and ease. Data requirements within two-dimensional models are also problematic and a limitation on their usefulness (Rassam & Littleboy, 2003). Due to many variables, a physical based approach is required for the estimation of groundwater recharge (Jyrkama & Sykes, 2007).

2.5.2. Point-to-Block Data Representation

The usage of different scales is determined by the required outcome needed and the importance of certain processes at that specific scale (Dumanski *et al.*, 1998). Hillslope hydrology is at a small scale and data is obtained through field measurements (Heuvelink, 1998). As the scale increases, measurement becomes impractical and other data formats such as statistics and soil maps become more important (Groot *et al.,* 1998). According to Webster (2000), the assigning of new classes must be based on the principle that there is substantial lower variance in the class compared to the study area. He also stated that punctual prediction, where a certain point that supports the sample area is measured, is a respected classification tool used to construct spatial classes.

2.5.3. Modelling Issues

Most modelling approaches are based on existing models with certain modifications as are needed to apply them under a wider variety of basin conditions, with the main focus on accounting for climate characteristics and basic knowledge that is not sufficient. Each method has a degree of success with the applicability regarding the methods that have been developed, but there are always a number of assumptions that have to be made as well as limitations regarding the interpretation of the results generated by the model. The most general problems that need to be addressed are the parameter estimation, model validation, scale, climate scenario generation and data (Leavesley, 1994).

The model that is used is determined by the objectives of the study. After determining the objectives, other factors like the scale (temporal and spatial) and possible data constraints influence model choice. The most notorious obstacle faced by water managers and researchers is the scale at which changes in the climate will be experienced. The problem occurs when climatic variances, water resource management and all aspects of the hydrological processes need to be reconciled (Hostetler, 1994). A further obstacle that abounds in the accurate use of climate models, is the simulation accuracy of climatic data in time and space (Lins *et al.*, 1997).

2.5.4. Verification and Validation of Results

Verification and validation are two words used in hydrology to describe the accuracy of modelling predictions compared to observational data (Jyrkama & Sykes, 2007). As the complete validation and verification of numerical models that are used in hydrology and other natural systems cannot be done, the confidence in model outputs and results can be increased (Oreskes *et al.*, 1994).

Sensitivity analysis refers to the process where variations regarding the input parameters on model outputs are evaluated in a systematic process (Lane & Ferreira, 1980; Saltelli, 2000). This is an indication of the effect of different model input parameters on the model outputs. By determining the factor with the greatest impact on model outputs, the factor can be applied with more precision.

Hydrological response can be defined as the understanding of how variability, catchment characteristics and climate interact within a catchment (Carillo *et al.*, 2011). Catchment classification can be done in two ways, firstly by empirically relating catchment characteristics and climate to the hydrological behaviour within the catchment and secondly by using a process-based model, to cross-examine how catchment data and climate interrelate to produce the hydrological response that is observed. The process-based models make use of catchment scale data including topography, vegetation, soil and geomorphological information. The condition parameters use temperature, precipitation and stream flow data (Carillo *et al.*, 2011).

Hydrological modelling has been used at catchment scale to investigate what the impact of changes regarding land use and climate will be on water resources. Sensitivity analyses found that a 10 % decrease in precipitation resulted in a 30 % decrease on a simulated hydrological response of a catchment in south central Ethiopia in tropical Africa and a discharge decrease of 15 % was simulated when an air temperature increase of 1.5 °C was simulated (Legesse *et al.*, 2003)**.**

Hydrological models provide water resource managers and planners with a framework to investigate and conceptualise the relationship that exists between water resources, climate and human activities such as land use and changes that can be expected regarding the use of land (Leavesley, 1994)**.**

2.6. CONCLUSION

Hillslope hydrology is a complex system with a wide variety of different parameters that have an influence on the system. Hillslope hydrology are a reflection of different interacting processes at a small scale that are a reflection of systems that occur at a larger scale. At hillslope scale, climate are the main driving factor behind the soil water consitions on the hillslope, while the soil water conditions can be seen as the interface towards groundwater conditions. Due to this interaction, hillslope hydrology are very significant and important within the hydrological system and in terms of expected changes that may occur due to a change in climate. Currently there are no predictions of the impact that a change of climate will have on groundwater, although it is expected to impact the hydrological system through changes in precipitation patterns and intensities, temperature and evapotranspiration.

This will result in changes in land use patterns and agricultural activities, which will impact on groundwater recharge and salinization. It is therefore necessary that predictions be made to determine the impact of different factors on hillslope hydrology and groundwater recharge.

The impact of climate change will differ around the globe, with Southern Africa and the Mediterranean regions experiencing the greatest impact. Southern Asia and Africa will most likely experience the sharpest pressure increase on regional water resources.

Different factors contribute to the expected changes in hydrological systems, including the climate, land use- and land cover changes, water and salinity. The IPCC stated that there has been an increase in the surface temperature and that it will have a widespread impact on hydrological processes, vegetation patterns, ice sheets, and extreme weather events like droughts and floods. The level of sustainability in the agricultural sector within semi-arid regions is directly linked to the knowledge of water movement in the landscape and quantity and quality changes can be expected. Salinity is a major concern in semi-arid regions and causes a decline in water quality. This will be influenced by future changes in the temperature, soil texture and soil water content.

Estimating future groundwater conditions will enable water management agencies to manage water resources in a more sustainable way. The importance of hydrological models will increase and play a more important role in predicting future hydrological conditions.

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CHAPTER 3 MATERIAL AND METHODS

3.1. INTRODUCTION

All required data was collected during 2011 and 2012. Data collection took place at all the different sites to ensure that all hydrological data at point scale on the hillslope were recorded.

3.1.1. Study Area in the Swartland Region

The study area is situated north of Malmesbury in the Swartland district of the Western Cape province, South Africa (Figure 3.1). This area forms part of the Berg River Catchment (BRC) which covers 9 000 km^2. The Berg River stretches 285km from Franschhoek in a northern direction towards the West Coast where it drains near Laaiplek into the Atlantic Ocean. Granite soils together with the Hottentots Holland Mountains border the area to the east, while sandier soils of the Sandveld border the area to the west (Dietrich *et al*., 2004). The Swartland district is a major agricultural region in the Western Cape and most of the arable area is cultivated. It is also known as the breadbasket of the province, with wheat and canola as the main crops, while lupines and lucerne are planted for grazing.

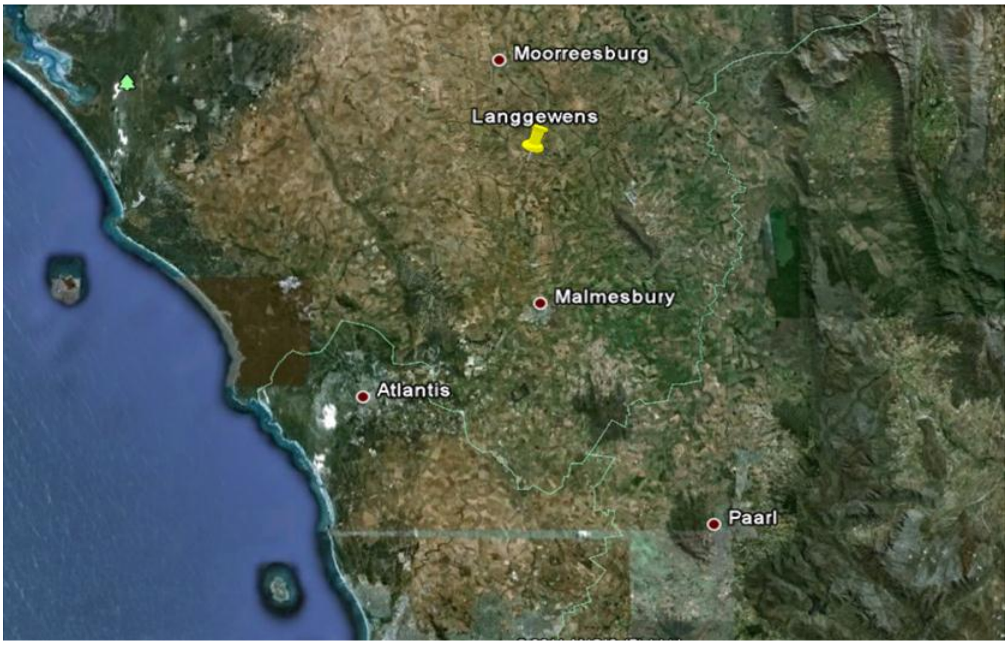

Figure 3.1: Location of Langgewens Experimental Farm, situated between Malmesbury and Moorreesburg in the Swartland region of South Africa.

3.1.2. Climate of the Swartland region

This semi-arid region has a Mediterranean climate and the annual rainfall varies between 250 mm and 600 mm (Boucher and Moll, 1981). The summer months are associated with warm, dry and windy atmospheric conditions, while the winters are cold and wet due to cyclonic cold fronts and orographic rainfall. The Atlantic Ocean to the west and the Indian Ocean to the southeast contribute to the water level in the region (Midgley *et al.*, 2003).

Up to 80 percent of the annual rain falls from April to September. Rainfall distribution is directly linked to altitude, with high altitude areas receiving approximately 700 mm and the lower lying areas receiving about 400 mm (Figure 3.2). Due to the Mediterranean climate, mild temperatures are characteristic of this area (Table 3.1). During the summer, temperatures can rise up to 40°C and in winter the area remains mostly frost free. Wind in winter in this area is seasonal and rarely exceeds 20km/h. During the summer higher wind velocities are experienced, with lowest wind speeds occurring from April to July (Lambrechts, 1998). The climate data are recorded by the ARC long-term weather station on the Langgewens Experimental Farm.

Table 3.1: Long-term climatic data for Langgewens Experimental Farm.

Months	Precipitation	Relative Humidity (%)		Temperature (°C)		Wind speed (m.s^{-1})
		Max	Min	Max	Min	
January	11.3	71.6	24.5	30.7	18.2	2.4
February	10.8	70.4	27.0	31.0	18.6	2.3
March	6.4	71.6	22.4	30.0	16.2	2.3
April	34.6	84.0	26.0	27.8	13.7	2.3
May	55.9	88.9	25.9	23.9	11.2	2.5
June	60.9	90.6	34.8	19.7	9.6	2.8
July	71.4	89.9	36.6	18.4	9.0	2.5
August	68.8	88.8	43.6	18.7	8.9	2.2
September	42.7	84.7	33.8	20.9	10.1	2.0
October	18.6	76.8	25.8	25.3	12.0	2.2
November	23.4	76.1	24.8	28.3	14.1	2.2
December	11.3	72.3	28.1	28.7	17.3	2.3
Total	416.1					
Average	34.7	80.5	29.4	25.3	13.3	2.3

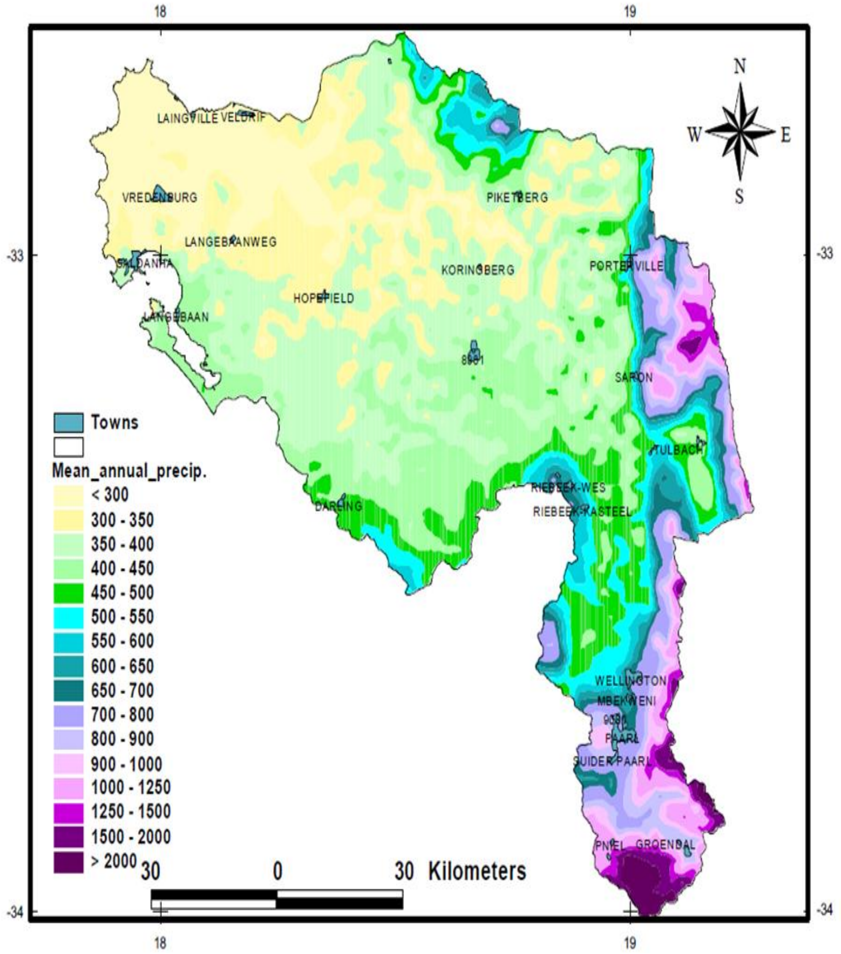

Figure 3.2: Annual precipitation distribution in the BRC area (de Clercq *et al*., 2010).

3.1.3. Geology

On the eastern side, the West Coast forelands are surrounded by the Elandskloof Mountains, consisting primarily of sandstone that forms part of the Table Mountain Group, as well as the Olifants River. On the western side, shale that is overlain with aeolian deposits of sand borders the foreland. Within the West Coast foreland, three terrains are found, namely Tygerberg terrain, Boland terrain and Swartland terrain, with the latter comprising the Berg River, Moorreesburg and Klipplaat Formations (Rozendaal *et al.*, 1999).

The Berg River formation has a complex lithology containing greywacke, chlorite schist, phyllite, cherty limestone lenses as well as quartz schist that is found on top. The Klipplaat formation, consisting of quartz-sericite chlorite schist with interlayers of limestone and phyllite, overlay the Berg River formation (Walton, 2005).

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The Klipheuwel formation is also present in small zones within the area and is made up of mainly sandstone and conglomerates that contain a small concentration of shale bands. This formation is harder than the more common Malmesbury formation (Merryweather, 1965). Sandy brownish soils that develop from the Malmesbury Shale rocks are susceptible to sheet wash and gully erosion (Talbot, 1974). Soils that are derived from shale and granite have relatively high pH-values, are base-saturated and can be seen as fertile soils (Ellis, 1973). Due to the high clay content of these soils, drainage properties and infiltration may be affected (Kruger, 1979).

3.1.4. Vegetation Composition and Distribution

Natural vegetation in the BRC area is under threat due to cultivation for agricultural activities. The natural vegetation that is found in this area is classified by Mucina & Rutherford (2004) as Swartland Shale Renosterveld. This forms part of the Fynbos Biome and falls under Coastal Renosterveld, which at a later stage was classified as West Coast Renosterveld (Low & Rebelo, 1998). This vegetation is inconsistent throughout the catchment and small areas are found where it is still in its natural pristine condition. The four main types of vegetation within the BRC area indicated in Figure 3.3.

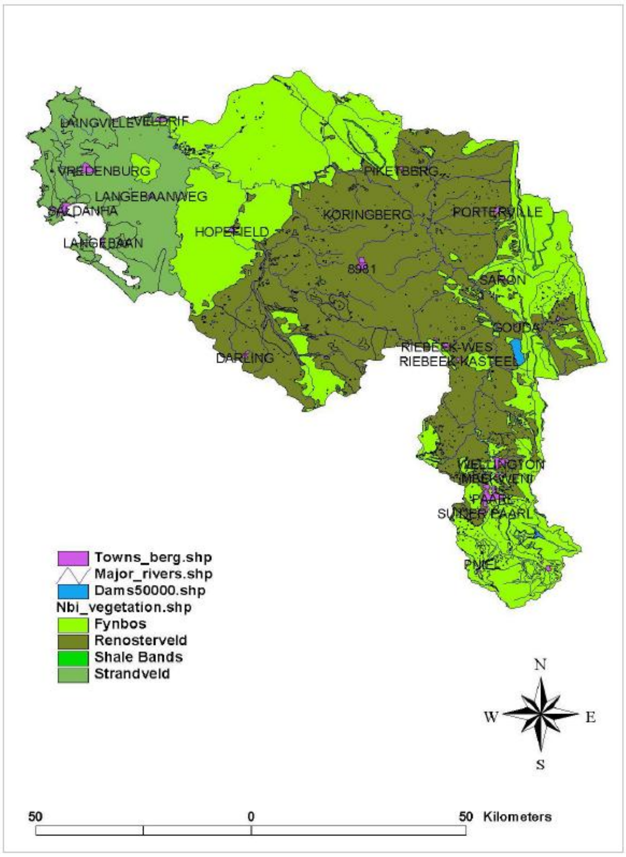

Figure 3.3: Distribution of different vegetation types throughout the Berg River Catchment (BRC) area (de Clercq *et al.*, 2010).

3.1.5. Study Site at the Langgewens Experimental Farm

The research was conducted at the Langgewens Experimental Farm (33° 16' S, 18° 41' 59'' E, Average elevation: 144 m) that is situated north of Malmesbury in the Swartland district of the Western Cape province, South Africa (Figure 3.1). A concave hillslope with a south-western facing aspect was selected on the Langgewens Experimental Farm. The hillslope was selected on the basis of its large heterogeneity with regard to slope, different forms of vegetation, different soil forms/families and land use to form a toposequence and represent the larger BRC area. A toposequence is described as “A number of different soils, occurring down the length of a slope, each with properties attributable to its relative position in the landscape” (Soil Classification Working Group, 1991).

Six profile pits (Figure 3.4 & Table 3.2) were made using an excavator. The position of each profile pit was determined by a series of factors such as elevation, vegetation, management practices, expected soil forms and position within the toposequence with regards to the other profile pits. This was done to obtain the highest possible degree of variation between the different sites. Limiting factors that influenced the depth of each pit included the topography, depth of parent material and the mechanical capability of the digger. Landscape characteristics, specific landmarks and dominant vegetation were used to name the different sites. The six sites are Upper Renosterveld, Lower Renosterveld, Borehole, Next-to-Road, Dam and Saltbush.

Figure 3.4: Selected research sites on the west-facing hillslope at Langgewens Experimental Farm.

3.1.6. Point-to-Block Data Representation

Different source information files were used to expand measurement at data points to create blocks with similar characteristics with regard to landscape (Figure 3.5), vegetation, expected soil patterns and hydrology.

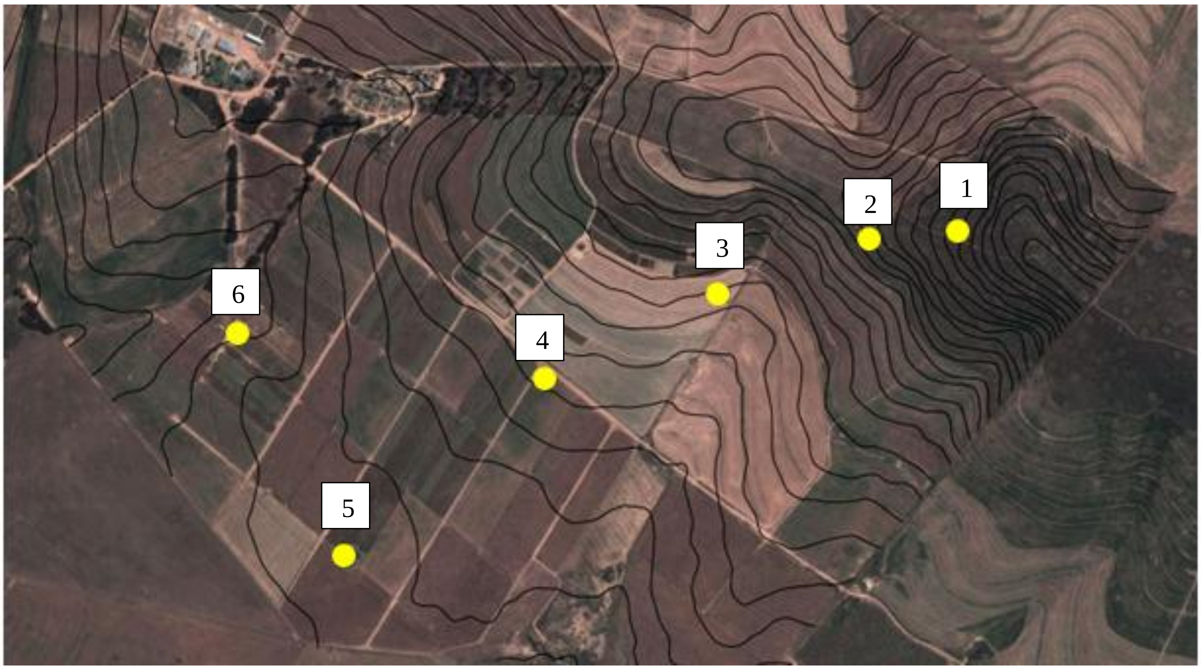

Figure 3.5: Contour map of the studied hillslope at the Langgewens Experimental Farm illustrating the change in slope.

Table 3.2: Numbers, sites names and co-ordinates of the different sites on the hillslope at the Langgewens Experimental farm.

Site Number	1	2	3	4	5	6
Site Name	Upper Renosterveld	Lower Renosterveld	Borehole	Next-to-Road	Dam	Saltbush
Co-ordinates	33°16'48.82"S 18°43'19.66"E	33°16'48.02"S 18°43'12.60"E	33°16'52.68"S 18°42'59.76"E	33°16'58.32"S 18°42'43.94"E	33°17'11.00"S 18°42'26.39"E	33°16'56.57"S 18°42'21.51"E

3.2. SOIL CHARACTERIZATION

Six profile pits were inspected to determine the following soil physical and chemical properties – Munsell colour, soil structure, particle size distribution, bulk density, coarse fragment content, pH, EC, soil form and soil family.

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3.2.1. Material and Methods

Representative soil samples were taken from each profile pit for the different horizons by using a geological hammer. The Munsell colour of each horizon was determined under dry and wet conditions. The soil structure was determined and recorded in the field. Soil samples were dried to acquire physical and chemical properties of each horizon at the different study sites.

3.2.2. Soil Physical Properties

The particle size distribution was determined using Gee & Bauder (1986) method. Organic material was removed from all the samples before further analysis was done. The pipette method was used to determine the silt- and clay fraction (<0.05 mm), while separate sieving was used to determine the sand fraction (2 – 0.05 mm) (Gee & Bauder, 1986). The texture of the soil was then determined by using the texture triangle.

Bulk density was determined for all the soil profile horizons using the excavation method, except at the Next-to-Road site where the *Troxler neutron probe* (*model 3401-B*) was used (Blake & Hartge, 1986). This was due to the profile being described by the Honours 2010 class without recording the bulk density of the profile.

The Gee & Bauder (1986) method was used to determine the coarse fragment distribution in each sample of the different horizons.

3.2.3. Soil Chemical Properties

Soil can be classified into three different classes, depending on their pH value. Alkaline soils have a pH (KCl) > 7, soils with a pH of 7.5 – 5.5 are classified as neutral soils, and acid soils have a pH (KCl) < 5. The soil pH was determined in KCl (1:2.5) and water (1:2.5), according to White (1997), using a *744 pH lab Metrohm Swiss mode* pH meter.

Electrical conductivity (EC) was determined using the 1:2.5 ratios between soil and distilled water. 25ml Distilled water was added to 10g of soil and the EC was measured using a Jenway 4510 Electric Conductivity meter.

3.2.4. Hydrological Monitoring

To interpret the hydrological system along the hillslope, several measurement strategies were put in place to determine the contribution of different factors towards the hydrological system. This included subsurface measurements of gravimetric water content and subsurface flow, as well as surface measurements that include overland flow (Figure 3.6) and infiltration (Figure 3.7).

Gravimetric Water Content

The gravimetric water content was determined after every rainfall event using the oven drying method by Gardner (1986). Soil samples were measured in the field and placed in a drying oven at 105 °C for 48 hours after which they were weighed again.

Overland Flow and Infiltration

Overland flow is calculated using a stainless steel ring with an 80 cm radius and 15 cm height that is connected to a container. Overland flow accumulates in the ring, flowing from the ring through a pipe and into a container from where the amount of overland flow can be calculated (Figure 3.6) (De Clercq 2011, Personal communication).

Figure 3.6: Infiltration is calculated by using the precipitation and overland flow values. Infiltration is the total overland flow subtracted from the total amount of precipitation.

Lateral Water Flow

Each site was monitored throughout the season for free water in each horizon. The occurrence of free water was determined by placing an empty bottle at different depth and closing the hole to prevent surface water from filling the bottle. If there was free water present, the bottle would be filled with water, otherwise it would remain empty.

Figure 3.7: Illustration of hydrological data collection at the Lower Renosterveld site.

3.3. SOIL PHYSICAL AND CHEMICAL CHARACTERISTICS

The results of each site are reported in Appendix 1 and Appendix 2. Although the Upper- and Lower Renosterveld sites had very similar soil characteristics, there were significant differences between the different sites along the hillslope.

3.3.1. Soil Physical Properties

Bulk Density

The bulk density was recorded for modelling purposes, and not for comparisons between different sites. The bulk density varied between 1.30 $g.cm^{-3}$ and 1.87 $g.cm^{-3}$. At all the sites, lower bulk density was recorded in the top horizon, facilitating infiltration into the soil profile. Bulk density contributes significantly towards soil water conditions because of its effect on soil hydraulic properties (Sharda, 1977). The effect of a higher bulk density on soil water conditions can be due to increased water storage capacity as the micropore volume increases and less water becomes available for the plant (Jamison, 1953). As the bulk density of the soil increases, infiltration reduces. Water movement through the soil also decreases with an increase in bulk density. This can be attributed to the reduction in cross-sectional flow as the amount of larger pores is reduced (Sharda, 1977). Tortuosity as a soil property is affected by the bulk density and increases with an increase in bulk density, attributed to an increased contact area per volume of soil (Sharda, 1977). As infiltration through the soil increases, less overland flow occurs, more water is stored in the soil and an increase in deep drainage that contributes to groundwater recharge follows.

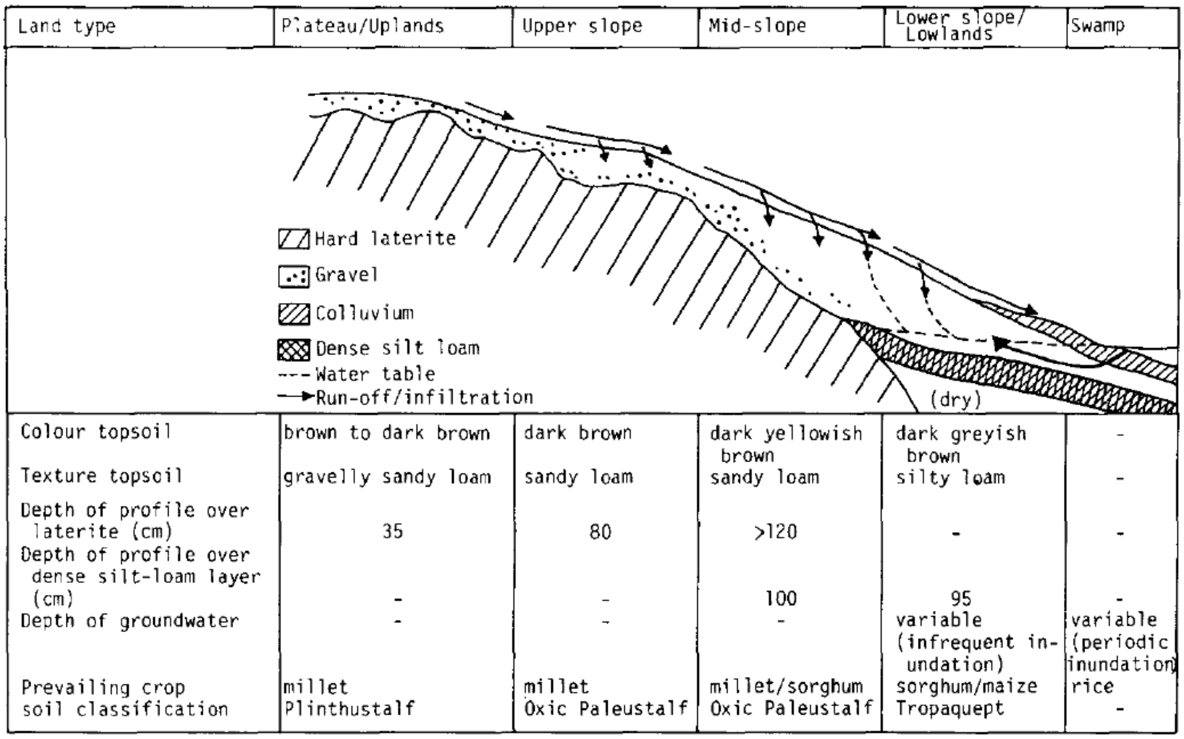
Coarse Fragments

Hydraulic and physical properties are influenced by coarse fragments and this has an effect on infiltration, resulting in soil- and groundwater condition changes (Brakensiek & Rawls, 1994). Coarse fragments in the soil are normally associated with increased infiltration rates, mainly due to more macropores (Rawls, 1996). The coarse fragment content varies greatly within the different profiles as well as between the different sites. At the borehole site, there is a horizon that is transported into the profile with a coarse fragment content of 56.33 %. It is also important to note that the transitions between the horizons are abrupt and will influence infiltration and water movement.

Particle Size Distribution

The effect of soil texture on water retention in soil is much greater than the effect of organic matter (OM) content and bulk density (Vereecken, 1989). The potential of a soil to preserve its water content is directly linked to the texture class of the soil, where soils with a finer texture have greater water retention potential (Pachepsky *et al*., 2006).

The transport and deposit of fine particle soils may occur in areas where a slope is present due to the slope wash action, resulting in the accumulation of soils with a fine texture in the valley region and soils with a more coarse texture at the crest and upper slope region (Figure 3.8). Due to reduced drainage caused by increased clay content in the foot slope and valley floor area, saturated conditions are more likely to occur (Ticehurst, 2007).



Land type	Plateau/Uplands	Upper slope	Mid-slope	Lower slope/ Lowlands	Swamp
Colour topsoil	brown to dark brown	dark brown	dark yellowish brown	dark greyish brown	-
Texture topsoil	gravelly sandy loam	sandy loam	sandy loam	silty loam	-
Depth of profile over laterite (cm)	35	80	>120	-	-
Depth of profile over dense silt-loam layer (cm)	-	-	100	95	-
Depth of groundwater	-	-	-	variable (infrequent inundation)	variable (periodic inundation)
Prevailing crop	millet	millet	millet/sorghum	sorghum/maize	rice
soil classification	Plinthustalf	Oxic Paleustalf	Oxic Paleustalf	Tropaquept	-

Figure 3.8: A schematic representation of the Kamboinse toposequence and corresponding pedological characteristics (Van Staveren & Stoop, 1985)

3.3.2. Soil Chemical Properties

pH

The pH (KCl) varied between 4.04 and 5.91, except at the Saltbush site where the pH (KCl) was between 6.86 and 8.15. These soils were more alkaline than the rest and are found at the lowest area of the toposequence. The high pH in the lowest site of the toposequence can be attributed to the possible accumulation of salts in this area, although analysis should be done to confirm this.

Electrical Conductivity (EC)

Electrical conductivity is influenced by several factors, and increases along the toposequence from top to bottom. There is a substantial difference between the Saltbush site and the rest of the toposequence that may be attributed to the accumulation of salts down the hillslope in this area, also corresponding with the higher pH value.

3.3.3. Soil Morphological Properties

Morphological properties have a substantial influence on soil water conditions. The structure, particle size distribution, the amount as well as nature of clay-sized minerals and organic matter influence water characteristics (Williams *et al*., 1983; Childs, 1940).

Before the classification of each profile pit was done by means of the South African Soil Classification System (Soil Classification Working Group, 1991), the surrounding area was noted according to guidelines by the FAO (2006) in terms of aspect, slope, vegetation and position in the landscape.

Each site has different morphological properties, although some sites correspond in a number of ways due to their position in the landscape. The Upper Renosterveld- and Lower Renosterveld sites are similar in a number of ways. Both are situated in an area where the natural vegetation is Renosterveld and the surface is mostly covered by the vegetation. As the rainy season progressed, more grass was present on the soil surface, influencing infiltration and overland flow. Roots were concentrated mostly in the Orthic A-horizon, with a few present in the Lithocutanic B-horizon.

Within the Borehole site, a horizon is present that will influence the hydrological properties of this area in a significant way. To ensure that the presence of this horizon was not related to the procedure that was followed when the borehole was installed, another profile pit was made 15m up the slope. Both pits had the same composition. Roots were still present beneath the transported horizon in the Pedocutanic B-horizon. The transition between the layers was abrupt and mottles were present in the Pedocutanic B-horizon.

The following site along the hillslope that was selected is situated below the road within the toposequence. Due to the anthropogenic influences on the hydrological system which is related to the road, there are several factors influencing the movement of water along the slope. A gravel road is present between the Borehole site and the Next-to-Road site which has a major influence on water movement. Overland flow from the upper regions of the slope is transported away by a furrow system on the upper side of the road. Precipitation that accumulates on the lower side of the road is also transported away from the cultivated land in which the site is situated. Different soil horizons with distinct morphological properties are present at this site. Both the Pedocutanic B- and Saprolite horizons have a high clay content which influences percolation, lateral flow, overland flow and infiltration.

The Dam site is situated in the lower part of the toposequence and a small depression is present in this area. Water accumulation takes place during the winter season and this is evident through the mottles that are present in the Pedocutanic B- and Saprolite horizons. This is an indication of a variable water level that occurs throughout the year, but mainly during the wet season. The Pedocutanic B-horizon has a fine blocky structure. As this site is near a natural dam, the water level tends to rise up until it nears the surface. This happens mainly during the early part of the wheat growing season, as the water uptake by plants increases as their biomass increases and root systems develop to deeper levels, resulting in a lower water table.

Saltbush has been planted in rows at the Saltbush site, influencing the hydrological conditions. The Orthic A-horizon varies in depth as a result of small ridges that have been made during the establishment of the Saltbush vegetation. This has been done to increase the effective depth, as the underlying Prismacutanic B-horizon has a very strong structure, affecting root depth. An abrupt transition between the Orthic A- and Prismacutanic B-horizon is present, while the Saprolite-horizon contains signs of wetness in the form of mottles. Grazing, which results in compaction of the top soil, contributes to high overland flow and low water infiltration volumes. This affects recharge and salinity in the lower area of the landscape.

3.4. CONCLUSION

Characterizing each site enables research to be done along the hillslope where heterogeneous-soil, vegetation and landscape characteristics exist. The full description of each profile is in appendices 1. As water moves down the hillslope, it encounters different conditions related to the soil, topography, hydrological conditions at certain positions in the landscape as well as different surface conditions.

By investigating the medium through which the water moves down the hillslope, a better understanding of hydrological processes within the landscape can be created. This information can be used to determine the contribution of several different factors towards the hydrological system down the hillslope in the landscape, as well as the impact of changes that have been made.

Thus, by having an accurate understanding of the terrain through which water movement takes place, more significant and improved conclusions can be made with regard to the hydrological processes at certain points in the landscape.

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CHAPTER 4 HILLSLOPE CHARACTERISTICS, THE EFFECT OF WEATHER EVENTS ON HYDROLOGICAL CONDITIONS AND HYDROLOGICAL MODELLING

4.1. GENERAL INTRODUCTION

Hillslope hydrology is a complex system with a wide variety of different parameters that have an influence on the system. Hydrological conductivity within a hillslope is defined as the connection between channels and different areas (Kirkby *et al.,* 2002). The connectivity can be at different scales – between patches, flow from hillslope to main channel and on a large scale between a headwater area and main channels. Within a hillslope, there are several control mechanisms that influence flow processes and factors such as vegetation patterns, microclimate, soil properties and the soil water regime (Bachmair & Weiler, 2012). Bachmair & Weiler (2012) classified these factors into two groups: Static and Dynamic. Static factors include the topography and parent material, while dynamic factors include vegetation and the soil water. Famiglietti *et al.,* (1998) concluded that the soil water dynamics in the upper region affect several hydrological systems at different scales. Precipitation is the driving force behind groundwater recharge and is strongly dependent on the rainfall characteristics namely duration, intensity and temperature.

To enable researchers to understand the movement of water through the soil, which can be through several processes (Nejadhashemi *et al.,* 2011), baseline data must be collected. By knowing through which medium water moves, processes within the medium can be understood and analysed. It is of further importance to determine the different components of water movement through the landscape, as water movement is dependent on the landscape characteristics. Waymira & Gupta (1998) found that the challenge of hydrological processes is contained in the complex interaction between topography, vegetation, soils and variability in the climate.

Climate is the driving factor behind the hydrological system and must be recorded to determine the water input and output in the hydrological system. The physical and chemical properties of the soil have a significant influence on the water movement through the system

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and their properties must be known to be able to determine their influence. Determining the overland flow and presence of lateral flow at different sites along the hillslope enables researchers to track the water movement through the landscape. This can be monitored by determining and cross-referencing the data with the rainfall and soil water content data. The water table is reflected in the depth of the borehole on the hillslope and is an indication of the water level throughout the season.

Monitoring hydrological conditions, including volumetric water content, overland flow, infiltration, lateral water flow and the depth of the water table at two points, empowers us to understand the hydrological system along the hillslope, similar to the illustration by Flügel (1995) in Figure 4.1. Salinity was not investigated during the research, but the graph by Flugel (1995) on a hillslope in the same area is an indication of the seasonal changes with regards to the water table and soil water characteristics.

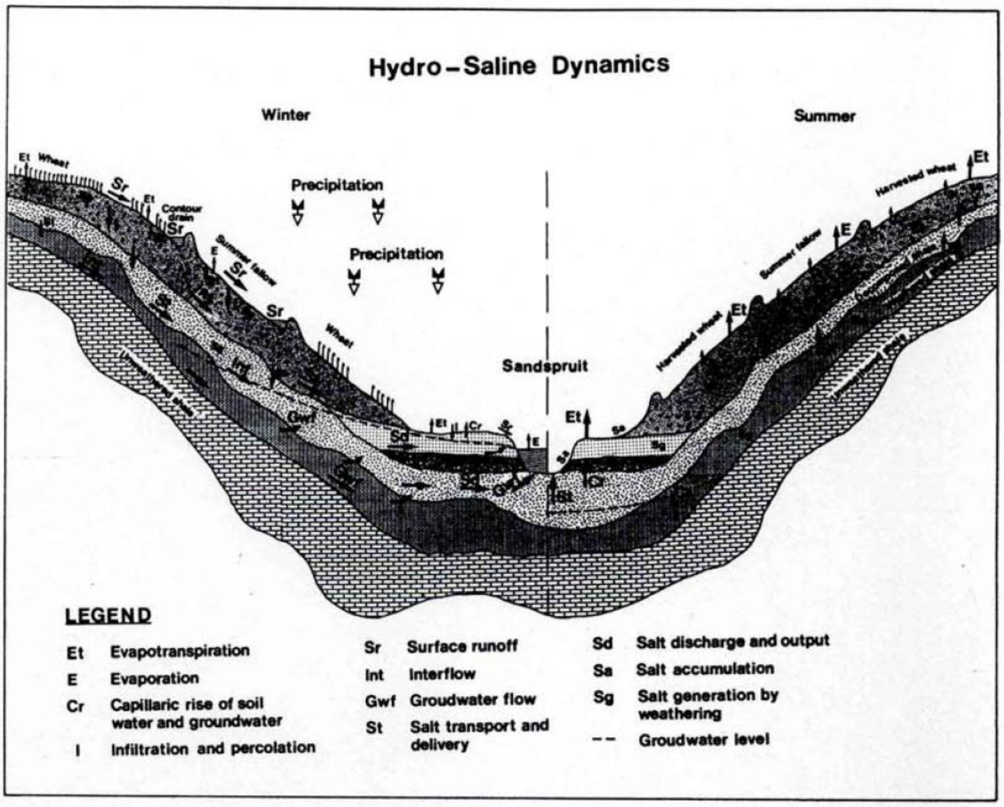

Figure 4.1: Hydrological dynamics within a hillslope in the BRC area (Flügel, 1995).

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4.2. RESULTS AND DISCUSSION

4.2.1. Climate Data at Langgewens Experimental Farm 2011

Several weather stations in the nearby area were used to collect weather data from the region. Each weather station recorded hourly data including temperature (°C), relative humidity (%), sunshine (hours), wind direction, wind speed (m.s^{-1}) and rainfall (mm) (Table 4.1). As the sites were all situated on a slope with a western aspect, there was no rain shadow effect present and thus the different sites received the same amount of precipitation during rainfall events.

Table 4.1: Climate data during the 2011 as measured by an on-site weather station. The data for December is not available due to errors in data recording.

Month	**Precipitation (mm)**	**Relative Humidity (%)**		**Temperature (°C)**		**Windspeed (m.s-1)**
		Max	**Min**	**Max**	**Min**	
January	11.6	95.77	10.2	39.83	14.36	3.64
February	2.8	94.84	11.67	38.49	14.28	3.36
March	9.4	95.64	13	38.88	11.63	3.46
April	33.8	94.66	12.34	35.69	6.28	3.83
May	94.4	95.83	14.68	31.71	6.98	3.44
June	101.6	95.58	28.49	26.77	5.9	3.15
July	29.8	95.61	32.68	24.36	4.66	3.12
August	45.6	94.91	28.85	24.7	3.66	2.97
September	21.6	95.54	13.87	32.82	5.29	2.26
October	15.6	94.88	8.34	35.9	5.95	2.59
November	18.4	96.39	10.73	38.57	7.11	3.42
December	N/A	N/A	N/A	N/A	N/A	N/A
Total	384.6					
Average	34.96	95.42	16.80	33.43	7.83	3.20

4.2.2. Rainfall Data along the Hillslope (2012)

Rainfall data was gathered along the hillslope to ensure that a homogeneous rainfall pattern exists. Rainfall was measured at two sites along the hillslope, in the Renosterveld at the crest and at the Dam site at the bottom of the hillslope. It was found that there is not a major difference in the rainfall at the two sites (Figure 4.2), thus eliminating the effect of a rainfall gradient as a possible reason or different hydrological conditions along the hillslope.

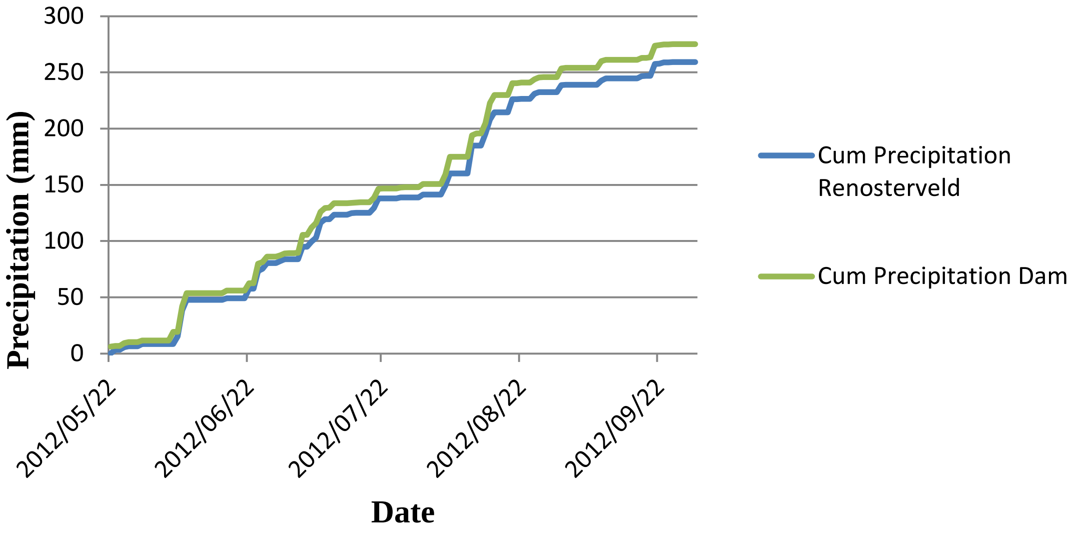

Figure 4.2: Rainfall distribution along the hillslope at the Langgewens Experimental Farm.

4.2.3. Soil Physical and Chemical Properties

Soil properties (Appendix 1 - Appendix 3), landscape characteristics and the hydrological system changes along the hillslope (Figure 4.3), affecting the movement of water. A complex system of intertwined factors contributes to the hydrological changes down the slope, with physical and chemical properties of the soil contributing significantly towards water movement, through the soil profile towards the underlying water table.

In the diagrams, lateral water flow is indicated by red arrows and infiltration and percolation by blue arrows. The arrows are only an indication of where lateral flow and percolation can be expected with regards to the soil properties of each site and the possible limitations for water movement within the profile. This relates to the different soil horizon properties which include soil texture, coarse fragments, organic content and other factors related to the hydrological properties along the hillslope. As the hillslope was investigated at point scale, the net lateral flow at each site was zero, as the lateral flow in and out at this position in the landscape was the same (De Clercq 2012, Personal communication).

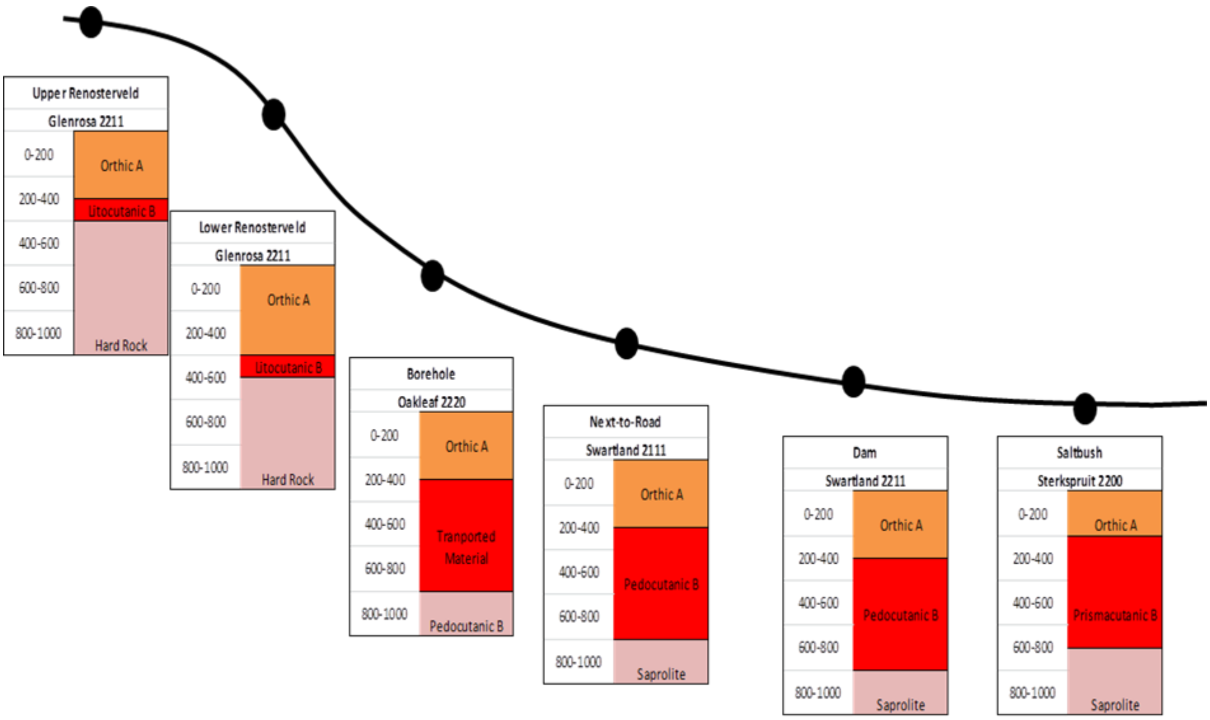

Figure 4.3: Soil profiles along the hillslope at the Langgewens Experimental Farm.

Upper Renosterveld

This site is situated in the natural vegetation type, Renosterveld, near the crest of a hill. It is 279 m above sea level. The soil form is Glenrosa 2211 (Figure 4.4) and it is situated near the crest of the terrain, with a slope of 16 %.

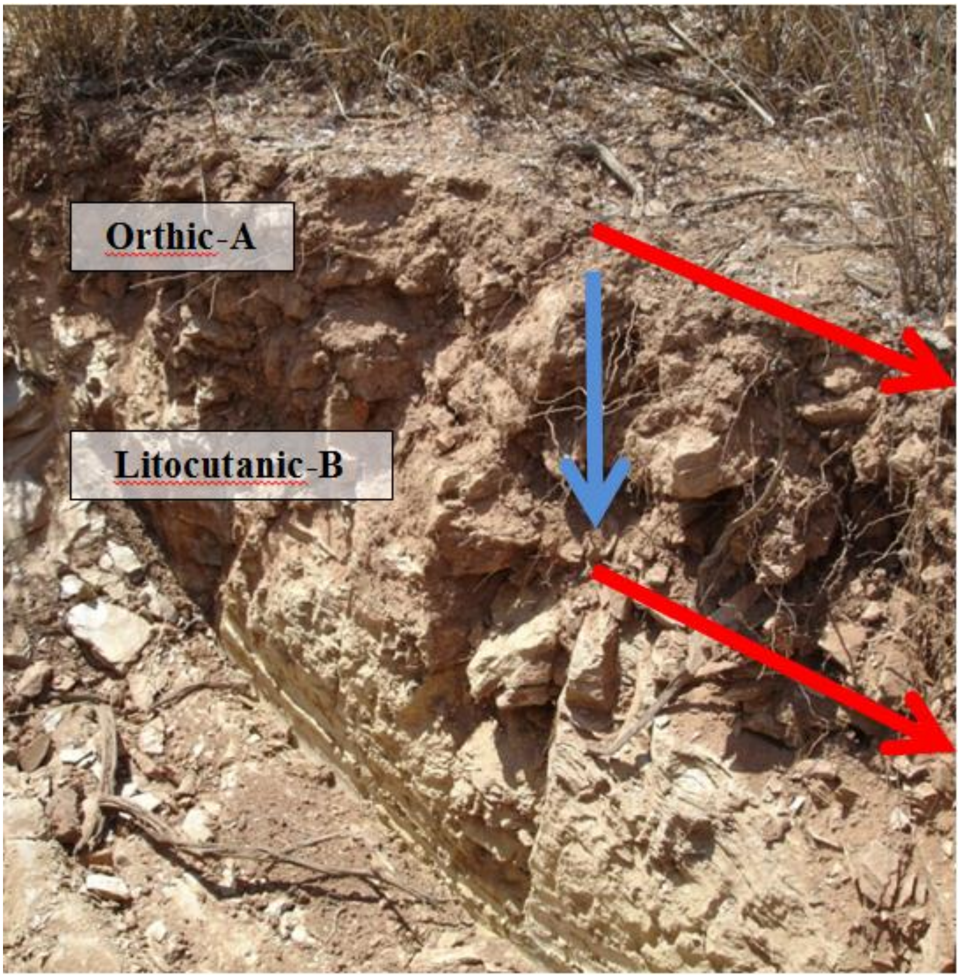

Figure 4.4: Glenrosa soil profile at the Upper Renosterveld site on the Langgewens Experimental Farm.

Lower Renosterveld

This site is situated lower on the slope in the Renosterveld at 247 m above sea level. The soil form is Glenrosa 2211 (Figure 4.5). It is situated on the upper slope with a decline of 12 %.

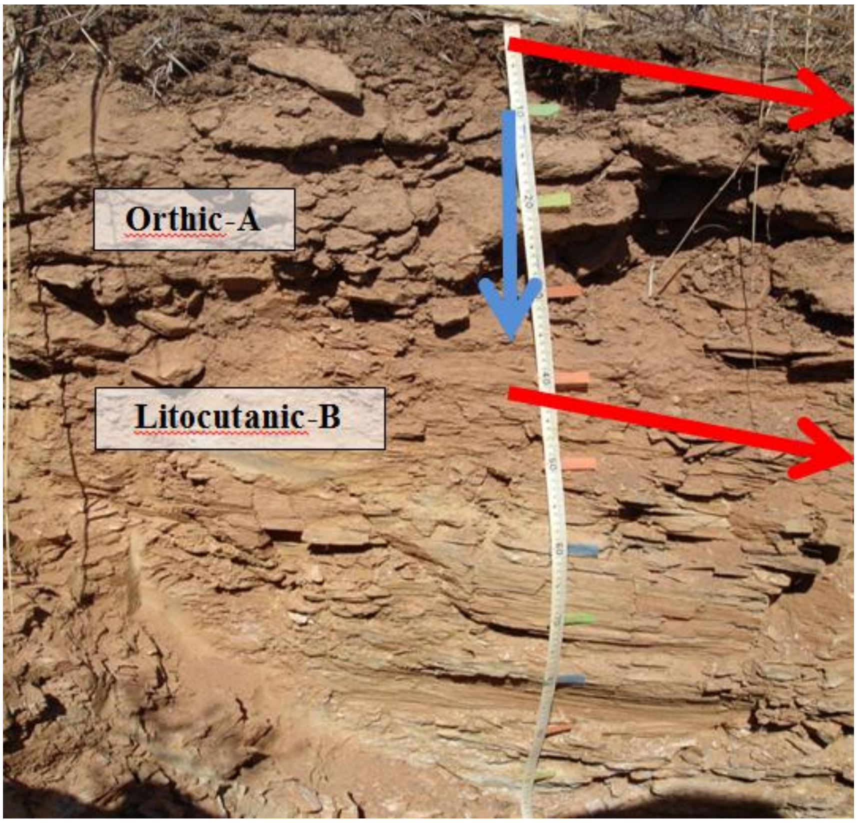

Figure 4.5: Glenrosa soil profile at the Lower Renosterveld site on the Langgewens Experimental Farm.

Borehole

This site is situated at 205 m above sea level in a cultivated land. The soil form is Oakleaf 2220 (Figure 4.6). It is in the mid slope with a gradient of 3-4 %. Crop rotation is prevalent on an annual basis. Grazing of crop residues occur after the harvest.

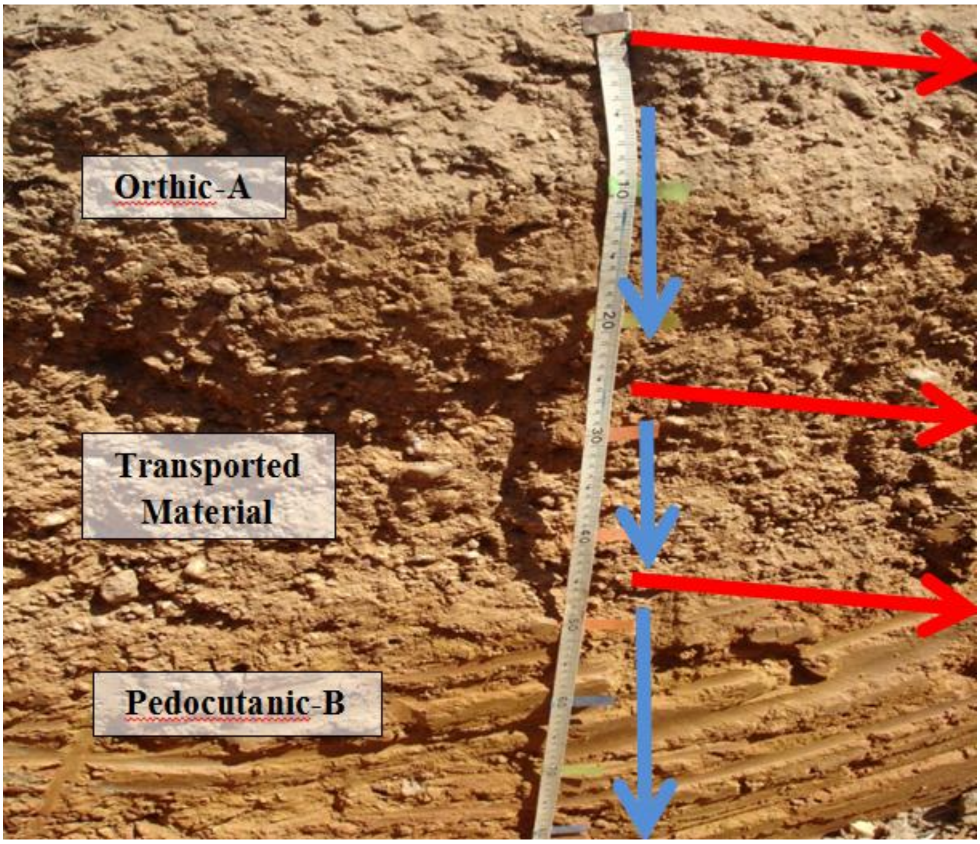

Figure 4.6: Oakleaf soil profile at the Borehole site on the Langgewens Experimental Farm.

Next-to-Road

This site is situated in a cultivated land and groundwater data has been collected at this site in recent years. It is 190 m above sea level. The soil form is Swartland 2111(Figure 4.7) and the slope is 2-3 %.

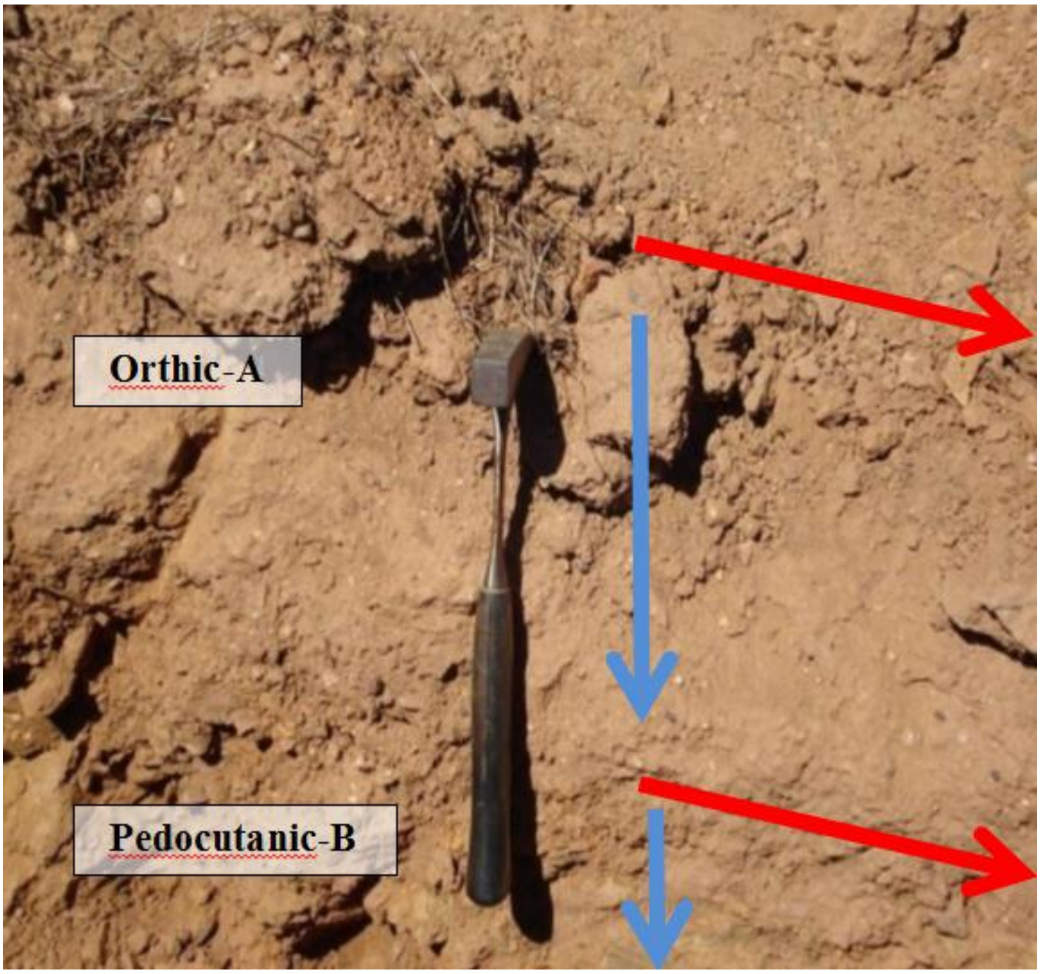

Figure 4.7: Swartland soil profile at the Next-to-Road site (Hons Class, 2010) on the Langgewens Experimental Farm.

Dam

The site is situated 171 m above sea level at the foot slope of the terrain with a gradient of 0-1 %. The soil form is Swartland 2211 (Figure 4.8). A small earth dam is present 15 m away from the site.

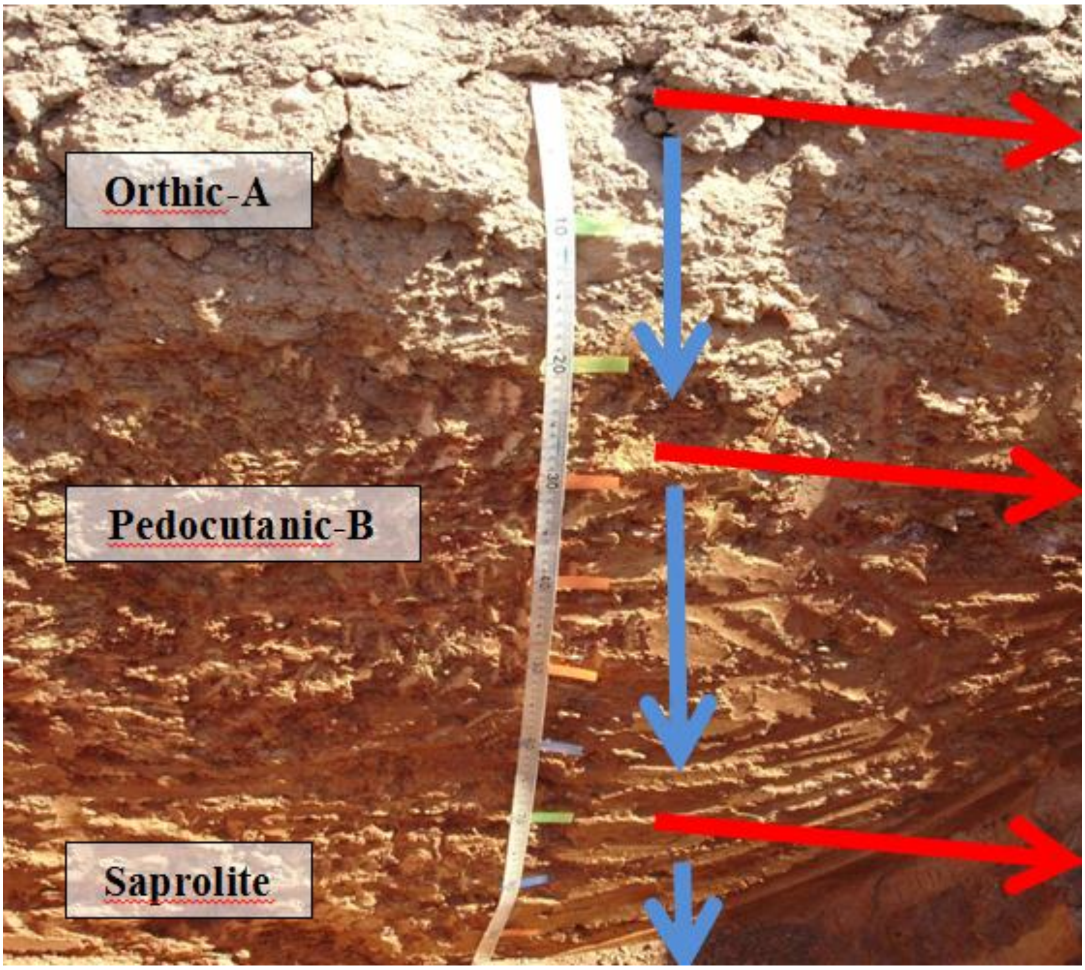

Figure 4.8: Swartland soil profile at the Dam site on the Langgewens Experimental Farm, which is the lowest part of the toposequence.

Saltbush

Saltbush has been planted in this area, which is 167 m above sea level on the mid slope. The gradient is ± 2 %. The soil form is a Rooi Sterkspruit 2200 (Figure 4.9).

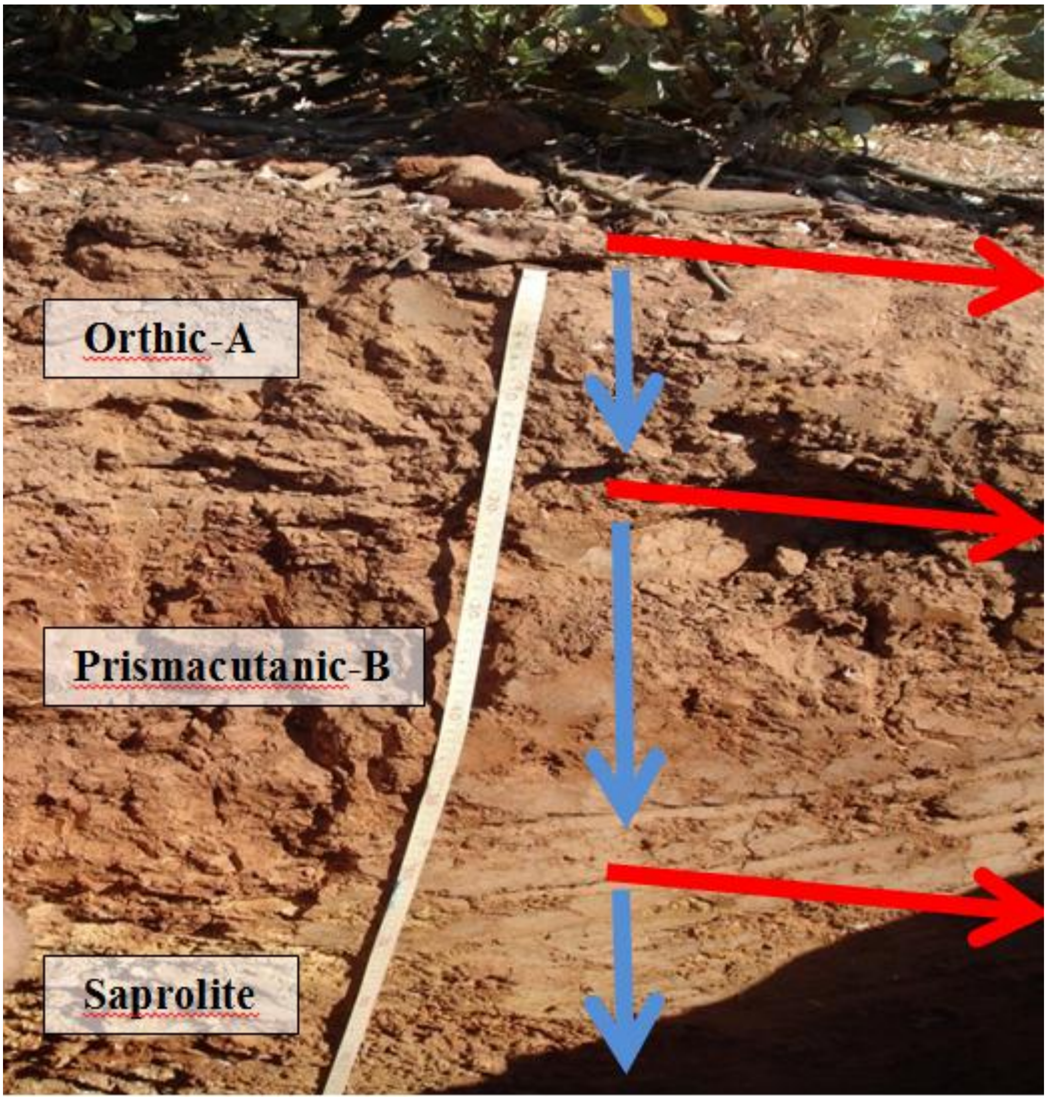

Figure 4.9: Sterkspruit soil profile at the Saltbush site on the Langgewens Experimental Farm.

4.2.4. Soil Water Content Measurements

Variability in soil water dynamics can be attributed to several factors, including meteorological factors, total water content, water table depth, soil properties, vegetation composition and topography (Famiglietti *et al.*, 1998). Interception by vegetation was the only factor not taken into consideration in the hydrological system. Overland flow contributes to less infiltration and lower soil water content. Kirkby *et al.*, (2002) stated that an increase in slope gradient is generally accompanied by an increase in overland flow. This is due to high channel density and low overland flow threshold values. Gravimetric data was collected during the 2011 season with the aim of determining the accuracy of modelling results and to be used as a tool for model calibration, validation and verification. Volumetric water content

(VWC) was determined using Gravimetric water content data and the bulk density of each horizon. Several hydrological models are available to model hydrological conditions and scenarios under different conditions. For the purpose of this study, the Hydrus-1D model was preferred due to the functionality that was required for this study, the availability of the model and the parameterization that can be done at this scale. The Richardson equation is used to simulate soil water content in the model and a model by Feddes *et al.* (1987) to simulate the uptake of water by roots (Simunek *et al.*, 2005). Hydrus-1D expresses water content as water per volume, thus water content is expressed in volumetric units.

Several recent modelling studies with regard to climate-vegetation-soil interactions found correlations between vegetation and groundwater recharge. Studies by Rodriguez-Iturbe *et al.,* (1999), Guswa *et al.,* (2002) and Laio *et al.,* (2001) found that more groundwater recharge occurs under bare soils compared with vegetated soils on the same soil. This can be attributed to the effect of ET and water retention which is greater than evaporation from the surface. VWC measurements as the season progresses confirm this as more water uptake by plants results in less groundwater recharge. This is confirmed by the decrease in soil water content despite precipitation and lower evaporation caused by lower temperatures. As the plant mature, water uptake increase due the root system and higher water demands by the plant. Although the surface conditions change during the season, this phenomenon is present at all the sites. Needelman *et al.,* (2004) found that overland flow within agricultural lands is influenced by management practices which include tillage practices, alterations to natural surface cover and crop rotation systems. Lateral water flow (Table 4.3) measurements correspond with the seasonal changes and the effect of vegetation and the resulting evapotranspiration on groundwater recharge. Although these measurements only confirm if lateral water flow occurred, the number of lateral water flow events decrease as surface conditions change and water uptake by roots increases. After the first rain event and before high evapotranspiration rates by vegetation, percolation results in high groundwater recharge levels. Figure 4.10 - Figure 4.14 and Figure 4.17 illustrates changes in the VWC at different depths at each profile throughout the season, as well as the amount of overland flow and infiltration that occurred. The amount of rainfall in each graph is the sum of the overland flow and infiltration.

Upper Renosterveld

The Upper Renosterveld site is situated within a pristine Renosterveld area where interception by the vegetation has a major influence on infiltration and overland flow.

Overland flow only occurred after major rainfall events in the early part of the rainy season (Figure 4.10).

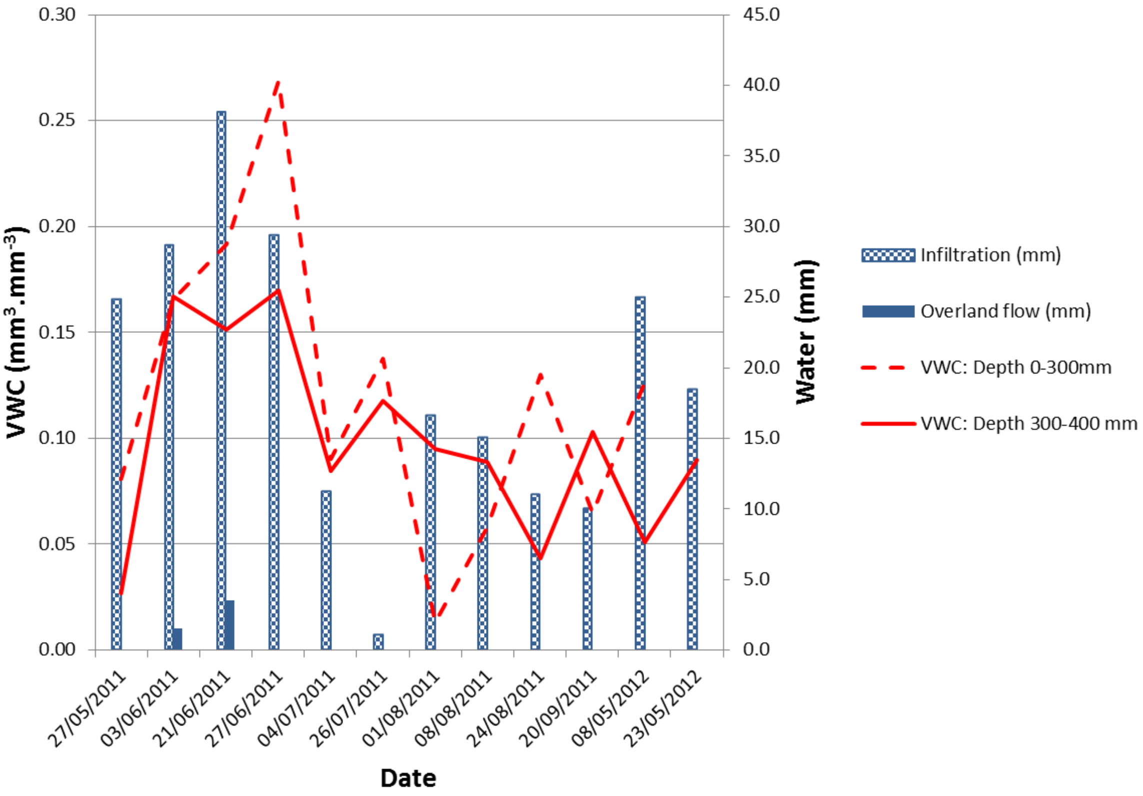

Figure 4.10: Changes in the volumetric water content (VWC), infiltration and overland flow throughout the season at the Upper Renosterveld site.

The Upper Renosterveld site is situated within a pristine Renosterveld area where interception by the vegetation has a major influence on infiltration and overland flow. Overland flow only occurred after major rainfall events in the early part of the rainy season. This explains the increase of vegetation (Figure 4.18) on the surface as more favourable soil water conditions are present for vegetation, which facilitates infiltration and lower overland flow due to interception, less surface compaction by raindrops and lower surface flow rates. Although more infiltration occurs, higher ET results in less groundwater recharge.

Within the top 400 mm of the profile, the clay content (Appendix 2) is relatively low, directly impacting percolation and soil water retention within the profile. Coarse fragment content is high in the 0-150 mm horizon (Appendix 3) and increases significantly in the Lithocutanic B-horizon where it is 99 %. This decreases the soil volume in each horizon significantly and also affects soil water retention. The response with regards to the VWC is greater in the upper soil layer as more infiltration and evapotranspiration takes place, causing greater fluctuations compared to the lower soil layer where the water retention and fluctuations are not as severe. During the dry period in June, a significant decrease in soil water was still present in the upper layer after a rainfall event, indicating percolation to the deeper soil layer where the VWC was higher with less fluctuation.

Lower Renosterveld

Similar to the Upper Renosterveld site, this site is also situated within a pristine Renosterveld area where interception by the vegetation has a major influence on infiltration and overland flow (Figure 4.11).

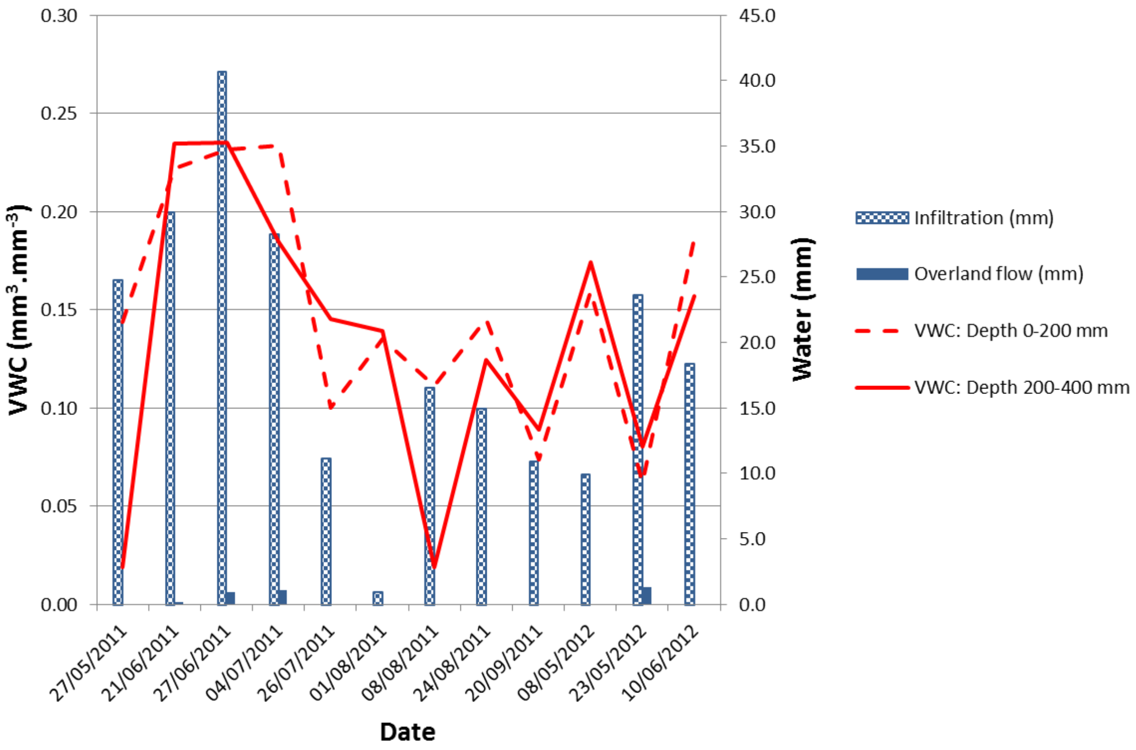

Figure 4.11: Changes in the volumetric water content (VWC), infiltration and overland flow throughout the season at the Lower Renosterveld site.

Although the slope has a lower decline compared to the Upper Renosterveld site, the higher presence of vegetation and grass-like species on the surface contributes to more infiltration and less overland flow. As the vegetation is much denser on this slope, more interception and stem flow occurs, while less surface compaction by raindrops is present. Overland flow only occurred after rainfall events with high precipitation levels, although this can also be attributed to the high VWC content that was present in the soil. This directly affects infiltration as a certain pore volume is already filled with water.

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Changes in the VWC can be directly linked to rainfall events, as well as to the time elapsed between successive events. The soil horizon has a very low clay content of 4.44 %, which directly influences the soil water retention within this layer. During the dry period in July, there was a small increase in VWC in the upper soil layer after a small rainfall event, but a rise in the lower soil layer was not evident, although there was a small plateau at that stage. The rainfall event following the dry period indicates a significant difference between the top and lower soil layer, with limited percolation present, resulting in a very low VWC in the lower soil layer. Although soil properties are the same between the layers, the difference in VWC is mainly due to the impact of vegetation and evaporation in the upper layer, as well as limited percolation.

Borehole

The soil profile at this site is unique due to the presence of an imported alluvial layer with Neocutanic B-horizon properties between the upper Orthic A-horizon and the lower Pedocutanic B-horizon (Figure 4.6). Although the origin is not exactly known, it is strongly suspected that it is transported into this area by water. The horizon has a high coarse fragment content of 56.3 %, greatly impacting the hydrology through the loss of soil volume. A very high clay content of 57.21 % is present in the Pedocutanic B-horizon, causing the accumulation of water in the alluvial horizon.

Cultivation of this land occurs yearly, greatly impacting the hydrological system. As in the Upper- and Lower Renosterveld sites where natural vegetation has a major impact on the overland flow and infiltration, planted crops species and their specific characteristics such as growth season and water use influence the VWC throughout the year (Figure 4.12).

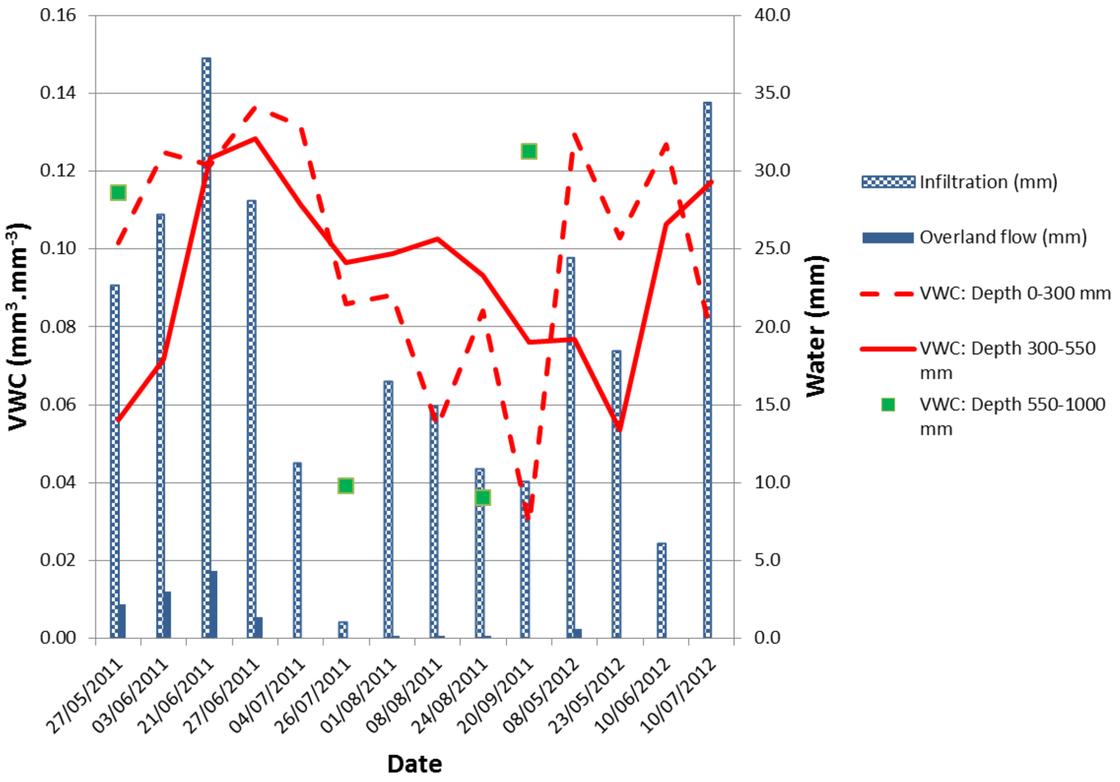

Figure 4.12: Changes in the volumetric water content (VWC), infiltration and overland flow throughout the season at the Borehole site.

Although big rainfall events did not occur in the latter stages of the rainy season, overland flow was only present after big rainfall events and when crops were still in their juvenile growth stage, limiting factors such as interception and stem flow. As the crops grow and their transpiration rates increase, there was a decrease in the VWC over time even though rainfall occurred.

Under the current crop rotation system, the root depth is approximately 200-300 mm. As the crop growth and its water consumption increases, the VWC in the top horizon decreases to below the VWC of the alluvial layer. This can be directly linked to the extraction of water by the crop in the top horizon. Before planting, when minimal water extraction from the soil profile occurred, the VWC in the Pedocutanic B-horizon was approximately the same as during the latter parts of the growing season, when water excretion by crops diminished, leading to higher percolation and resulting in a high VWC within this horizon.

Next-to-Road

Many anthropogenic factors have a strong influence on the hydrological system at this study site. Although the site is below the road, landscape changes above and below the road in the immediate area, where data is collected, influenced the hydrology. A contour that has been created to reduce the amount of overland flow from the slope carries the water away from the site. Another land bank at the lower area of the road prevents water from flowing from the road into the neighbouring land. These changes have a direct impact on the hydrology and must be taken into account when data is interpreted. High volumetric water contents at a depth of 400 – 600 mm are present during the fallow period. This is due to the absence of water extraction from this layer by vegetation and evapotranspiration.

During the early stages of crop growth, overland flow occurs after each rainfall event, but this diminishes as the crops grow and more infiltration occurs due to reduced surface flow, more interception and stem flow. The VWC follows the same trend in the two upper soil layers, with the only main difference during the end of the growing season (Figure 4.13). This can be due to evaporation from the soil surface in the top layer.

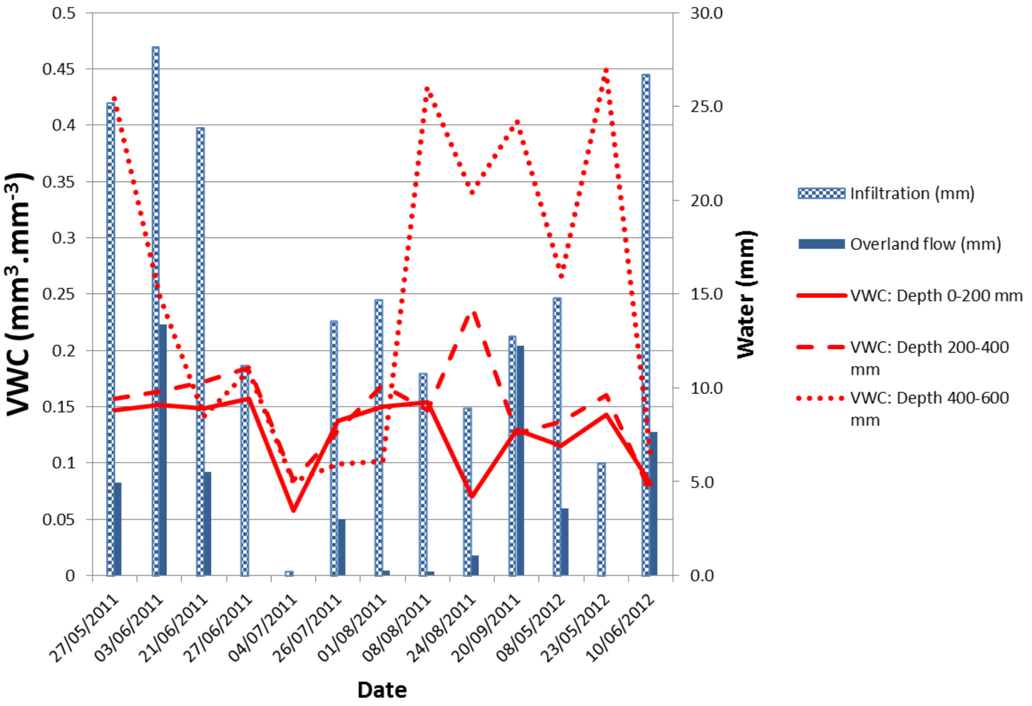

Figure 4.13: Changes in the volumetric water content (VWC), infiltration and overland flow throughout the season next to the road.

Dam

As this site is situated on the foot slope of the hill, water accumulation occurs throughout the wet season. This area is situated in the same region as an earth dam that is filled with water during the rainy season. Higher water contents in the soil at this site can be attributed to the movement of groundwater from the higher areas down into this area. Although there is no major rainfall event during the middle period of the rainy season, an increase occurs in the VWC in the 300-750 mm and 750-1000 mm soil horizon, which is a clear indication of subsurface water flow down the slope (Figure 4.14).

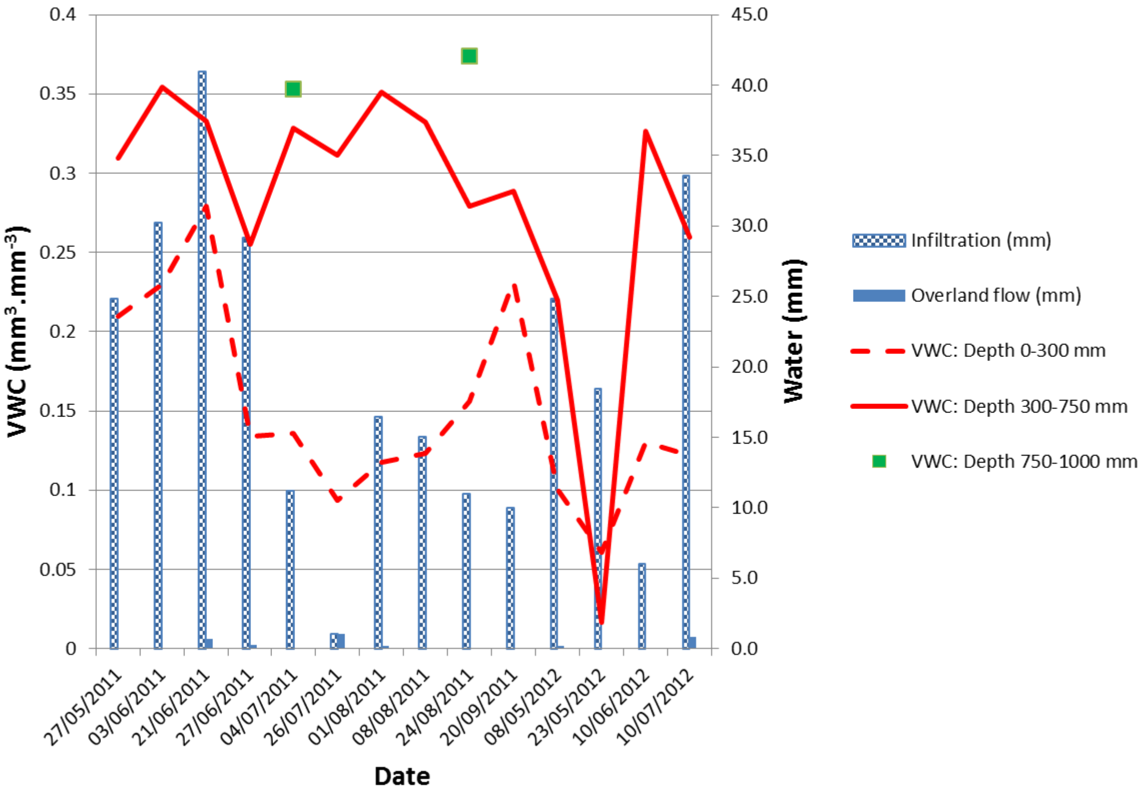

Figure 4.14: Changes in the volumetric water content (VWC), infiltration and overland flow throughout the season at the Dam site.

Very little overland flow and maximum infiltration occurred in this area mainly due to the flat slope and influence of vegetation during the wet season. The overland flow that was measured 25/07/2011 was likely caused by a high intensity rainfall event, with the only other overland flow occurring after a big rainfall event on 21/06/2011.

There is a substantial difference between the VWC at different depths in the soil. Although the VWC within the Orthic A-horizon and Pedocutanic B-horizon corresponds well during the early stages of crop growth, the VWC drops significantly in the upper soil horizon compared to the middle and lower soil horizons. This can be associated with the water uptake by crops, as there is a VWC increase towards the same level as the middle soil horizon as the growth season of the plant ends and less water uptake occurs. Another factor that contributes to the difference in VWC at different depths is the shallow water table. The water table rises through the season and at this specific point in the landscape, which is close to the surface, the water table contribute to the high VWC measurements within the deeper soil layer.

Water accumulation occurs naturally at the valley floor of the hillslope within a depression in the landscape. Figure 4.14 indicates inconsequential overland flow occurring within the footslope area in the landscape, indicating that the presence of water in the dam is as a result of a rising water table. Conductivity levels of more than zero indicate the presence of standing water in the depression (Figure 4.15), as seen during the winter months. A Solinst water level meter was used. This phenomenon is also illustrated in Figure 4.1 by Flügel (1995).

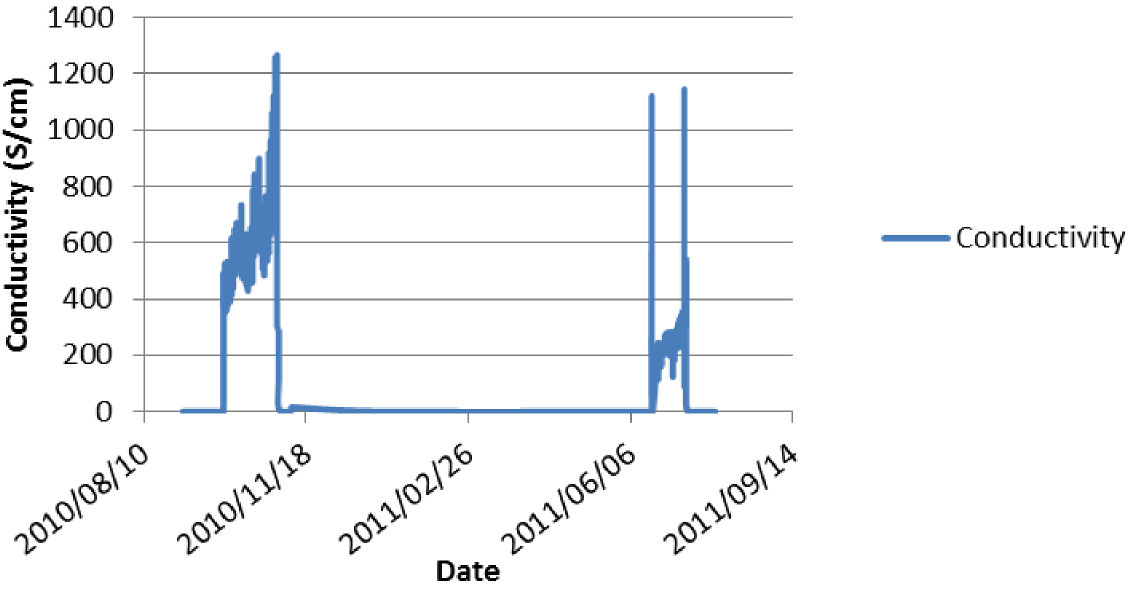

Figure 4.15: Presence of water in the depression indicated by higher than zero conductivity levels and the conductivity of the water.

The Electrical Conductivity (EC) is directly linked to the water level in the dam (Figure 4.16). As the water table rises through the rainy season, the amount of water within the dam changes. This directly influences the EC of the water in the dam. As the water level increases, there is a decrease in the water salinity. The reference level of the surface is at 2 m, thus a water level higher than 2 m indicates the presence of water in the dam.

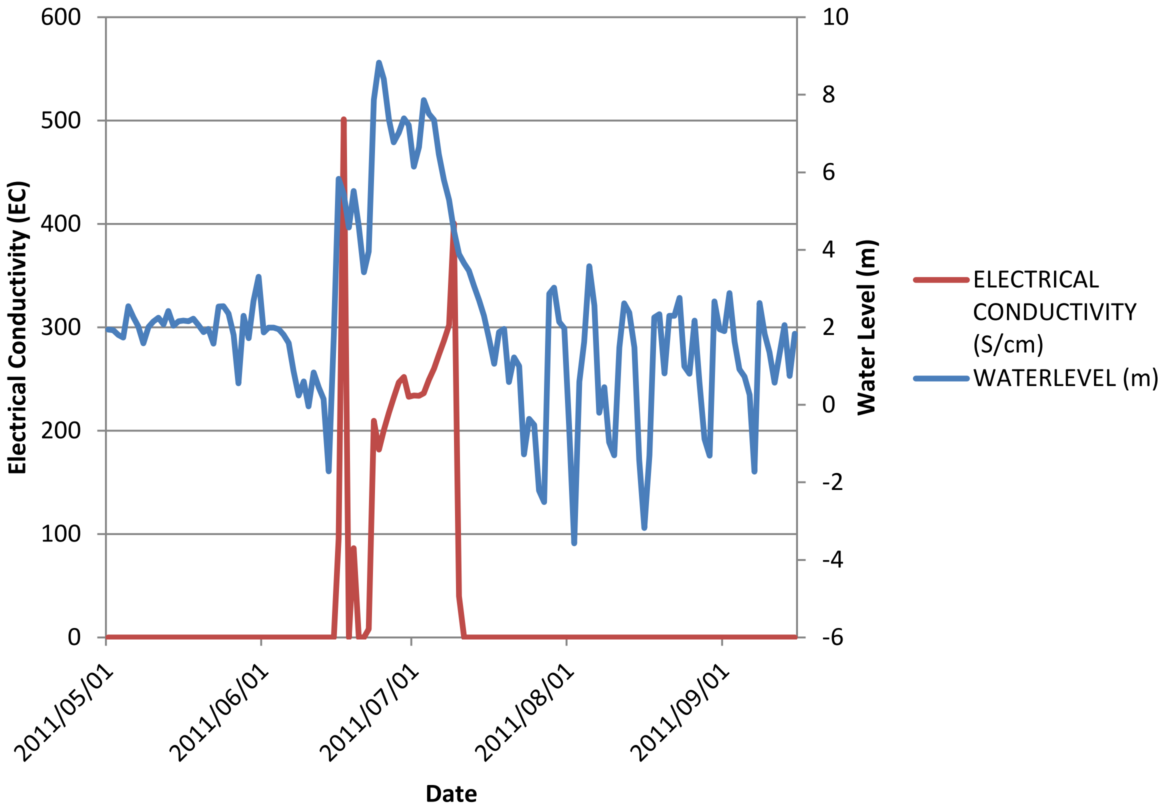

Figure 4.16: The water level and corresponding electrical conductivity (EC) in the dam during the 2011 season.

Saltbush

The vegetation that is present at this study site is Saltbush, which in the past was planted in areas with low agricultural potential due to salinity problems. Chemical analysis of the Electrical Conductivity (Appendix 3) in the different soil horizons indicates the presence of salts in this area. As water accumulates in this region, it is possible that salt movement occurs from the higher areas down into the valley floor, as there is also an increase in the salt content lower down in the soil profile.

Salinity often causes soils to form a crust on the surface that limits infiltration and causes high overland flow rates (Figure 4.17). A crust that is formed on the surface will directly impact on soil water conditions due to lower infiltration rates and higher overland flow that may occur at these soils. As these soils have not been analysed with regard to chemical parameters such as the presence of salts, a statement regarding the impact of certain salts cannot be made. Another factor contributing to the low infiltration rate of the soil is the lack of vegetation between the Saltbush rows. As grazing occurs during the year, the surface is bare and compaction by animals also contributes to the formation of a surface crust.

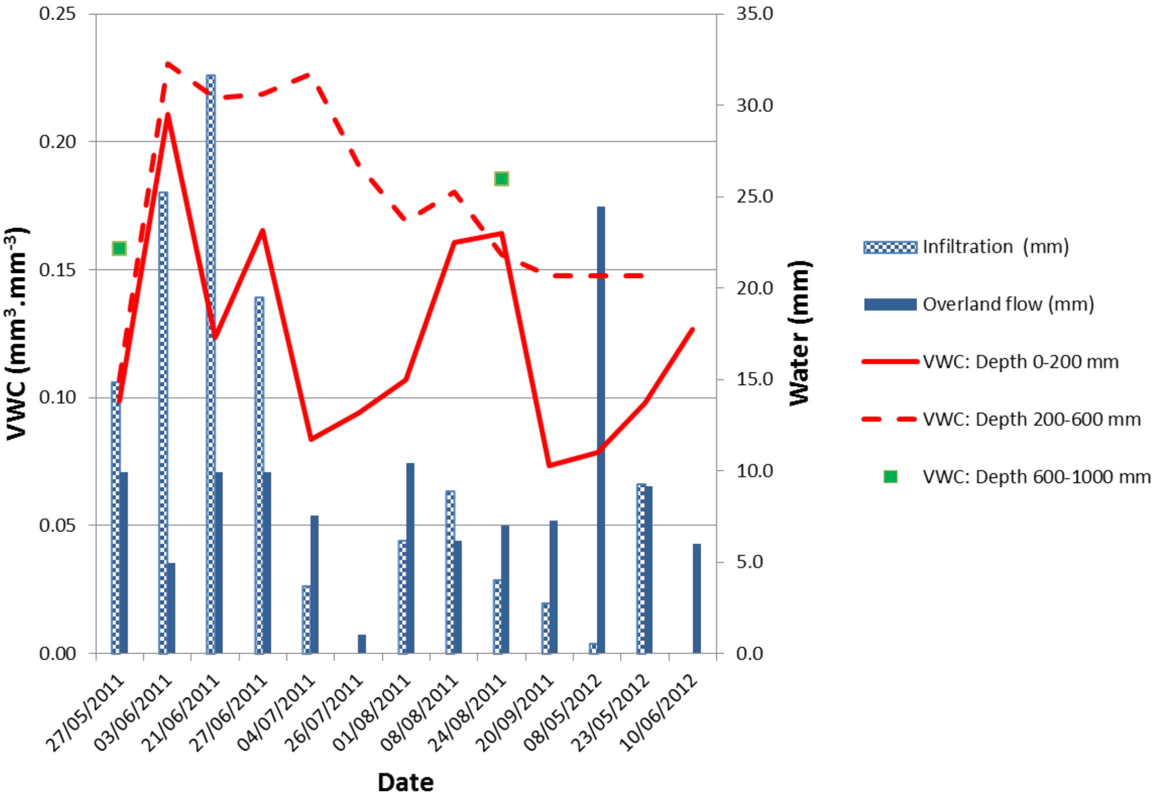

Figure 4.17: Changes in the volumetric water content (VWC), infiltration and overland flow throughout the season at the Saltbush site.

The Prismacutanic B-horizon has a clay content of 51.39 %, resulting in a high water retention capacity. This is reflected after the biggest rainfall event of the year where optimal infiltration occurs. The VWC in the upper soil layer remains relatively constant, with drastic changes in the VWC of the lower soil layer. As the clay content in the Prismacutanic B-horizon is so high, little water movement occurs beneath this layer, resulting in a possible stable VWC in the lower layer, although more data is necessary to confirm it.

4.2.5. Overland Flow along the Hillslope

According to Beven & Kirkby (1979) overland flow occurs due to several major reasons. This happens when maximum infiltration rate is exceeded by rainfall intensity throughout the basin or in areas where saturated soil conditions are present. The presence of overland flow at the difference sites is related to the rainfall intensity and maximum infiltration tempo of the soil (Table 4.2). Overland flow occurs when the rainfall intensity exceeds the infiltration

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capabilities of the soil. Surface cover by vegetation decreases overland flow and increases infiltration due to slower water flow rates over the surface (Figure 4.10 - Figure 4.14 and Figure 4.17).

As studies by Rodriguez-Iturbe *et al.*, (1999), Guswa *et al*., (2002) and Laio *et al*., (2001) found, overland flow is effected by vegetation and has a ripple effect on groundwater recharge as it displaces water from one point on the surface to another lower lying area. Seasonal increases in the leaf area index affect overland flow in several different ways. Interception increases in correlation with vegetation cover (Larcher, 1983), resulting in less overland flow. Infiltration and percolation are significantly higher in areas with greater vegetation cover compared to bare soils (O'Conner, 1985) with root channels as preferential flow paths accelerating infiltration rates (Le Maitre *et al.*, 1999). This greatly influences the hydrology down the hillslope as water concentrates at certain points. All of the above factors contribute to the decrease in overland flow volumes as the growth season of different vegetation types and crops progresses.

The hydrological changes due to vegetation changes also corresponds with the studies by Rodriguez-Iturbe *et al*., (1999), Guswa *et al.*, (2002) and Laio *et al.*, (2001), who concluded that surface overland flow, lateral water flow and soil water are strongly related.

Figure 4.18: Seasonal changes in vegetation cover at the Upper Renosterveld site (21/06/2011;26/07/2011;20/09/2011).

Table 4.2: Rainfall, infiltration and overland flow data from different sites.

Date		Upper-Renosterveld		Lower-Renosterveld		Borehole		Next-To-Road		Dam		Saltbush	
	Rainfall	Infiltration	Overland flow	Infiltration	Overland flow	Infiltration	Overland flow	Infiltration	Overland flow	Infiltration	Overland flow	Infiltration	Overland flow
26/05/2011	24.8	24.8	0.0	24.8	0.0	22.6	2.2	21.1	3.7	24.8	0.0	14.9	9.9
02/06/2011	30.2	28.7	1.5	30.0	0.2	27.2	3.0	25.2	5.0	30.2	0.0	25.2	5.0
21/06/2011	41.6	38.1	3.5	40.7	0.9	37.3	4.3	28.2	13.4	40.9	0.7	31.7	9.9
27/06/2011	29.4	29.4	0.0	28.3	1.1	28.0	1.4	23.9	5.5	29.2	0.2	19.5	9.9
03/07/2011	11.2	11.2	0.0	11.2	0.0	11.2	0.0	11.2	0.0	11.2	0.0	3.7	7.5
25/07/2011	1.0	1.0	0.0	1.0	0.0	1.0	0.0	0.2	0.0	1.0	1.0	0.0	1.0
01/08/2011	16.6	16.6	0.0	16.6	0.0	16.4	0.2	13.6	3.0	16.4	0.2	6.2	10.4
07/08/2011	15.0	15.0	0.0	15.0	0.0	14.8	0.2	14.7	0.3	15.0	0.0	8.9	6.1
24/08/2011	11.0	11.0	0.0	11.0	0.0	10.8	0.2	10.8	0.2	11.0	0.0	4.0	7.0
29/09/2011	10.0	10.0	0.0	10.0	0.0	10.0	0.0	8.9	1.1	10.0	0.0	2.7	7.3

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4.2.6. Lateral Water Flow

Lateral flow, also known as subsurface flow, is complex with high variability within a small scale area (Bachmair & Weiler, 2012). Soil properties that are related to the response of subsurface flow within a hillslope include hydraulic conductivity, infiltration capacity, preferential flow paths, unsaturated zone volume, water content and porosity (Weiler & Naef, 2003; Weiler & McDonnell, 2004; Anderson *et al.*, 2009). Numerous studies, including Jones (1997) and Kienzler & Naef (2008), found that a large segment of subsurface flow that occurs on a hillslope can be attributed to preferential flow paths. Lateral flow occurred only on a few separate occasions throughout the rainy season (Table 4.3 and Table 4.4). The position of the site within the hillslope is of critical importance as lateral water flow only occurred on the lower parts of the slope. This can be ascribed to several factors, which include the following:

- Amount of overland flow is low due to low slope gradient which promotes infiltration and ultimately leads to percolation
- Accumulation of water from higher positions in the landscape
- Slower movement of water due to lower gravity potential with regard to slope
- Soil profiles that contain horizons with high clay contents, causing accumulation at lower boundary of the specific horizon.

Only the presence of free water was determined at each site. This was done as each site was seen as a stable system, meaning the same amount of water moves into the profile through lateral flow as moves out at the same time. As the hillslope was studied at different elevation points and not as a unit, the lateral flow was not measured, but only the presence of lateral flow after different rainfall events was recorded. Table 4.3 and Table 4.4 indicate changes in the number of lateral water flow events during the season.

The presence of free water occurred mostly at the Dam site (Table 4.4). This is a natural spatial accumulation point for water down the hillslope (Figure 4.19). Surface conditions have a great impact on subsurface hydrological conditions. As found by Rodriguez-Iturbe *et al*., (1999), surface cover and corresponding microclimate conditions on the surface and underlying subsurface directly influence lateral water flow. Supported by Table 4.3 and Table 4.4, it is evident that the existence of lateral water flow decreases as the growth season advances. This is due to higher water use by plants and less percolation through the soil profile.

Table 4.3: Presence of lateral water flow through the season at the Upper- and Lower Renosterveld and Borehole sites.

Site	Date	Upper Renosterveld			Lower Renosterveld			Borehole		
Depth (cm)		**10**	**20**	**30**	**20**	**30**	**45**	**25**	**55**	**80**
Date of Water (1 = water present 0 = no water)	2011/06/03	0	0	0	0	0	0	1	0	0
	2011/06/21	0	0	0	0	0	0	0	0	0
	2011/06/27	0	0	0	0	0	0	0	0	0
	2011/07/04	0	0	0	0	0	0	0	0	0
	2011/07/26	0	0	0	0	0	0	0	0	0
	2011/08/01	0	0	0	0	0	0	0	0	0
	2011/08/08	0	0	0	0	0	0	0	0	0
	2011/08/24	0	0	0	0	0	0	0	0	0
	2011/09/20	0	0	0	0	0	0	0	0	0
	2011/10/20	0	0	0	0	0	0	0	0	0
	2011/11/17	0	0	0	0	0	0	0	0	0
	2012/01/17	0	0	0	0	0	0	0	0	0
	2012/05/02	0	0	0	0	0	0	1	0	0
	2012/05/08	0	0	0	0	0	0	0	0	0
	2012/05/23	0	0	0	0	0	0	0	0	0

Table 4.4: Presence of lateral water flow through the season at the Next-to-Road, Dam and Saltbush sites.

Site		**Next-to-Road**			**Dam**			**Saltbush**		
Depth(cm)		**20**	**40**	**55**	**30**	**55**	**90**	**20**	**45**	**80**
Date of Water (1 = water present 0 = no water)	**2011/06/03**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**
	2011/06/21	**0**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**0**
	2011/06/27	**0**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**0**
	2011/07/04	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**
	2011/07/26	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	2011/08/01	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**
	2011/08/08	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	2011/08/24	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	2011/09/20	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	2011/10/20	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	2011/11/17	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	2012/01/17	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	2012/05/02	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**
	2012/05/08	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	2012/05/23	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Figure 4.19: Presence of free water at the different depths at the Dam site correlates with the high water level of the water in the earth dam on 04/07/2011.

Lateral water flow accumulation, also known as free water, was still present at the Dam site when data was collected on the 04/07/2011 (Figure 4.19). As this site is on the foot slope of the terrain, free standing surface water was observed within the observation system for lateral water flow. This is an indication that the water level was near the surface during this time and correlates with the high water level of the dam.

Flügel (1995) illustrated the upward movement of a water table during the wet season in Figure 4.1. Overland flow is not the most significant factor contributing to water in the dam. This is confirmed by Figure 4.14 where overland flow only occurred once during the wet season, eliminating the contribution of overland flow towards water in the dam. A rising water table, similar to the illustration by Flügel (1995) in Figure 4.1, leads to surface water at the dam. Another confirmation of this theory is the presence of free water in holes used to monitor lateral water flow. Free water is directly linked to the water table depth and vanished as the season progressed and more water uptake by growing crops occurred.

A recent study by Bachmair and Weiler (2012) indicated that spatial variability in subsurface flow is mainly attributed to topography and the corresponding soil properties. The study also found that vegetation played a negligible role and that the dominant controlling factor of subsurface flow within a hillslope is topography (e.g. Hopp & McDonnel, 2009; Bogaart & Troch, 2006).

4.2.7. Borehole Monitoring and Water Table Fluctuations

An integral part of groundwater and hydrological system investigation is the importance of a water table and its characteristics (Gillham, 1984). The importance of the water table is associated with the effect on groundwater flow rate and direction, as it is also an indication of the upper level with regard to saturated hydrological conditions in the soil.

Yeh & Eltahir (2005) indicated that more uniform and steady soil water conditions exist where the water table is deep and its effect on the water regime is negligible. The nearer the water table is to the surface, the greater its effect on the soil water regime. The water table has a significant effect on drainage, overland flow, evapotranspiration and infiltration, with its biggest effect in the vadose zone's lower section.

The water level within the borehole is a more accurate reflection of groundwater movement through the toposequence down the slope and is important in hydrological studies (Gillham, 1984). This is a reflection of the upper boundary of the water table (Figure 4.20) and Meyboom (1967) found that shallow water tables, as in this area, often have disproportionate responses to rainfall events. Barlow *et al.,* (2000) stated that a capillary fringe that is near the surface will result in a sudden rise in the water table if water is added to the system. Disproportionate rises in relation to rainfall have been noted in this study area where a shallow water table is present, and confirm the findings by Meyboom (1967). As the first two rainfall events did not contribute to a rise in the water table, a third rainfall event caused a significant increase in the depth of the water table.

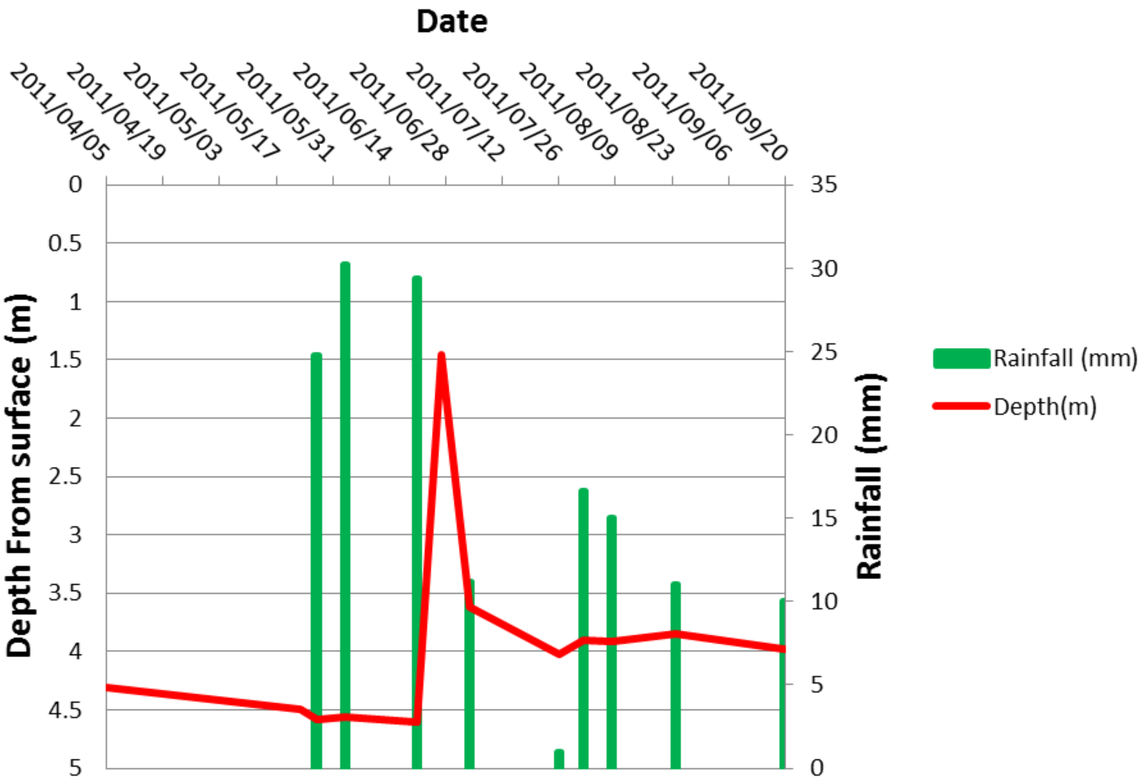

Figure 4.20: Changes in water level of the borehole after rainfall events, with a significant rise after several rainfall events.

Before the first rains of the season the water level drops at a constant rate after which it remains constant until the third rain event. At this point the water level rises significantly and this can be attributed to lateral water flow down the hillslope. Rosenberry & Winter (1997) also found that a rapid rise in a water table can be attributed to the capillary fringe that is present in the soil. After a dry period during the middle part of the winter, the water level fluctuations correlate with rainfall.

Mottles that are present in the soil can be a result of different processes, including inter alia wetness, biological activity and weathering of rocks under well drained conditions (Soil Classification Working Group, 1991). As measurements of the water table depth and presence of water at the Dam site indicate the inter alia movement of water, mottles that are present at the Borehole and Dam sites can be attributed to the change in hydrological conditions.

As the water level in the borehole is a direct reflection of the water table’s upper boundary, it provides useful information with regard to changes and the correlation in the depth of the water table and precipitation events.

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4.2.8. Point Scale Hydrological Units

Many factors contributed to the hydrological response on this hillslope at the Langgewens experimental farm. Areas with similar hydrological properties are grouped together as units, also known as hydrological response units (HRU). Hydrological response units (HRUs) are sub basin elements that are grouped together in terms of their specific hydrological characteristics (Leavesley & Stannard, 1990). Dooge (1986) stated that HRUs integrate uniting concepts with regard to the hydrological cycle and that these regions respond uniformly to meteorological events.

Effective HRUs can be defined by using dominant controlling factors in the hydrological system. According to Devito *et al.*, (2005) there are five factors that have an influence on each other on a different scale within the hydrological cycle and must be considered when defining HRUs. This includes the climate, bedrock geology, surficial geology, soil type and soil depth and the topography and correlating drainage network. Computational limitations and data availability limits the usage of accurate HRUs (Kouwen *et al.*,1993).

Slope and aspect are two of the major components that contribute to the variation in soil forms on a slope. As seen in Figure 4.21 and Figure 4.22, the different sites along the profile represent a wide variety of different aspect and slope combinations. It can therefore be used as a representation of the different hillslope hydrological units. Figure 4.21 and Figure 4.22 confirms the heterogeneity regarding the difference in terms of hydrological responses on a hillslope. These images do not represent HRU maps, it is only an indication of the differences along the hillslope related to the relevance of the measured positions and the area they represent.

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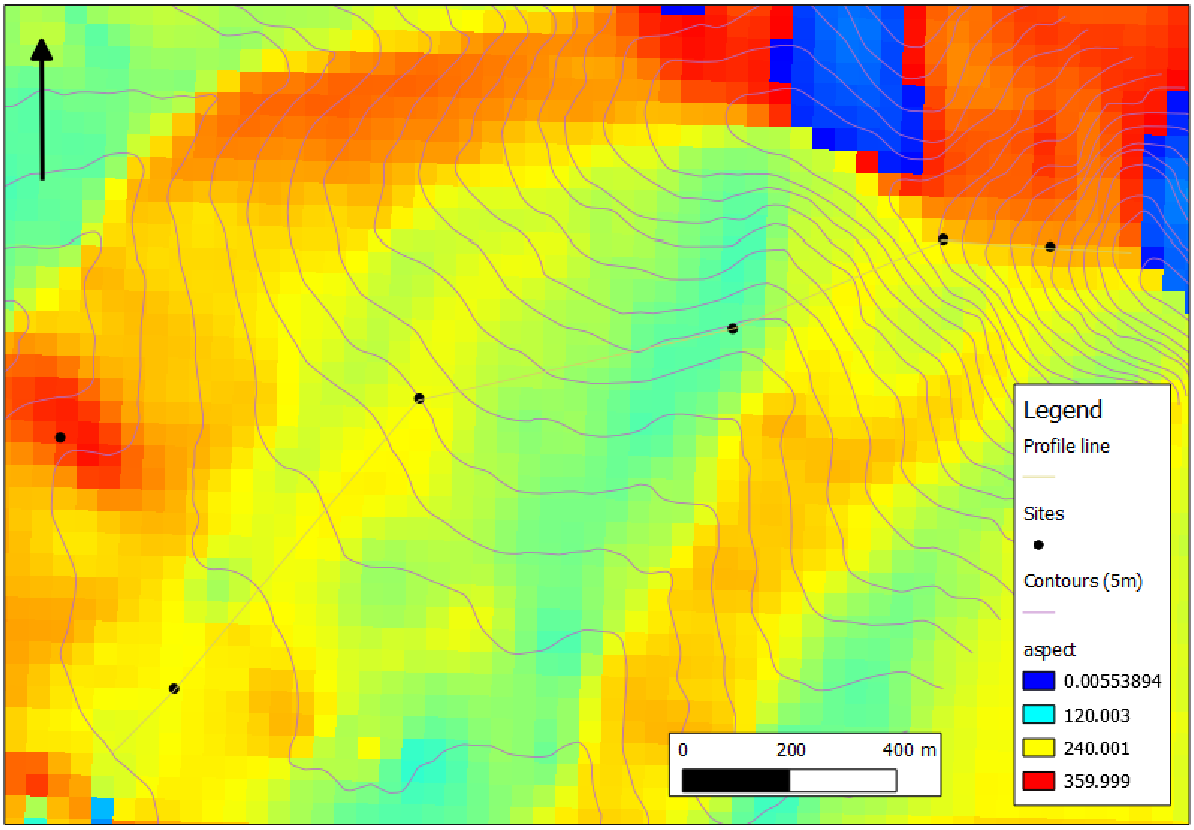

Figure 4.21: Aspect map of the study area on the Langgewens Experimental Farm.

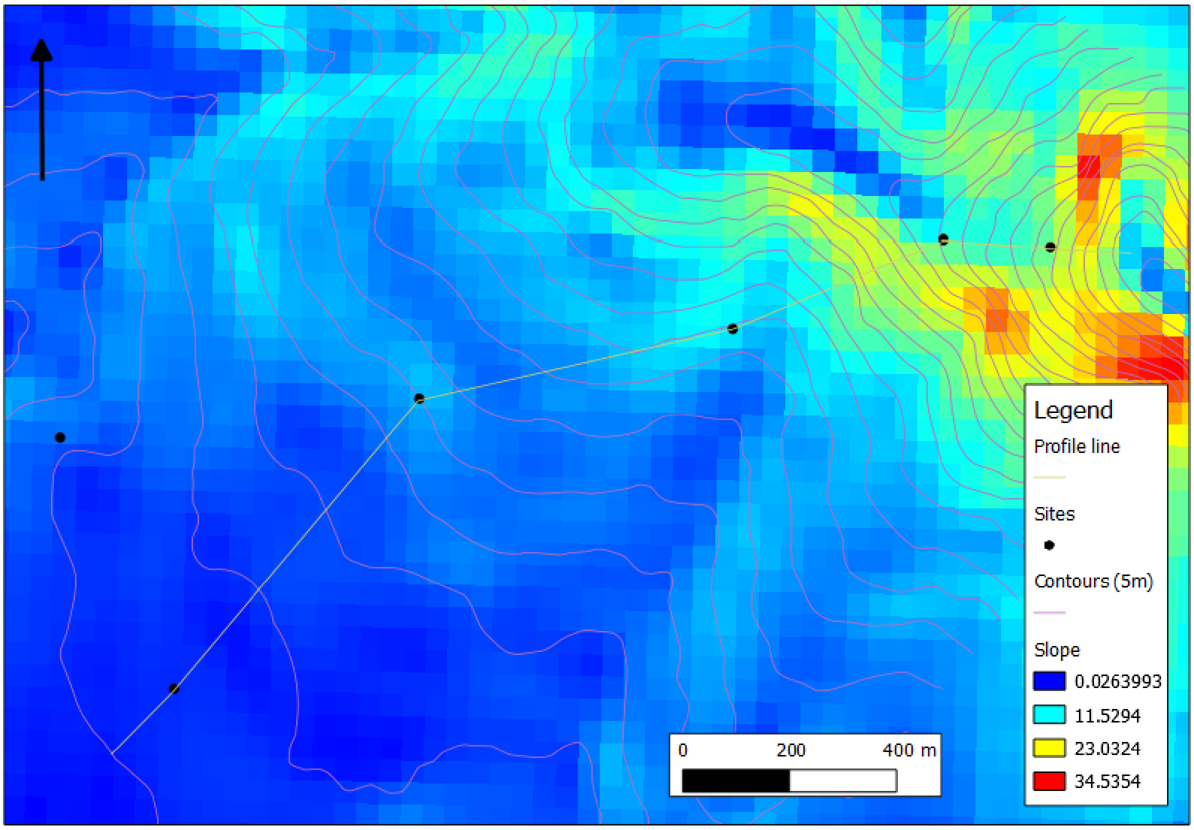

Figure 4.22: Slope map of the study area on the Langgewens Experimental Farm.

4.3. MODELLING GROUNDWATER UNDER CURRENT CLIMATE CONDITIONS

4.3.1. Modelling Setup Methods

Si and Kachanoski (2000) stated that the model application success rate for water movement in unsaturated hydraulic environments is strongly related to the quality of model parameters. As the sites along the toposequence down the hillslope differ, different modelling strategies are required. Four different models were applied to each soil horizon at the different sites to ensure more accurate modelling with lower Root Mean Square Error (RMSE). Models that were selected include single-porosity with and without root water uptake as well as dual-porosity with and without root water uptake.

Evaporation and potential transpiration was determined using the FAO-PM model. Generated data was then imported into the Hydrus-1D model along with other important properties, including soil texture and bulk density. Each site was modelled according to the physical parameters present and compared to measured volumetric water content throughout the season.

4.3.2. Interpretation of Modelling Results

Different model setups (Table 4.5) resulted in different modelling results, mainly due to changes in the model configurations. Figure 4.23 illustrates the different modelling results at the Upper Renosterveld site at the 10 cm depth using the four different models. As the model can be set up according to site-specific requirements, the most comprehensive setup include the Dual-Porosity hydraulic model and the activation of the Feddes Root Water Uptake Model in the Hydrus-1D model. These different models are illustrated in Figure 4.23 as used for the Upper Renosterveld site at a depth of 10 cm. The different model strategies that were tested are seen in Figure 4.23.

Table 4.5: Different modelling strategies as used in Hydrus-1D.

Modelling Strategy	**Comment**
Single Porosity, No LAI	Simulate water movement in a partially porous medium Uniform wetting front Exclude root water uptake
Dual Porosity, No LAI	Simulate water movement in soil where single porosity and preferential flow occurs Exclude root water uptake
Single Porosity, LAI	Simulate water movement in a partially porous medium Uniform wetting front Incorporates root water uptake Use LAI for different vegetation types through different seasons (related to a crop factor)
Dual Porosity, LAI	Simulate water movement in soil where single porosity and preferential flow occurs Incorporates root water uptake Use LAI for different vegetation types through different seasons (related to a crop factor)

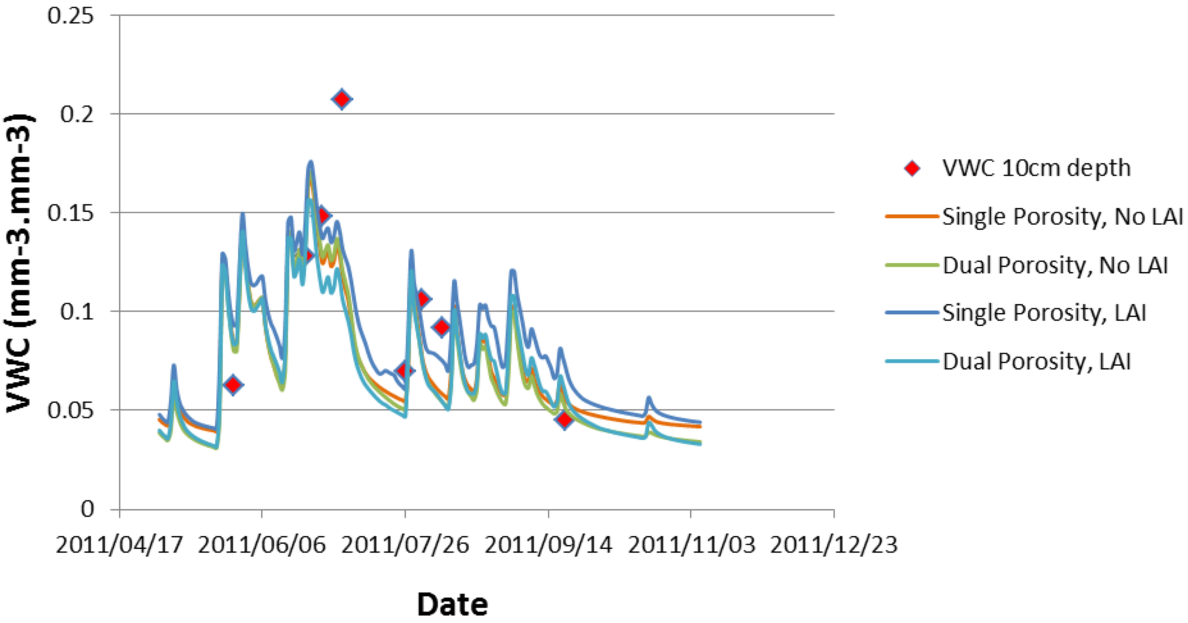

Figure 4.23: Modelling water content at 10 cm depth at the Upper Renosterveld site before 10 % correction.

As Figure 4.23 and Table 4.6 indicate, there is only a slight difference between the different model applications in Hydrus-1D, compared to volumetric water content measurements at each of the different study sites. As each model has the same input data, e.g. climatic parameters, soil properties (particle size distribution and bulk density per horizon) and leaf area index (LAI), differences between the models can be attributed to the accuracy of site specific soil conditions and the influence of vegetation on soil water properties as seasonal changes occur.

Table 4.6: The average difference between modelled and measured volumetric water content at each site using the four different model setups at two different depths.

Site	Depth (cm)	Single Porosity, No LAI	Dual-Porosity, No LAI	Single Porosity, LAI	Dual-Porosity, LAI
Upper Renosterveld	10	4.88	4.75	6.16	4.39
	30	9.07	9.15	10.15	9.29
Lower Renosterveld	10	3.97	4.46	5.82	4.87
	40	7.58	7.92	8.45	8.97
Borehole	15	-	-	14.10	14.10
	40	-	-	11.66	11.66
Next-to-Road	15	-	-	13.27	15.77
	30	-	-	13.93	16.60
	45	-	-	16.75	19.05
Dam	15	4.92	3.97	8.01	0.06
	40	0.16	-3.33	5.56	-0.01
Saltbush	10	9.45	9.80	9.84	6.40
	40	11.59	10.08	11.94	-1.10

Table 4.6 states that, at most of the sites, the Dual-Porosity model setup where root water uptake is activated is the most accurate model with the lowest average difference compared to volumetric measurements in the field throughout the season. The Dual-Porosity, LAI models had the lowest average difference compared to volumetric water content measurements in the field. This was for all the sites except the Lower Renosterveld site where the Single Porosity, No LAI model had the lowest average difference compared to the other models.

Sensitivity analysis forms an important part of hydrological modelling and must be incorporated into model predictions to determine deviation between measured and predicted values. With an increasing number of environmental, climatic and hydrological models, it is important to perform sensitivity analysis and to determine the precision and accuracy of the models (Willmott & Matsuura, 2005). Different models require different performance indicators and this vary significantly, such as the Root-Mean-Square Error and the Mean Absolute Error (MAE). Schaap & Leij (1998) determined different RMSE values for the Hydrus-1D model according to the level of input data, enabling researchers to use this as performance indicator. The root-mean-square error (RMSE) enables researchers to measure differences between observed values and the values predicted by the model. As stated by Schaap & Leij (1998), the RMSE for Hydrus-1D is between 0.108 with Model 1 and 0.063 with Model 5. This is strongly related to the accuracy of input parameters, e.g. particle size density and bulk density. The parameters that were used in Hydrus were the soil properties (texture classes, bulk density, soil profile depths) and daily climate (precipitation, potET) and LAI (Crop factor and ET).

To determine the RMSE, Equation 1 is used with the following input parameter – number of observations, measured water content and the predicted water content. The results of the RMSE calculation are specified in Table 4.7.

Equation 1: Calculation to determine the Root Mean Square Error value.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (Obs_i - Sim_i)^2}{n}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

where: $RMSE$ = Root-mean-square error with:

n = Number of observations

Obs_i = Measured water content

Sim_i = Predicted water content

Table 4.7: Calculated Root-Mean-Square Error (RMSE) for each site as predicted using the Dual-Porosity, LAI model setup.

Site	Depth	RMSE
Upper Renosterveld	10 cm	0.066
	30 cm	0.099
Lower Renosterveld	10 cm	0.055
	45 cm	0.081
Borehole	15 cm	0.142
	40 cm	0.117
Next-to-Road	15cm	0.162
	30cm	0.171
	45cm	0.206
Dam	15 cm	0.087
	40 cm	0.049
Saltbush	10 cm	0.111
	40 cm	0.109

The RMSE was determined after calculating the standard deviation between in field measurements and the predicted value as calculated by Hydrus-1D. According to the threshold value, as specified by Schaap & Leij (1998), only the Borehole site consists of a bigger RMSE than stated as acceptable.

4.3.3. Modelling Results at the Different Sites along the Hillslope

Upper Renosterveld

The Upper Renosterveld site is characterized by dense Renosterveld vegetation and increased surface cover as the rainfall season progresses and more water becomes available (Figure 4.24).

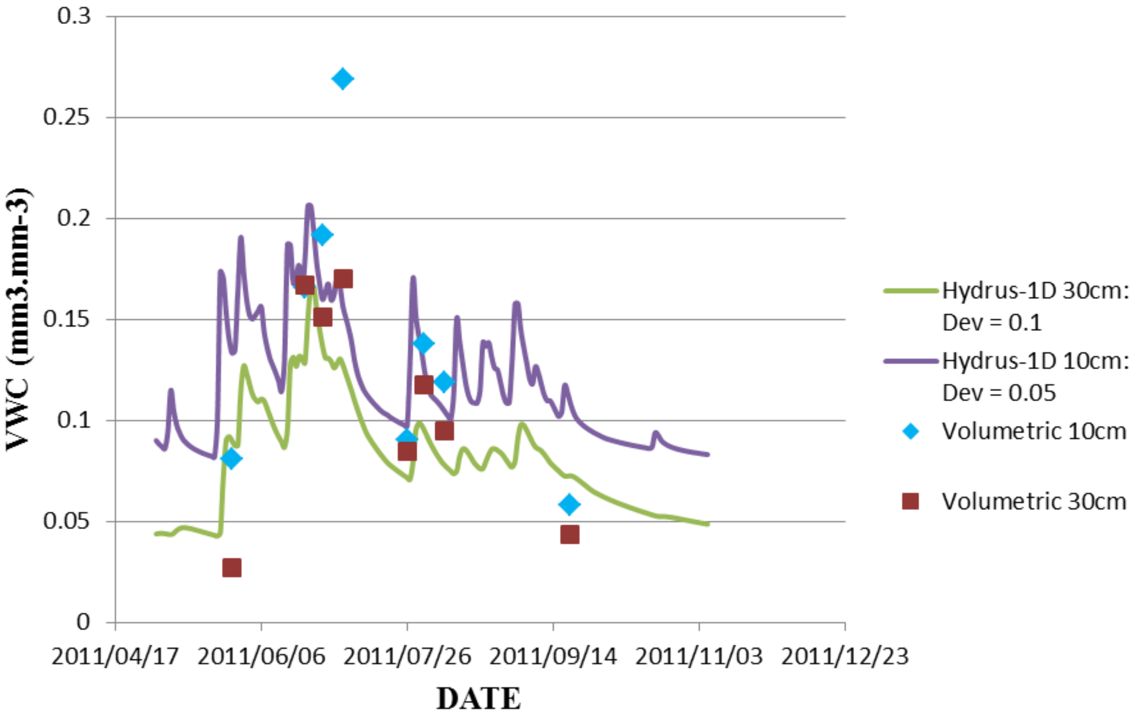

Figure 4.24: Comparison between predicted and measured soil water content at 10 cm and 30 cm depths at the Upper Renosterveld site.

As seen in Table 4.6 and Table 4.7, there is a difference between the measured and predicted soil water contents, but this is at acceptable RMSE levels according to Schaap & Leij (1998).

Fluctuation differences can be attributed to several factors, which also vary between the different horizons. Variation in soil texture was described by Vachaud *et al.*, (1985) and Crave & Gascuel-Odoux (1997) as the most significant factor that influences soil water distribution patterns. Soil water level fluctuations differ at different depths as soil texture differences occur, together with coarse fragment and organic material content. Together with the soil properties, landscape characteristics also influence the soil water distribution patterns and resulting fluctuations differences between the horizons.

The fluctuations as represented by the Hydrus-1D predictions of soil water content, are related to the hydrological parameters of the soil. Soil water content fluctuations are a result of water input through rainfall and extraction through evaporation and root water uptake. With higher root densities in the upper horizon near the surface, root water uptake occur mainly in this zone resulting in higher fluctuations compared to deeper in the horizon. This was confirmed through a study by Vermeulen (2010) on a Glenrosa soil form in the BRC area. Lithocutanic B-horizon is a limiting factor with only insignificant amount of roots found into the horizon.

Fewer water content fluctuations occurred deeper in the horizon at a depth of 30 cm. This is illustrated in Figure 4.24 where smaller water variations were present and predicted by Hydrus-1D. As the depth increased, lower soil water fluctuations occurred due to less water input and extraction. Small precipitation events resulted mainly in water content changes in the upper soil horizon near the surface with a small amount of water infiltrating through to the deeper soil horizons. Lower amounts of water extraction occurred deeper in the soil profile due to the low root density and the absence of evaporation.

Soil particle-analysis indicated low clay content in the Orthic A- and Lithocutanic B-horizons, indicated by field measurements. This is directly linked to the high fluctuation in soil water content at the 10 cm and 30 cm depth. Due to the high sand fraction in the soil, the water retention capabilities of the soil are extremely low with high percolation rates present. The high coarse fragment content and preferential flow paths (such as root channels and termite nests) contribute to the low soil water retention-capabilities and the high water content fluctuations.

Lower Renosterveld

Comparable soil, vegetation and landscape characteristics exist at this site (Figure 4.25) and the Upper Renosterveld site, except for its lower elevation. Renosterveld is the dominant vegetation type with an increase in grass cover as the water content in the upper soil horizon increases.

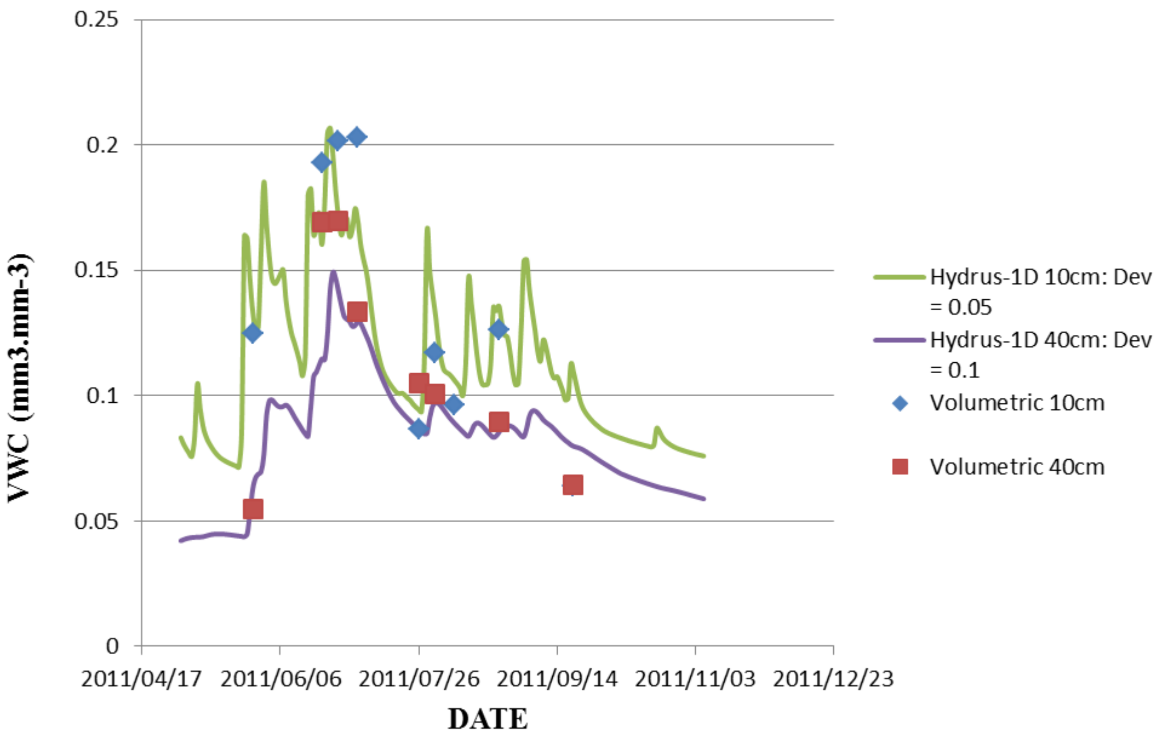

Figure 4.25: Comparison between predicted and measured soil water content at 10 cm and 40 cm depths at the Lower Renosterveld site.

A strong correlation exists between the Upper- and Lower Renosterveld sites' soil water regimes due to similarity in soil, vegetation and landscape characteristics. The most significant difference is found in the depth of the Orthic A-horizon, which is 100 mm deeper than the Orthic A-horizon at the Upper Renosterveld site. These sites are very similar in terms of position in the landscape, slope, vegetation, soil form and soil properties - therefore the same hydrological parameters and water content distribution exist.

Compared to the soil texture of the Upper Renosterveld site, a low clay content, which results in low water retention capability, is found at the Lower Renosterveld site. Higher fluctuations in the soil water content in the upper soil region can be ascribed to the extraction of water by roots, and the shallow depth of infiltration after low quantity rainfall events.

Borehole

Soil characteristics are the most important contributing factor to the soil water regime at this site (Figure 4.26).

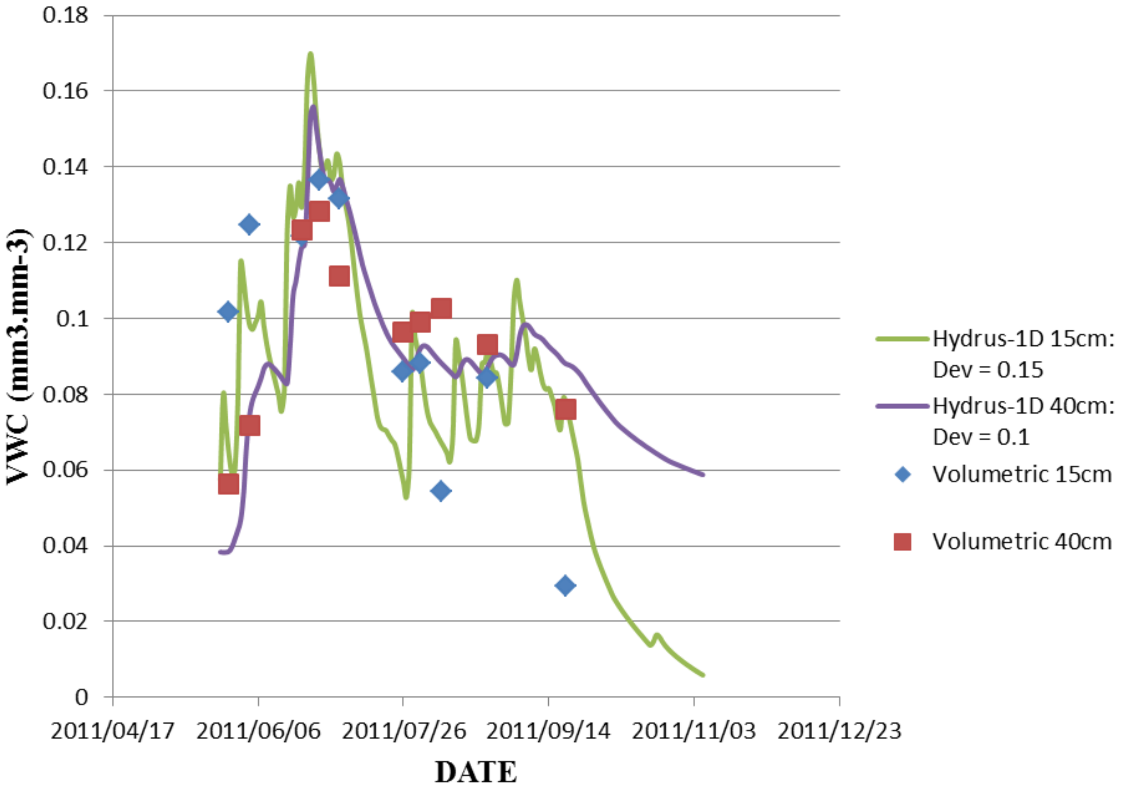

Figure 4.26: Comparison between predicted and measured soil water content at 15 cm and 40 cm depths at the Borehole site.

The transported horizon under the Orthic A-horizon that contains a high coarse fragment content (Appendix 3), is the most significant factor that influences the hydraulic parameters in the soil. Rock fragments have an effect on infiltration, bulk density and the volumetric water content (Brakensiek & Rawls, 1994).

Similar to the prediction in Hydrus-1D at the Upper- and Lower Renosterveld sites, there is a higher fluctuation in modelled and measured water contents in the upper horizon compared to the horizon beneath due to the influence of evaporation and root water uptake as well as other soil properties such as hydrologic conductivity and porosity. Soil texture, as one of the main factors controlling water content and distribution, is a key factor according to Vachaud *et al.*, (1985) and Crave & Gascuel-Odoux (1997). Higher clay content results in lower fluctuations due to higher soil water retention capabilities (Leeper & Uren, 1993). The underlying Pedocutanic B-horizon has a significant clay content impacting infiltration and percolation from the overlying horizons to the groundwater zone.

Peak water content levels as modelled in Hydrus-1D correspond significantly with measured volumetric water content at the different depths as well as the significant rise in the water table level monitored through the borehole (Figure 4.20).

Soil limitations are limiting factors that influence root penetration to deeper layers, resulting in shallow root systems causing the majority of root water uptake to be confined to the upper soil horizons. Due to the high coarse fragment content (Appendix 3), the roots are able to extract water from the deeper soil horizon, resulting in fluctuations and lower soil water content together with higher fluctuations than normally expected at this depth. This can also be contributed to the texture of the transported material, where low clay content is present, thus a low water retention capacity exist. Cresswell & Kirkegaard (1995) stated that roots' ability to penetrate dense B-horizons is less efficient.

Next-to-Road

Anthropogenic factors contribute significantly to the difference between measured and modelled volumetric water content. There are mainly two factors that could cause these results, namely the road and the attached weir that causes an interruption in the overland flow from the upper hillslope towards the valley floor. As this area is close to the road, the effect is severe. Another contributing factor could be the measurement of bulk density using the *Troxler 3401-B* model as described in 3.2.2.

Natural water flow is altered due to farm management practices and has a significant influence on the hydrological modelling at this site. Due to these changes, soil water modelling prediction by Hydrus-1D is over predicted (Figure 4.27).

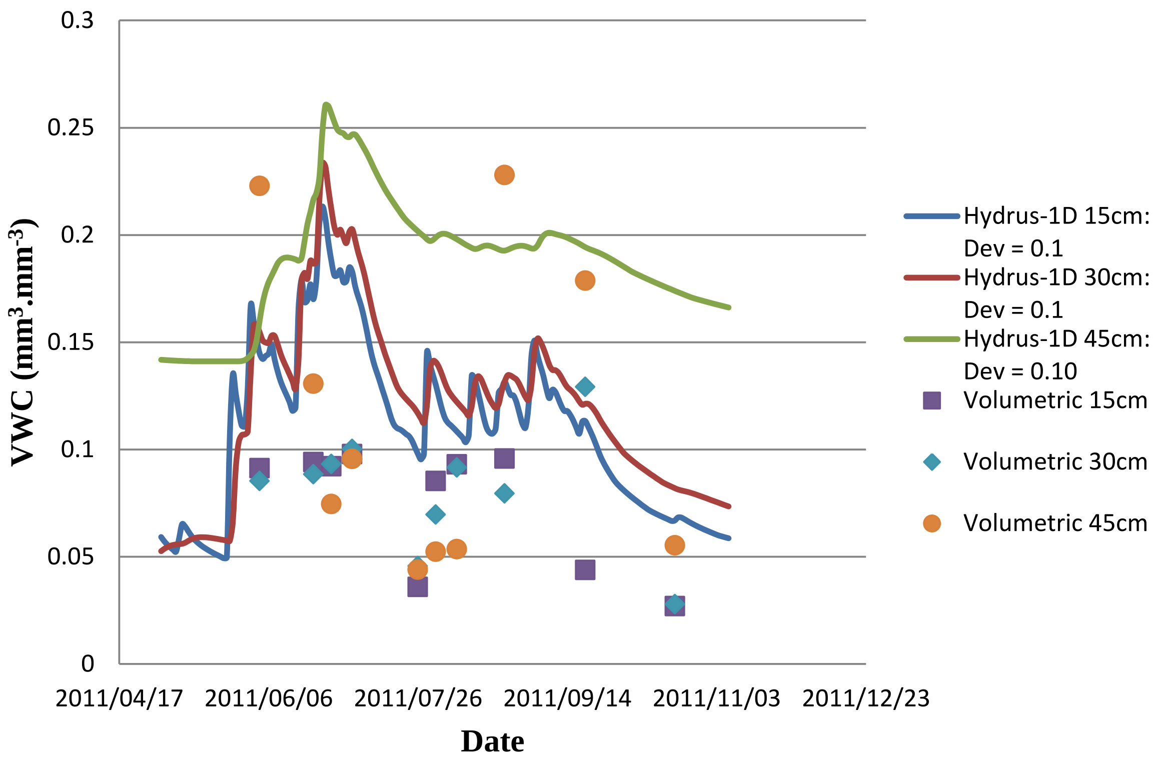

Figure 4.27: Comparison between predicted and measured soil water content at 15 cm, 30 cm and 45 cm depths at the Next-to-Road site.

Dam

The Dam site is within the foot slope area on the hillslope terrain, with significant soil and hydrological conditions present. As the lowest lying point on the hillslope, water accumulates in the nearby earth dam mainly due to the rise in the water table level. This has a significant influence on the soil water regime (Figure 4.28).

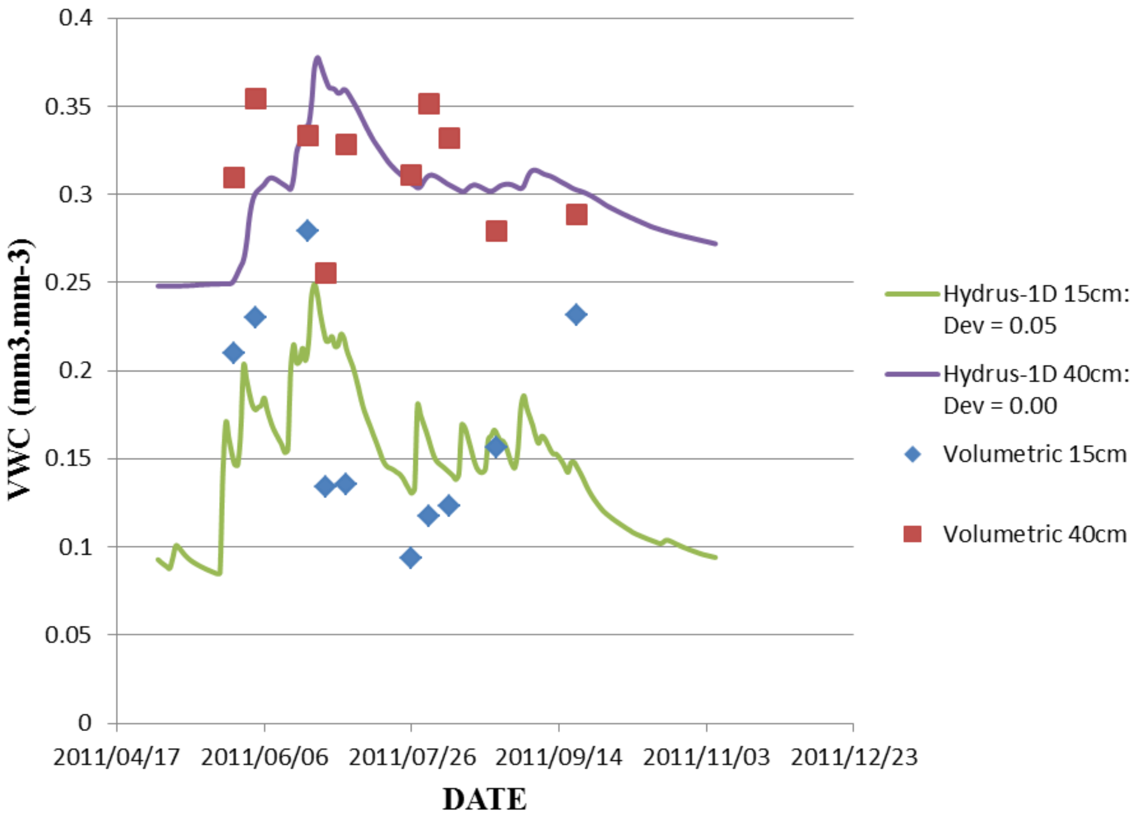

Figure 4.28: Comparison between predicted and measured soil water content at 15 cm and 40 cm depths at the Dam site.

Landscape characteristics have a significant impact at this site, where a shallow water table has a great influence on hydrological conditions and soil water movement. Similar water table movement as illustrated by Flügel (1995) (Figure 4.1) is present here with a shallow water table as the rainy season progresses, as indicated in Figure 4.20.

The particle size distribution is critical in the water movement through the different horizons. As a high clay percentage is present in the Pedocutanic B- and Saprolite horizons, the upwards movement of water from the water table greatly affects soil water conditions through capillary rise. The upward movement of water, known as capillary rise (Carman, 1941), occurs in this scenario from the water table, where saturated conditions are present, into the upper region where unsaturated conditions exist. With a decrease in clay content nearer to the surface, the soil water content is lower while higher fluctuations occur.

Overland flow during a rainfall event has a significant impact on the amount of water that infiltrates into the soil and contributes to the soil water. As very little overland flow occurred at this site during the year (Figure 4.14), it can be accepted that the rainfall infiltrated into the soil. This contributes to the high water levels in the soil.

A significant difference between the soil water content of the different horizons is found as the water table rises (Figure 4.14 and Figure 4.19). Until the water table rise to reach the Pedocutanic B-horizon, similar water contents are present in the Orthic A- and Pedocutanic B-horizon. As the water table reaches the Pedocutanic B-horizon, the soil water content remains significantly higher than the soil water content in the Orthic A-horizon. This can be ascribed to the higher water retention characteristics of the soil in the Pedocutanic B-horizon and the contact of the soil horizon with the upper part of the water table. As the rainy season concludes, the water table subsides and the soil water content in the profile decreases.

Rooting systems vary between different species and this influences their ability to penetrate deeper into the soil profile past limitations in the soil. Hanson *et al*., (2002) found that frequent rainfall result in shallower rooting depths compared to less frequent and higher amounts per rainfall event. Water extraction from wheat is mostly confined to the upper soil region, resulting in soil water peaks mostly occurring in the Orthic A horizon. This is also related to the particle size distribution. Cresswell & Kirkegaard (1995) stated that roots' ability to penetrate dense B horizons is less efficient. According to Hanson *et al*., (2002) cereal plants with shallow root systems like wheat are able to increase their fine root concentration in the soil during droughts, resulting in better production in dry, shallow soils compared to other plants like canola and legumes that have a deep rooting system.

Saltbush

This specific site (Figure 4.29) is not part of the toposequence, but the hydrological modelling was done to include the hydrological response unit for further studies in the BRC.

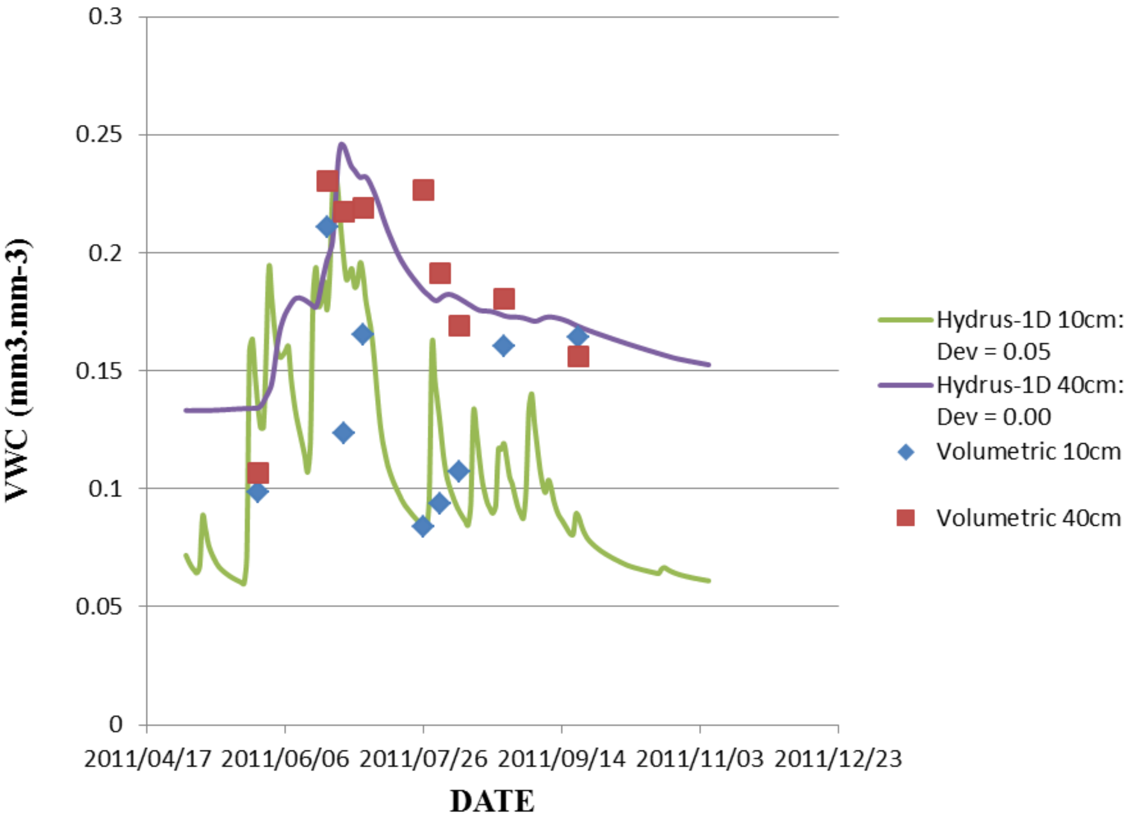

Figure 4.29: Comparison between predicted and measured soil water content at 10 cm and 40 cm depths at the Saltbush site.

Salinity problems are the main reason for the establishment of Saltbush (*Atriplex nummularia*) in this area. Saltbush is a valuable fodder shrub and useful for the utilization of saline areas (Lefroy *et al.*, 1992). As it carries leaves throughout the year, it is an ideal feeding supplement in times of drought (Emms, 2008). Due to its drought resistance, high concentrations of animals graze in this area. Grazing is one of the main contributors to soil compaction according to Orodho *et al.*, (1990). No tillage practices take place at this site, resulting in increased compaction levels. Due to compaction, infiltration is limited. High overland flow values which greatly influence soil water content are observed in Figure 4.17 and Table 4.2.

Renosterbos consists of a sound rooting system, with root penetration up to and beyond 7 m (Scott & van Breda, 1937). This conclusion did not take soil factors into consideration, with limitation such as bedrock and bulk density a restriction on root depth. According to Canadell *et al.*, (1996) rooting depth and general root structure may be influenced by environmental conditions. This has a direct effect on soil water conditions through the soil profile as root water uptake is affected.

The Prismacutanic B-horizon consists of strong a prismatic structure with a clay content of (51.39 %). During the profile description very little root activity was recorded in the Prismacutanic B-horizon, with the highest concentration of root in the Orthic A-horizon near the soil surface. This is also seen in Figure 4.30 where roots are visible on the surface and the strong structure is visible through the prismacutanic peds.

Figure 4.30: Root activity near the surface at the Saltbush site, due to the strong structure of the Prismacutanic B-horizon.

Due to limitation in rooting depth caused by the strong soil structure, root water uptake occurs mainly in the upper Orthic A-horizon, although roots are present in the deeper soil horizons. This is seen in the Hydrus-1D model where the 40 cm depth prediction shows little fluctuation compared to the prediction at a depth of 10 cm. The high clay content in the Prismacutanic B-horizon results in a significant water retention capacity, which leads to the high water content throughout the season. The root system that was observed at the Saltbush occurred widely within the Orthic A-horizon near the surface, with a lower density of roots moving into the Prismacutanic B-horizon. An in-depth root study will need to be performed to determine the root distribution pattern within this soil. For modelling purposes, the model setup in terms of water uptake by the root system was similar to the Renosterveld vegetation.

High fluctuations in the soil water level of the Orthic A-horizon can be ascribed to the extraction of water by roots and other grass-like species throughout the rainy season, as present in Figure 4.31.

Figure 4.31: Seasonal grass species results in high soil water fluctuation during the rainy season in the Orthic A-horizon.

4.4. CONCLUSION

Hillslope Hydrological Characteristics

Knowledge of water movement through the landscape is of critical importance within the agricultural sector to ensure sustainable practices. Sivapalan (2003) stated that hillslope hydrological processes have a high heterogeneity and complexity, resulting in an extensive study of the hydrological processes at this site. It was found that the subsurface

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characteristics and heterogeneity together with the surface slope conditions was crucial in the hydrological response of a hillslope. Although infiltration- and percolation rates, which are strongly influenced by rainfall intensity, are key factors that contribute to groundwater, several other factors influence the hydrological system within the landscape and hillslope. The study found topography to be the most important factor that affects water movement in space, as it influences water storage capability and gravity response within the hillslope, confirming the findings of Creutzfeldt *et al.,* (2010). Precipitation can only contribute towards groundwater through deep percolation, thus moving past the vegetation cover on the surface, the root system and ultimately percolating through the entire soil profile (Jyrkama & Sykes, 2007).

It is evident through the research that changes within the hydrological system occur along the hillslope and those heterogeneous environmental conditions with regard to soil, vegetation, land use and topographical characteristics have a great influence. By selecting heterogeneous sites, it enables us to determine the effect of different factors. From the changes in water content of the soil relative to the amount of rainfall and infiltration, the effect of different variables can be determined. The changes can also be correlated with the land use, as seasonal crops extract more groundwater later in the growing season from the upper soil horizon, leading to lower water content in this region and directly affecting infiltration, overland flow, lateral water flow and percolation. Decreases in the presence of lateral water flow also confirm the findings of water extraction later in the growing seasons by plants. Overland flow, which occurs when the rainfall intensity exceeds the infiltration rate of the soil, is strongly correlated with the slope and landscape characteristics. All the above-mentioned factors ultimately contribute to the water table, which often responds disproportionately to the precipitation events (Meyboom, 1967). This is evident in Figure 4.20 and is also an indication of the many factors that influence and contribute to the complexity of the hydrological system along a hillslope of this structure.

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By monitoring hillslope hydrological conditions under the existing climatic conditions enables further research to be done using hydrological models like Hydrus-1D. Current data can then be used to calibrate models and validate model efficiency that will enable water managers to predict future groundwater conditions.

Hydrological Modelling Conclusion

Accurate modelling will become more valuable in the near future as pressure on water resources increase and resources management becomes a high priority case (Jyrkama & Sykes, 2007). As Bronstert & Plate (1997) stated, hillslopes are a combination of smaller units, making it possible to use hillslope modelling at hillslope scale. Through the modelling of different sites along the hillslope, several hydrological response units were modelled. Through the thorough understanding of hillslope hydrological conditions, improved management decisions can be made (Hughes, 2010).

Model accuracy is very important and is directly linked to the credibility of the input parameters with regard to site specific soil parameters and climatic data. Each site required a unique model setup due to variation between sites in terms of soil and landscape characteristics. As four model setups were implemented at each site, several output values were compared to the in-field measurements. As the Dual-Porosity, Leaf Area Index (LAI) was the most accurate representation of field conditions, it was selected for all the sites. The RMSE and deviation of the different models must be calculated to determine their accuracy and the model sensitivity.

Hydrus-1D predicted the volumetric water content very accurately at the different sites, with only a larger than expected RMSE value at the Borehole site. This is likely caused by the transported soil horizon in the soil profile containing a large coarse fragment content. Coarse fragments directly influence the soil hydrology through different parameters. These parameters include percolation, infiltration and overland flow rates, resulting in hydrological changes (Poesen & Lavee, 1994). The rest of the sites had RMSE values that corresponded with outer boundaries set by Schaap & Leij (1998) as well as Schaap *et al.* (1998). Water content trends are similar for the different hydrological units, although variation occurs due to soil characteristics, land use and seasonal changes in the vegetation composition. Other contributing factors include preferential flow paths caused by root channels and termite activities.

As Hydrus-1D incorporates different models, the accuracy of predictions is related to the accuracy of input data. By improving the input data in terms of different parameters, prediction accuracy will improve. In terms of rainfall data, interception by plants is not incorporated into the input climate data. The amounts of precipitation that are intercepted depend on rainfall intensity and duration, the surface roughness and area of the plant or litter which intercepts water (Larcher, 1983). Interactions between climate and soil are time bound, with more data records and smaller time intervals allowing more accurate import data. As rainfall is the main driver behind soil water changes and water contribution towards groundwater, the more accurate rainfall data is, the more accurate the model will be. By recording the rainfall intensity, duration and interval, improved soil water predictions can be attained.

The set-up of accurate hydrological models under current climate conditions will enable researchers and water managers to apply the same models using forecasted future climatic conditions. Hydrological models provide a framework for researchers to investigate different parameters concerned with the hydrological system (Leavesley, 1994). Using the different models at point scale at the hillslope on Langgewens Experimental Farm will enable researchers to determine the impact of climate change and land use change on the hydrological system in this environment.

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CHAPTER 5 FORECASTING FUTURE HYDROLOGICAL CONDITIONS AND LAND MANAGEMENT STRATEGIES DUE TO CLIMATE CHANGE

5.1. INTRODUCTION

Pressure on water resources will increase in the future as climatic changes and increased human population are experienced. Currently there are no predictions of the impact that a change of climate will have on groundwater. Estimations indicate that by 2025 about 5 billion of the total expected world population of 8 billion people will live in countries that experience water stress, thus using up to 20% of their total available resources (Arnell, 1999). According to Woldeamlak *et al.* (2007) the need for forecasting future hydrological conditions is amplified by changing climatic conditions and increased population levels aggregating pressure on water resources.

All phases of the hydrological system are influenced by climate and a change in a single parameter will have an impact on the entire hydrological system. The impact will vary around the globe with differences in land management, vegetation and population distribution contributing to the expected changes. Frederick & Major (1997) stated that water management strategies depend on changes in precipitation, runoff and land use changes. As food security is directly related to the sustainability within the agricultural sector, it is of critical importance to determine the effect of climate change on agricultural productivity. Hatch *et al.* (1999) stated that climate change will have a severe impact on the agricultural sector, although the level impact is uncertain (Frederick & Major, 1997).

Hillslope hydrology is a complex system and interaction between various factors must be considered. Soil resources will be impacted on by climate change through the changes in runoff and rainfall, resulting in sediment transport and soil erosion (Chaplot, 2007). Pruski & Nearing (2002) stated that the impact of precipitation changes is related to the landscape, landuse, vegetation and other parameters such as soil water content and surface roughness.

To estimate future hillslope hydrological conditions, it is important to forecast future climatic variables and their impact on spatial variation in the hydrological system along a hillslope (Jyrkama & Sykes, 2007).

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5.2. FORECASTING FUTURE CLIMATE CHANGES BASED ON HISTORICAL DATA

Several different types of climate models exist, of which dynamic models are the preferred models at regional and global scales in terms of climate change projections. Using dynamic regional climate models (RCMs), researchers are capable of obtaining detailed projections over designated areas by applying these models at a high resolution (Engelbrecht *et al.*, 2011). According to Lal *et al.*, (2008) and Roux (2009), RCMs can be applied at resolutions of up to 50 km at continental scale.

Projection validity is often under suspicion as verification will only become possible after a certain time period into the future. Engelbrecht *et al.*, (2011) stated that by applying and verifying climate projection models over multiple spatial- and time scales, growing confidence with regard to model usage can be expected. Two different approaches were used to determine the possible change in climate that can be expected in the Western Cape.

5.2.1. CLIMGEN Weather Generator

Global Circulation Models (GCMs) are widely used in climate projections and studies, but the use of these models are limited due to their low spatial resolution (Wilby & Wigley, 1997). Weather data is significant in hydrological-, environmental- and agricultural management. Stochastic weather generators, such as CLIMGEN, generate long-term weather based on historical data. This is not a climate model, but a weather generator that generates weather data based on historical data to be used in models such as Hydrus-1D. It is also capable of downscaling regional climate data to higher resolution localized data (Jovanovic *et al*., 2003). CLIMGEN is based on historical climate data and requires 20 years or more precipitation data and up to 10 years of minimum- and maximum daily temperatures to generate weather data that is reliable. Through CLIMGEN, researchers are able to generate minimum- and maximum daily temperatures and precipitation. Clemence (1997) assessed the CLIMGEN generator at several South African sites and found estimates to be acceptable.

Temperature and Precipitation Changes

According to the future climate predictions by the CLIMGEN weather generator, changes in the minimum- and maximum temperatures will be insignificant (Figure 5.1). The significant impact of the forecast is the decline in annual precipitation over time (Figure 5.2). Severe changes in the hydrological system can be expected due to this change. The impact will be through changes in groundwater recharge, lateral water flow, overland flow and infiltration. This will directly influence soil properties such as hydrological conductivity and infiltration rates through changes in the vegetation and general soil biological activity.

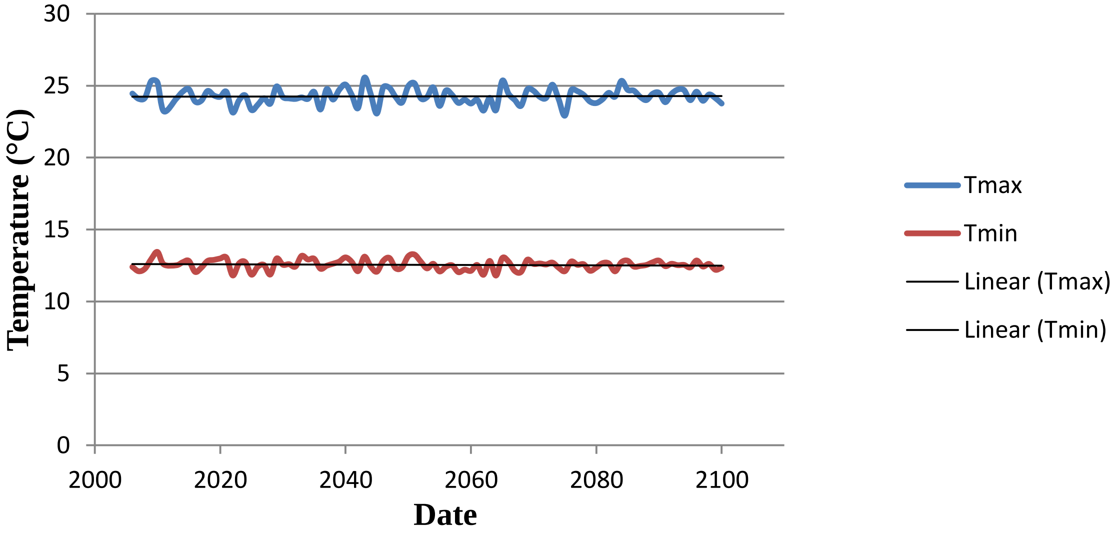

Figure 5.1: Expected changes in the minimum- and maximum temperatures as generated by the CLIMGEN weather generator.

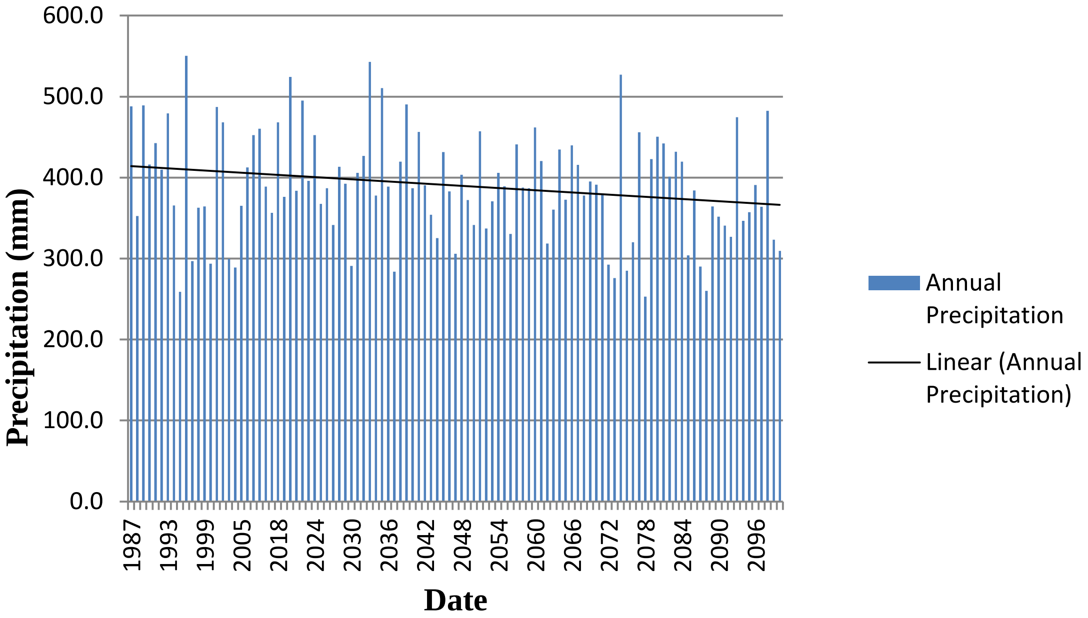

Figure 5.2: Annual decrease in precipitation as generated by the CLIMGEN weather generator.

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5.2.2. CCAM Model

Determining detailed projections of future climate changes requires the use of dynamic climate models. Climate models that are used at regional scales can be applied at a resolution of up to 50 km, allowing researchers to apply hydrological models to specific catchment areas. Different models are used for different purposes and the model selection depends on the necessary information required. Variable resolution models, such as the conformal-cubic atmospheric model (CCAM), are most suitable for simulations across different time and spatial scales. As these models can be applied over a selected area, they function as a regional climate model (Engelbrecht *et al.,* 2011). Engelbrecht *et al.,* (2005), Olwoch *et al.,* (2008) and Potgieter (2009) applied CCAM as simulation model over tropical- and southern Africa. Potgieter (2009) confirmed the validation of the model after comparing modelled climate data with observed data. Through the use of multiple spatial- and time scales, future climate predictions can be verified and used with a higher degree of confidence (Engelbrecht *et al*., 2011).

Temperature and Precipitation Changes

As the model is grid-based, historical climatic events such as flash floods or high intensity rainfall events in a small area within the grid is reflected in the total grid area. This is the major reason for the increase in minimum- and maximum temperatures (Figure 5.3) and the expected increase in rainfall (Figure 5.4). Although the Western Cape area experiences orographic rainfall which results in a more evenly distributed rainfall compared to the Highveld region, there is still an over estimation in the predicted rainfall (Midgley *et al*., 2003).

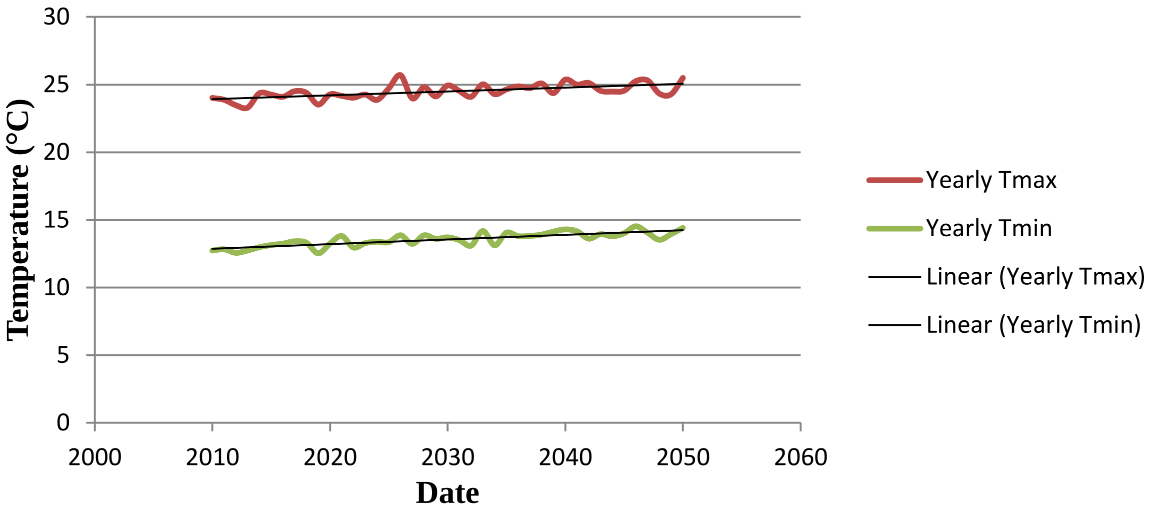

Figure 5.3: Expected changes in the minimum- and maximum temperatures as forecast by the CCAM model.

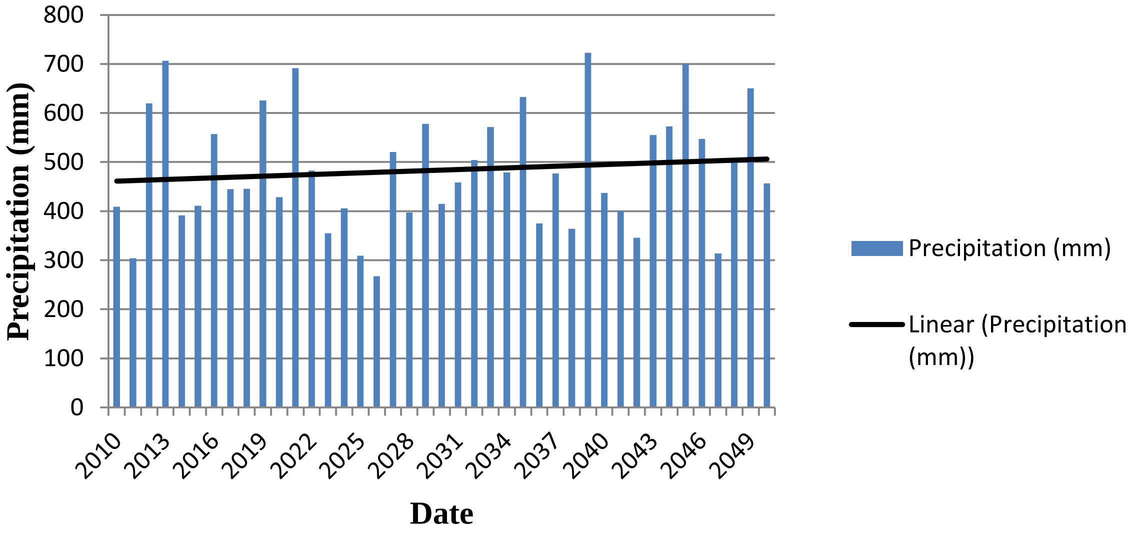

Figure 5.4: Annual increase in precipitation as forecast by the CCAM model.

5.3. MODELLING FUTURE SOIL WATER CONDITIONS USING HYDRUS-1D

The usage of different models to forecast climate change enables water management agencies to be better prepared. Through the CCAM and CLIMGEN generated climate scenarios, two possible outcomes are obtained. Due to the differences in temperature and precipitation forecasts generated, the outcomes can be interpreted as two possible scenarios that can be expected in the future with regards to soil water conditions. When analysing forecasts by models, it is important to incorporate scale differences that may exist. The CCAM model area applied at a resolution of up to 50km and due to several large differences within such an area, the accuracy of the modelled data at hillslope and point scale will only be validated after a certain period. This model was applied by Engelbrecht *et al.*, (2005), Olwoch *et al.*, (2008) and Potgieter (2009) over tropical- and southern Africa, while Potgieter (2009) confirmed the validation of the model. The CLIMGEN weather generator is more accurate as it is based on weather data at a much higher resolution than the CCAM model, as it is capable of downscaling regional climate data to higher resolution localized data (Jovanovic *et al*., 2003). If these two forecasts are compared, the CLIMGEN weather generator will have a lower level of uncertainty as it based on localized weather data compared to the low resolution data of the CCAM model. The exact level of uncertainty will only be known after a certain period of comparing modelled data with measured data.

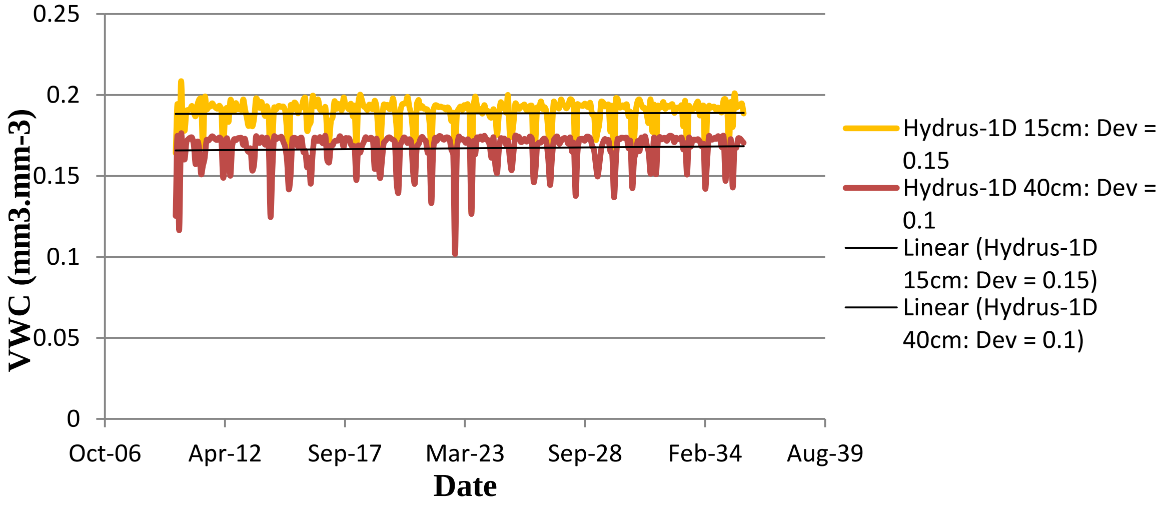

Figure 5.5: Hydrus-1D volumetric water content (VWC) predictions at the Borehole site based on the expected future climate generated by the CCAM model.

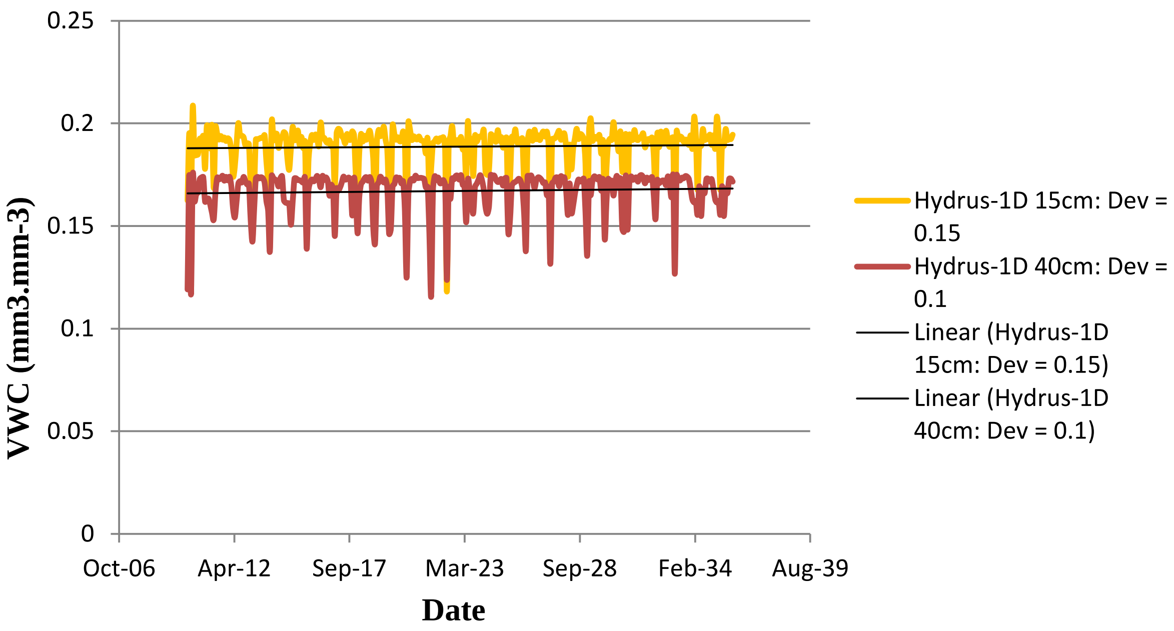

Figure 5.6: Hydrus-1D volumetric water content (VWC) predictions at the Borehole site at different depths based on the expected future climate generated by the CLIMGEN weather generator.

According to forecasts, the long term soil water content trend remains the same. The significant finding of both models is the wet-dry cycle that can be expected over the next 25 years (Figure 5.7 and Figure 5.10).This will have a significant impact on agricultural management with regard to multiple disciplines in the farming sector.

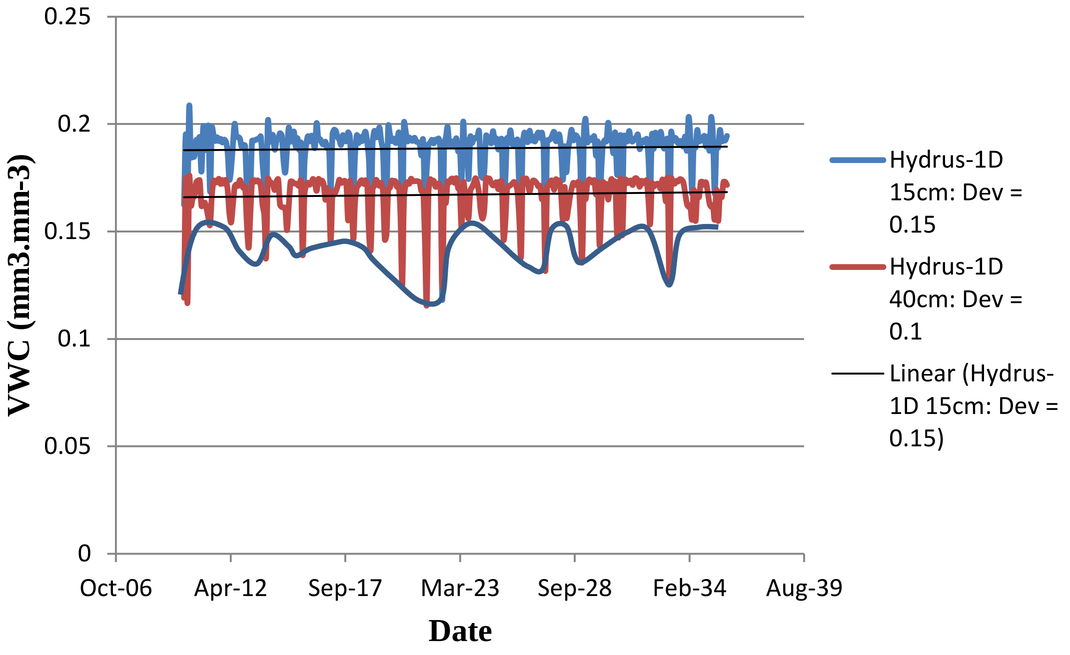

Figure 5.7: Expected soil water content cycle and fluctuations as predicted in Hydrus-1D by using the CLIMGEN generated data.

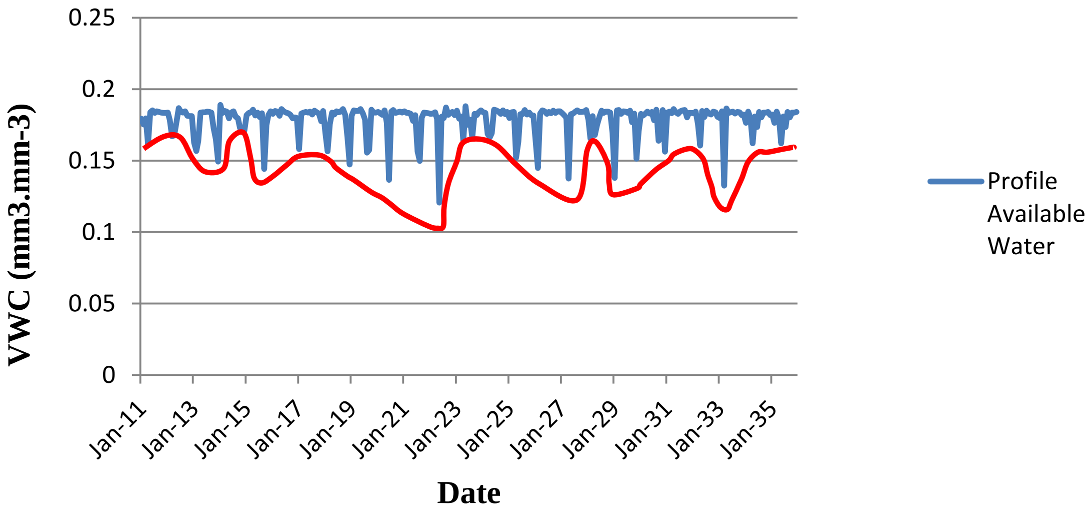

Figure 5.8: Expected changes in profile available water at the Borehole site under expected climate change conditions as generated by the CLIMGEN weather generator.

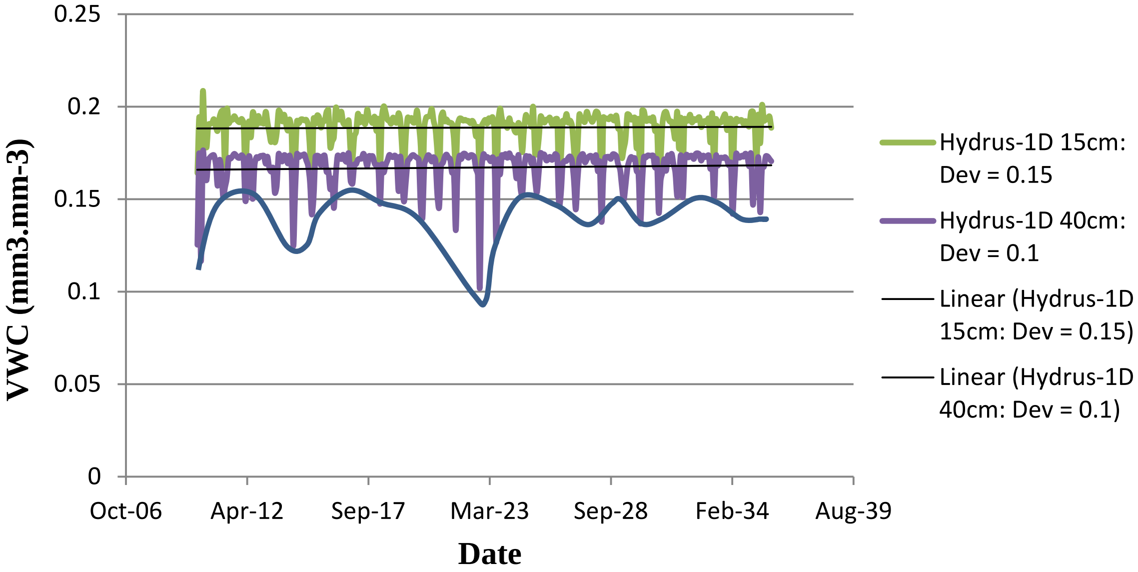

Figure 5.9: Expected soil water content cycle and fluctuations as predicted by the CSIR model.

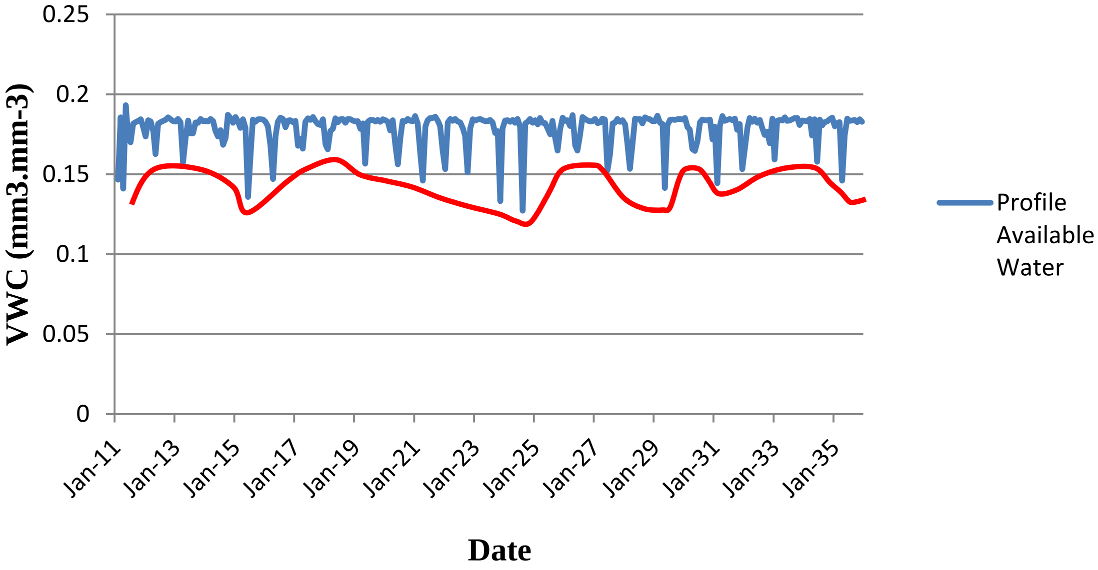

Figure 5.10: Expected changes in profile available water at the Borehole site under expected climate change conditions according to the CSIR model.

To enable researchers to predict hydrological conditions in the future, 2011 hydrological data must be used as reference point. From the viewpoint that soil systems will remain stable on the hillslope during the next 25+ years, it can be assumed that the hydrological system will change very little. Through the soil water content predictions by Hydrus-1D, hydrological processes such as overland flow, lateral water flow and deep percolation can be predicted.

If similar soil water conditions exist, the overland flow, lateral water flow and deep percolation trends can be assumed to be the same. As these factors are key contributors to the groundwater level, the movement of the water table can be expected to show the same movement pattern as seen during the 2011 season. The water table, which is a reflection of the groundwater level depth, is of critical importance in the Western Cape area, where salinity is a major problem.

Dryland salinity is a common occurrence in regions with a semi-arid climate such as the Western Cape Province of South Africa (De Clercq *et al.*, 2010). Salinity problems occur in semi-arid and arid regions due to inadequate annual rainfall that causes accumulation of salts in the root zone. Greiner (1998) found that the removal of natural vegetation with deep-root systems causes a rise in the groundwater table, mobilizes salts and contributes to salinity in the soil and water. Climatic factors such as temperature, rainfall and humidity contribute to the soil salinity present in this region. Salt concentration levels in the surface water and soil are further enhanced by evapotranspiration (Flügel, 1995). The impact of salinity on agricultural production will be influenced by the climate and the corresponding hydrological conditions. Through more accurate management of the hydrological system, salinity problems can be minimized and managed according to the forecasted hydrological conditions.

5.4. MITIGATION OF DROUGHT RELATED PROBLEMS

Drought is unavoidable and through accurate future climate and soil water predictions, valuable management plans and guidelines can be put in place. According to O'Farrel *et al.*, (2009), lower production and higher financial variability is a reflection of drought occurrence and variability in different climate parameters. It is also stated that farming strategies that are sustainable under variable conditions must be implemented to ensure financial stability. The level of response to drought conditions is directly linked to the financial position and stability of the involved party. More money will be available for drought mitigation projects on farms with higher financial stability compared to farms under a financial burden (Ziervogel *et al.*, 2006).

Several options are available to the agricultural sector to use management practices to minimize the effect of a decline in rainfall. Studies have found that water harvesting systems can be used with little financial input and simple management strategies to improve plant water availability and the capacity of plants to use the water that is available. Tillage

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practices can also be used to improve the rainfall infiltration and soil water storage capacity. This will increase the water use efficiency of the plants. (Rockstrom, 2003)

Drought related problems in the agricultural sector are widespread and vary greatly between different locations. The effect of drought on financial stability and production can be in the form of reduced crop production, water quality and quantity problems, additional feeding, higher occurrence of pests and diseases, lower pregnancy rates under animals, increased erosion, and emotional stress. To reduce the effect, manage the drought conditions and minimize the financial impact, several management strategies can be implemented under a drought mitigation management plan.

Different farming sectors will need to implement different plans, depending on their agricultural setups and requirements. Livestock can be managed through reducing cattle numbers (for example selling the cattle earlier or retaining fewer siblings), management of grazing systems such as a higher rotation rate or renting additional land, and supplying extra feed such as hay. Crop producing farmers are able to minimize the impact of droughts through tillage practices, such as minimum till or no till. Crop selection and crop rotation are important to create a more sustainable management plan. All of the above-mentioned practices need to be incorporated with a sound financial management plan to mitigate the effects of drought and the expected variability in climatic parameters (Knutsen *et al.*, 2006).

5.5. CONCLUSION

Forecasting future hydrological conditions will enable farmers and the agricultural sector to implement accurate management plans based on hydrological modelling results. Through the in-depth understanding of the hydrological system along the hillslope as discussed in CHAPTER 4, the movement of water coupled with future climate data can be used in long-term decision making and management plans.

From the CLIMGEN weather generator and the CSIR model data, it is evident that soil water conditions will fluctuate in the near future. Scale difference between the CLIMGEN weather generated data and the CCAM model nust also be taken into account. The CCAM model is at a regional scale with more factors influencing the forecasted data compared to the CLIMGEN data that were generated and modelled at point scale. As this is a prediction, a certain degree of uncertainty are related to the different expected scenarios, but this will only be known after comparing modelled data with measured data. According to the modelled data, dry and wet years will occur on a regular cycle, but this will need to be managed and evaluated within the

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different areas. Years where the soil water content is low and dry conditions are present can be expected, thus a sound management plan can be implemented to mitigate the effect on production and financial stability. The modelled soil water conditions that will be experienced in the years to come will need to be incorporated into management plans. During the period when drier conditions are expected, it is important to be pro-active in terms of cattle- and crop management. As dryland salinity is a major concern in the study area, measurements should be put in place to ensure minimum loss in production and land suitability.

Climate change will certainly influence agricultural production, but through accurate management plans the expected challenges can be minimized to ensure a stable production- and financial environment.

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CHAPTER 6 GENERAL CONCLUSION AND RESEARCH RECOMMENDATIONS

6.1. GENERAL CONCLUSION

Hillslope hydrology and the effect that a change in climate will have on the hydrological system have been investigated in this dissertation. Related studies have focused on the impact of climate change on surface water bodies, without investigating the impact on soil water conditions. Complex interactions between the landscape characteristics, vegetation composition and the soil properties, together with the climate, are the driving factors behind the hydrological system. By setting up hydrological models for the specific hillslope and different hydrological response units, expected future climatic conditions can be used to determine the effect on soil water conditions within this area.

This research indicated the movement of water through the landscape under heterogeneous landscape, vegetation and soil conditions at the different sites. Different components of the water movement, as indicated by Figure 4.1, were determined along the hillslope. Variations in overland flow, infiltration, lateral subsurface flow and deep percolation were found as conditions changed. As conditions changed during the season, the contribution of different components towards the hydrological cycle changed, greatly influencing groundwater conditions and the water table. Two of the most significant findings were the standing water in the dam and the movement of the water table that was monitored through the borehole. Water in the dam was due to the shallow groundwater level in this area of the hillslope and not due to overland flow, as was expected. The significance of the water level in the borehole is due to the response that is seen in the rise of the water table after rainfall events.

Soil water content measurements throughout the season at different positions on the hillslope have made it possible to use a hydrological model for the different sites along the hillslope. Significant differences in the soil water content along the hillslope can be attributed to the soil properties. Soil properties are the major controlling factor of water movement through the landscape.

Hydrus-1D has been used and calibrated against in-situ soil water measurements to ensure the model predictions are acceptable. A CCAM model and the CLIMGEN weather generator were used to determine two possible outcomes, indicating that similar soil water content trends can be expected in the future. By using these trends as a management tool, more

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accurate agricultural management decisions can be made. By managing different farming components according to the different conditions expected, improved decision making will lead to improved management systems and higher sustainability with regards to production and financial well-being.

6.2. FUTURE RESEARCH RECOMMENDATIONS

To improve the understanding of hillslope hydrology and climate change, research recommendations include the following:

- Executing a similar study on different slopes in terms of vegetation, land use, soil and landscape characteristics to determine the effect of different components on the hydrological system.
- Investigation into land use practices and vegetation patterns along a hillslope to minimize overland flow and improve rainfall use efficiency.
- A detailed study on the movement of soil particles and nutrients along a hillslope that will enable researchers to determine areas where possible changes in soil chemistry are likely to occur.
- Monitoring of salt movement along a hillslope to reduce the effect of salinity on production and improve management systems.

With severe droughts expected on a regular basis in the future, the importance of water management and water management related research will increase. This dissertation has presented researchers with an understanding of the complex interaction between soil, land use, vegetation, landscape characteristics and climate. This study will hopefully encourage young agriculturists and water managers to further research the hydrological cycle within the agricultural sector.

APPENDIX 1 - SOIL PROFILE DESCRIPTIONS

Profile	Upper Renosterveld		
Latitude	-33.280	**Soil Form**	Glenrosa
Longitude	18.722	**Soil Family**	2211
Altitude	279m	**Soil Map Unit**	
Terrain Unit	Crest	**Vegetation/Landuse**	Renosterveld
Slope	16%	**Parent Material**	Malmesbury Shale Formation
Aspect	North-West	**Underlying Material**	

Horizon	**Depth**	**Description**	**Diagnostic Horizon**
A	0-300	Dry; Dry colour: 5YR 5/6, yellowish-red; Moist colour: 5YR3/3, reddish brown; Consistence: Loose; Structure: Weak/Brittle; Roots present.	Orthic A
B	300-400	Dry; Dry colour: 7.5YR, yellowish-red; Moist colour: 7.5YR 4/6; Consistence: Very Hard;	Litocutanic B

Profile	Lower Renosterveld		
Latitude	-33.280	**Soil Form**	Glenrosa
Longitude	18.720	**Soil Family**	2211
Altitude	247m	**Soil Map Unit**	
Terrain Unit	Upper Slope	**Vegetation/Landuse**	Renosterveld
Slope	12%	**Parent Material**	Malmesbury Shale Formation
Aspect	North-West	**Underlying Material**	

Horizon	**Depth**	**Description**	**Diagnostic Horizon**
A	0-300	Dry; Dry colour: 5YR 5/6 yellowish-red; Moist colour: 5YR 3/3 Consistence: Hard; Structure: Moderate.	Orthic A
B	300-400	Dry; Dry colour: 7.5YR 5/8 , yellowish-red; Moist colour: 7.5YR 4/6 Consistence: Slightly Hard; Structure: Shale layers.	Litocutanic B

Profile	Borehole		
Latitude	-33.281	**Soil Form**	Oakleaf
Longitude	18.715	**Soil Family**	2220
Altitude	205m	**Soil Map Unit**	
Terrain Unit	Midslope	**Vegetation/Landuse**	Cultivated/Wheatfield
Slope	3-4%	**Parent Material**	
Aspect	North-West	**Underlying Material**	

Horizon	**Depth**	**Description**	**Diagnostic Horizon**
A	0-300	Dry; Dry colour: 10YR 5/6, dark yellow/brown; Moist colour: 10YR 4/4 Consistence: Hard; Structure: Moderate-Weak	Orthic A
Transported Material	300-550	Dry; Dry colour: 10YR 5/8, dark yellow/brown; Moist colour: : 10YR 4/4 Consistence: Slightly Hard; Structure: Weak; High small coarse fragment content.	Transported Material
B	550-1000	Dry; Dry colour: 7.5YR 5/8, yellowish, red; Moist colour: 7.5YR 5/6 Consistence: Soft; Structure: Moderate-Strong. Mottles present.	Pedocutanic B

Profile	Next-to-Road		
Latitude	-33.282	**Soil Form**	
Longitude	18.711	**Soil Family**	
Altitude	190m	**Soil Map Unit**	
Terrain Unit	Footslope	**Vegetation/Landuse**	Cultivated/Wheatfield
Slope	3-4%	**Parent Material**	
Aspect	North-West	**Underlying Material**	

Horizon	**Depth**	**Description**	**Diagnostic Horizon**

Profile	Dam		
Latitude	-33.286	**Soil Form**	Swartland
Longitude	18.707	**Soil Family**	2211
Altitude	171m	**Soil Map Unit**	
Terrain Unit	Valley Floor	**Vegetation/Landuse**	Cultivated/Wheatfield
Slope	1%	**Parent Material**	
Aspect	North-West	**Underlying Material**	

Horizon	**Depth**	**Description**	**Diagnostic Horizon**
A	0-300	Dry; Dry colour: 10YR 5/8, yellowish-brown; Moist colour: 10YR 4/3; Consistence: Hard; Structure: Moderate blocky; Bleached.	Orthic A
B	300-750	Dry; Dry colour: 2.5YR 4/8, reddish; Moist colour: 2.5YR 4/3; Consistence: Hard; Structure: Moderate-strong; Mottles present	Pedocutanic B
Unspecified	750-1000	Dry; Dry colour: 5YR 5/8, yellowish-red; Moist colour: 5YR 4/6, yellowish red; Consistence: Hard; Structure: Brittle	Saprolite

Profile	Saltbush		
Longitude	18.706	**Soil Family**	2200
Altitude	167m	**Soil Map Unit**	
Terrain Unit	Valley Floor	**Vegetation/Landuse**	Saltbush
Slope	1-2%	**Parent Material**	
Aspect	North-West	**Underlying Material**	

Horizon	**Depth**	**Description**	**Diagnostic Horizon**
A	0-200	Dry; Dry colour: 5YR 5/4, , yellowish-red; Moist colour: 5YR 3/4; Consistence: Hard; Structure: Moderate;	Orthic A
B	200-600	Dry; Dry colour: 2.5YR 5/6 reddish; Moist colour: 2.5YR 4/6; Consistence: Hard; Structure: Strong Blocky; Mottles	Prismacutanic B
Unspecified	600-1000	Dry; Dry colour: 2.5YR 5/6 reddish; Moist colour: 2.5YR 4/8; Consistence: Hard; Signs of wetness;	Saprolite

APPENDIX 2 - SOIL TEXTURE ANALYSIS

Site	Soil Form	Soil Horizon	Depth (mm)	Sand (%)					Silt (%)			Clay (%)	Texture Class	Sand grade
				Coarse Sand (%)	Medium Sand (%)	Fine Sand (%)	Very Fine Sand (%)	Total (%)	Coarse Silt (%)	Fine Silt (%)	Total (%)	Total (%)		
Upper Renosterveld	Glenrosa 2211	Orthic A	0-300	18.96	8.60	14.86	18.32	60.73	21.56	9.35	30.91	8.36	Sandy-Loam	Coarse sand
		Litocutanic B	300-400	13.64	8.83	14.92	16.21	53.60	34.97	0.00	34.97	11.42	Sandy - Loam	Coarse sand
Lower Renosterveld	Glenrosa 2211	Orthic A	0-400	22.97	9.38	14.85	16.82	64.02	31.49	0.05	31.54	4.44	Sandy - Loam	Coarse sand
		Litocutanic B	400-500	23.22	9.03	10.88	11.05	54.17	36.67	0.08	36.75	9.07	Sandy - Loam	Coarse sand
Borehole	Oakleaf 2220	Orthic A	0-300	15.23	8.17	16.29	15.86	55.56	35.55	0.11	35.66	8.78	Sandy - Loam	Coarse sand
		Transported Material	300-550	18.64	7.79	13.72	14.27	54.41	30.82	0.00	30.82	14.77	Sandy - Loam	Coarse sand
		Pedocutanic B	550-1000	5.25	3.45	6.08	4.61	19.39	5.79	17.61	23.40	57.21	Clay	Coarse sand

Site	Soil Form	Soil Horizon	Depth (mm)	Sand (%)					Silt (%)			Clay (%)	Texture Class	Sand grade
				Coarse Sand (%)	Medium Sand (%)	Fine Sand (%)	Very Fine Sand (%)	Total (%)	Coarse Silt (%)	Fine Silt (%)	Total (%)	Total (%)		
Next-to-Road	Swartland 2111	Orthic A	0-300	15.55	5.64	12.01	16.30	49.50	30.45	3.10	33.55	16.94	Loam	Coarse sand
		Pedocutanic B	300-800	12.02	3.91	8.06	8.86	32.85	12.50	9.50	21.99	45.15	Clay	Coarse sand
		Saprolite	800-1000	10.85	3.03	5.30	7.19	26.36	16.92	4.29	21.21	52.43	Clay	Coarse sand
Dam	Swartland 2211	Orthic A	0-300	19.85	8.56	17.16	19.24	64.81	17.85	4.51	22.36	12.83	Sandy - Loam	Coarse sand
		Pedocutanic B	300-750	6.69	2.65	3.16	1.96	14.45	1.72	13.89	15.61	69.93	Clay	Coarse sand
		Saprolite	750-1000	18.53	7.86	8.21	5.20	39.79	6.87	17.81	24.68	35.53	Clay - Loam	Coarse sand
Saltbush	Sterkspruit 2200	Orthic A	0-200	13.29	6.63	15.90	13.74	49.55	22.80	8.75	31.55	18.90	Loam	Coarse sand
		Prismacutanic B	200-600	4.45	2.64	4.91	5.21	17.21	31.40	0.00	31.40	51.39	Clay	Coarse sand
		Saprolite	600-1000	15.51	6.76	6.99	4.79	34.03	3.66	49.06	52.72	13.24	Silty-Loam	Coarse sand

APPENDIX 3 – PHYSICAL- AND CHEMICAL SOIL PROPERTIES

Site	Soil Form	Soil Horizon	Depth (mm)	Bulk Density (g/cm^3)	Coarse Fragments (%)	pH (H_2O)	pH (KCl)	EC (mS/m)
Upper Renosterveld	Glenrosa 2211	Orthic A	0-300	1.29701	34.84	5.42	4.26	8.3
		Litocutanic B	300-400		99.56	5.35	4.04	8.1
Lower Renosterveld	Glenrosa 2211	Orthic A	0-400	1.34929	27.56	6.48	5.42	6.6
		Litocutanic B	400-500		99.13	6.27	4.55	6.5
Borehole	Oakleaf 2220	Orthic A	0-300	1.55239	41.58	5.64	4.93	11.3
		Transported Material	300-550	1.86759	56.33	6.72	5.33	5.1
		Pedocutanic B	550-1000	1.72595	15.98	6.90	5.91	9.2
Next-to-Road	Swartland 2111	Orthic A	0-300	1.61013	52.57	6.75	5.94	5.8
		Pedocutanic B	300-800	1.84533	38.79	7.36	6.21	7.8
		Saprolite	800-1000	1.90233	36.77	7.24	6.19	15.2
Dam	Swartland 2211	Orthic A	0-300	1.60020	41.75	5.78	5.17	18.8
		Pedocutanic B	300-750	1.67495	23.09	6.14	5.11	10.5
		Saprolite	750-1000	1.81185	28.16	5.87	4.15	28.0
Saltbush	Sterkspruit 2200	Orthic A	0-200	1.31705	20.59	7.57	6.86	65.0
		Prismacutanic B	200-600	1.34842147	46.27	8.22	7.46	214
		Saprolite	600-1000	1.393497644	54.62	8.56	8.15	576