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Hydrosalinity Fluxes in a Small Scale Catchment of the Berg River (Western Cape)

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DECLARATION

I, Richard D.H. Bugan, hereby declare that,

“Hydrosalinity Fluxes in a Small Scale Catchment of the Berg River (Western Cape)”

is my own work, that has not been submitted at any other university for a masters degree in Environmental Science and that all the sources I have used have been indicated by means of proper references.

Signature:

Date: July 2008

Abstract

The occurrence of dryland salinity is widespread throughout semi-arid regions of the world. The sources of salts may be either rock weathering or rain deposition. Clearing of natural scrubland to make way for cultivated crops and pastures may also change the water balance, trigger salt mobilization and increase the salinity of water resources. These processes are suspected to be the main cause for salinization of the Berg river catchment (Western Cape). The objective of this study was to determine the hydrosalinity fluxes associated with overland and subsurface (vadose zone) flow for different soils and land uses. For this purpose, the following data were collected during 2005 and 2006 in a typical small scale catchment located near the town of Riebeeck-Wes: weather data, hydrological and water quality measurements, soil water contents and chemistry, and vegetation growth. The area is characterized by a Mediterranean climate receiving winter rainfall of approximately 300 mm a^{-1}. The chemical speciation of water and soil in the catchment is conservative, with Na^+ and Cl^- being the dominant ions. The results of the monitoring indicated that uncultivated (bare) soil produced more runoff and higher salinity compared to vegetated land. Overland flow varied between 5 and 17% of rainfall, mobilizing up to 23.55 g m^{-2} of salts during 2006, depending on soil properties, slopes, rainfall intensity and duration, and antecedent moisture conditions. Due to the typical low intensity of rainfall, the fluxes of salts during individual runoff events were steady. Soil water and salt contents varied seasonally. Fluctuations in salinity due to local processes were evident on a smaller scale at a catchment scale. Subsurface fluxes of water and salts were estimated with the HYDRUS-2D model. The model showed that approximately 700 g m^{-1} of salts were mobilized by subsurface flow along a 22 m long soil profile. Management practices at farm scale are required in order to reduce salt mobilization and salinization at catchment scale.

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Chapter 1

1. Introduction

It is becoming more and more evident that non-point source pollution greatly affects the quality of water in water bodies, with special reference to inorganic salts, eutrophication, sediments, pathogens, pesticides and heavy metals. Agricultural activities have been identified as a major source of non-point source pollution, in terms of sediments, pesticides, inorganic salts and nutrients both locally and internationally. It is also believed that these agricultural activities have indirectly caused the salinization of dryland areas around the world. Such is the case in the Western Cape region of South Africa. The most common result of dryland salinity is, amongst others, an increase in the salt concentration of the soil solution and surface water bodies. The Berg River, which flows in the Western Cape, is an example of a water body, which has been exhibiting increases in salt levels.

The occurrence of dryland salinity is widespread throughout the semi-arid regions of the world such as Australia, South Africa, Argentina and India. Its occurrence is characterized by the presence of dying vegetation, a decline in the vegetation cover density, and by the appearance of salt tolerant species, bare salty patches and the development of saline pools. The process generally encompasses the deposition/precipitation of salts at the soil surface and the increase of salinity in receiving waters through the mobilization of these salts. The salts may either be a product of the weathering of rock minerals or it may be brought into the landscape, from the ocean, by rain or wind. In Australia the problem of dryland salinity has assumed epic proportions throughout much of the country. The cause can be attributed to the clearing of natural scrubland to make way for cultivated crops and pastures, thereby changing the water balance (Greiner, 1998; Gilfedder *et al*, 1999; Acworth *et al*, 2001). According to Cullis *et al*, (2005), inorganic salts influence the salinity, acidity and alkalinity of water resources. The salinity of a water body may negatively affect the growth of aquatic plants or it may limit the possible utilization of the water.

In South Africa, the process is especially common to some of the major catchments in the Western Cape. Wheatlands in the Swartland and Overberg regions are known to contain saline patches which are recognized to be natural sources of salts. It is a possibility that changes in land use over the last century or more may have triggered the process of salt mobilization, similar to that which is so widespread in Australia. This seems especially likely in the semi-arid part of the Western Cape, which posses certain similarities to Western Australia in respect of climate, soils, natural salt levels in the regolith, topography and land use practices (Fey and De Clercq, 2004).

The process of dryland salinization poses a major threat to Integrated Water Resources Management (IWRM), environmental preservation and socio-economic development in South Africa. According to Gilfedder *et al* (1999), the effects of dryland salinity include an increase in stream salinity, and losses of remnant vegetation, riparian zones and wetland areas. It may also result in a decline in soil productivity, farm incomes and land value.

1.1 Aims and Objectives

A project, titled Land use impacts on salinity of Western Cape waters, was commissioned by the Water Research Commission (WRC) with the aim of studying the effects that land use change in the Western Cape has and is having on the hydrosalinity dynamics of the Berg River catchment and eventually on the Berg River itself. The approach taken involves relating groundwater and regolith salinity and geochemistry to climate, parent material, land use, meteoric factors (rain and wind), etc. The relevant data were used to study the seasonal salt flux into, within and out of a selected small scale catchment (SSC) and for modeling of the hydrosalinity dynamics.

The project on which this thesis was based forms part of the broader project which was commissioned by the WRC, and essentially focuses only on the selected SSC, i.e. Goedertrou, which is in close vicinity of the town, Riebeeck-Wes. The general objective of this project was to develop a thorough understanding of the water and salinity dynamics in runoff and in the soil and vadose zone of the small dryland catchment representative of semi-arid conditions. The quantity and chemistry of rainfall was also to be monitored to study its contribution, in terms of inorganic salts, to the SSC. These salinity dynamics were studied under different land use practices, ranging from dense vegetation to bare soil. These hydrosalinity fluxes were monitored at two scales, i.e. at a local processes scale, which involves the monitoring of runoff, soil salinity, soil moisture and climatic conditions, and at a field scale, which essentially involves monitoring of the water quality in the dam, which is situated in the SSC. It was aimed that these hydrosalinity dynamics be used to estimate the quantity of salts and water flushing out of the SSC. The monitoring at the local scale would also allow for a reasonable estimate to be made of how different land uses and different planting densities would affect these water and salt dynamics.

The specific objectives of the project were:

- To determine the hydrosalinity fluxes associated with overland flow from different soil types and land uses in a representative SSC of the Berg River.
- To monitor the subsurface (vadose zone) fluxes of water and salts for different soils and land management practices in a typical SSC of the Berg River.
- To determine the salinity and chemical speciation of waters, i.e. rainfall, overland flow and soil waters, of the SSC.
- To determine the dynamics of water movement and salt mobilization during individual rainfall events.

1.2 Thesis Outline

An introduction to the topic as well as the motivating factors is presented in Chapter 1. The aims and objectives are also outlined and highlighted. Chapter 2 presents information and data that were gleaned from relevant local and international literature. The most relevant topics and issues addressed in this thesis are thoroughly investigated and discussed. The experimental set-up, including a description of the study area, is illustrated and discussed in Chapter 3. Chapter 4 presents the results and findings in the form of graphs and tables. These are also discussed and extensively analyzed. Conclusions and deductions that were made from experimental results are presented in Chapter 5 and recommendations for further research are discussed in Chapter 6.

Chapter 2

2. Literature Review

2.1 Definition of Soil Salinity

Salinity is defined as the presence of salts in soil and water. It is most commonly expressed as EC (electrical conductivity). Electrical conductivity is the property of a material to conduct electricity. The ease with which the current passes through water is proportional to the salt concentration in the water. Therefore, the greater the salt concentration, the higher the EC. It is commonly expressed as Siemens, i.e. deciSiemens (dS), milliSiemens (mS) and microSiemens (µS), per unit distance of measurement. It may also be expressed as Total Dissolved Salts (TDS), measured in terms of Parts per Million (ppm), or mg L^{-1}. Salts are soluble mineral substances present in soil and water. The salts most commonly affecting soil and water are Sodium Chloride, Magnesium Chloride and Calcium Chloride (Department of Primary Industries, Water and Environment, 2006).

Peck and Hatton (2003) investigated the salinity and discharge of salts from catchments in Australia. They stated that surface soils (0–0.2 m depth) are said to be saline if salinity exceeds 0.1 % in loams and coarser (larger particle size) soils, or 0.2 % in clay loams and clays, and sub-soils are said to be saline when salinity exceeds 0.3 % (cited from Northcote and Skene, 1972). These criteria approximate an electrical conductivity (EC) of the saturation extract of about 4 dS m^{-1}, which is the criterion for saline soil used by the US Salinity Laboratory (Peck and Hatton, 2003) and which is used in many countries. In saline soils, crop growth is hampered by salt accumulation in the crop root zone. If the upward salt movement exceeds the downward movement, salt will accumulate in the root zone. Salt in the soil interferes with the crop growth when its concentration exceeds the tolerance limits of the crop (American Society of Civil Engineers, 1990; Karim *et al*., 1990; Somani, 1991, as cited by Mondal *et al*, 2000). Most plants suffer salt injury at a concentration equivalent to electrical conductivity of the soil saturation extract (ECe) of 4 dS m^{-1} or higher. At such a level of salinity, plant growth is restricted even though enough water may be present in the root zone (American Society of Civil Engineers, 1990; Karim *et al*., 1990, as cited by Mondal *et al*, 2000).

Dryland salinity affects land and water resources on site, e.g. at the farm scale, but also elsewhere in the catchment (downstream). On farms, salinity damages infrastructure, salinizes water resources, causes loss of farm flora and fauna and loss of shelter and shade. Salt may be mobilized as wash off from the land surface by water running into streams, as lateral sub-surface seepage or as groundwater seeping directly into streams and rivers as base flow. Salinity is also having a major impact on public resources such as water supplies, thereby affecting our sources of drinking water and irrigation (National Land and Water Resources Audit, 2001).

According to Chapman (1966), sodium chloride is the predominant salt determining salinity, followed by sodium carbonate or sodium sulphate and salts of magnesium. Where sodium chloride is concerned, a concentration of 0.5 % in the soil solution can be regarded as a critical concentration. He further states that at values exceeding 0.5 % sodium chloride, one may expect to increasingly encounter salinity problems, in respect of soil characteristics, plant metabolism and vegetation cover density.

Accordingly, the salinity of inland areas is influenced by various factors:

- Precipitation- its magnitude affects the degree of leaching and the depth of the salt layer.
- Nature of the soil- a soil that is composed of a high proportion of clay or silt as compared with the sand fraction will be more severely impacted in the presence of excess sodium and magnesium.
- The vegetation- if the vegetation is dense it will minimize the loss of water from the soil surface but the transpiration demand of the plants might result in the rising of soil water. This will in turn result in the mobilization of salts towards the surface. With a low vegetation cover density, evaporation will tend to increase, which may result in the surface layers of soils having very high concentrations of salts in the summer months.

- Slope of ground- influences the drainage pattern and the soil is usually more saline towards the foot of slopes, where water tends to accumulate.
- Depth of soil water table- a shallow water table usually results in more constant soil salinity.
- The depth of the salt deposit- the nearer this is to the surface, the more saline the surface layers will be unless there are periods of heavy precipitation.
- Water inflow into a region- commonly, water inflow into arid regions comes from surrounding higher-lying areas. Such water is usually less-saline, which results in dilution of salts in the basin. In many areas, however, the inflow of fresh water still does not exceed the average losses by evaporation, which maintains the high salinity.

2.2 Sources of Salts

Meteoric Factors (Rainfall and Wind)

A possible explanation for the occurrence of salts in a landscape is the combination of a semi-arid climate with close proximity to the ocean. Rainfall and wind can transport salts of marine origin and deposit them on land and in surface waters. A study undertaken by Flügel (1995), in the Western Cape, reported that the mean annual rainfall is approximately 400 mm, and has a salt concentration, from the ocean, of 37 mg L^{-1}. Sodium and chloride, transported by wind and rain from the Atlantic Ocean, were the dominant ions. Hingston and Gailitis (1976) also reported that the annual accumulation rate of salt, i.e. mainly sodium and chloride, in the wheat belt of Western Australia was 100-250 kg ha^{-1} in high rainfall coastal areas and approximately 10-20 kg ha^{-1} 300 km inland. Chapman (1966) presented similar findings. He stated that in South West Africa, it occurs that salts are blown in from the sea over centuries and deposited inland (aeolian salts). According to Bresler *et al.* (1982) the atmospheric salt composition changes with increasing distance from the coast. Absolute Cl^- and Na^+ concentrations in the rainfall decrease as the air mass moves further inland.

Fossil Salts

The presence of fossil salts may also produce dryland salinity. Fossil salts are salts deposited in marine sediments of ancient seas. These sediments are buried, lithified, then uplifted and become parent material for the soil. Evaporation of groundwater can concentrate these salts at the surface thereby degrading the soil. The present hard pans and soils of the North- western coastal area of Western Cape developed as a result of inland sea water intrusion (Malherbe, 1953).

Inland lake basins, in which the natural drainage outlet ceases to exist, resulting in the drying up of the former lake may also act as a source of salt (Chapman, 1966). This produces an intense concentration of salts that accumulates in the waters.

Mineral Weathering

Sedimentary rocks in South Africa (e.g. Dwyka Series, the Malmesbury shale and the Enon conglomerate) are rich in soluble salts that if weathered to soil material may cause an accumulation of salts under low rainfall conditions (Malherbe, 1953). These salts may remain in the original soils resulting in the area becoming saline. During the wet winter, flood and seepage water transport salts from the higher- to lower-lying areas where the water evaporates and the salts are left to concentrate at the soil surface. The salts in the districts of Malmesbury and Picketberg in the Western Cape are believed to have originated from the sea as well as from the weathering of the underlying bedrock (Malherbe, 1953).

Anthropogenic Sources

The dominant human activities, which may produce saline areas are land use activities such as irrigated agriculture and mining. The improper use of fertilizers or irrigation with poor quality water adds to the salinity of a landscape (McBride, 1994). The clearing of natural veld has also, in many instances, resulted in the salinization of dryland areas (Greiner, 1998; Gilfedder *et al*, 1999; Acworth and Jankowski, 2001).

2.3 Types of Salinity

Primary Salinity

Primary soil salinity occurs naturally in the landscape and affects the development of that landscape over time. Examples of areas affected by primary salinity are marine plains, coastland regions, salt lakes and pans. Primary salinity develops as a result of the deposition of oceanic salts or as a result of the salt transporting action of rain and wind (Hingston and Gailitis, 1976). In a primary soil salinization process, salt stored in the soils or groundwater is concentrated through evaporation and transpiration by plants.

Secondary Salinity

Secondary soil salinity is the salinization of land caused by human activities, which alter the hydrological cycle. This category of soil salinity emanates from irrigation and dryland management systems which result in rising water tables mobilizing salt in the soil (Cartwright *et al*., 2004). Secondary salinity is also termed dryland salinity. Dryland salinization is induced by extensive changes to the vegetation cover in a catchment, which is generally associated with the clearing of native vegetation (Greiner, 1998; Gilfedder *et al*, 1999; Acworth and Jankowski, 2001). The introduced farming systems generally use less water and resultantly larger volumes of runoff are produced and/or larger amounts of rainfall recharge the groundwater system. An increase in recharge produces a rise in the water table (Figure 1). The groundwater dissolves and mobilizes salts that were stored above the old water table in the previously unsaturated regolith and brings them to the surface. This produces an increase in soil, and eventually stream, salinity. Peck and Hurle (1973) as cited by Peck and Hatton (2003), used stream gauging and rainfall records, and measurements of the salinity of rainfall to estimate the chloride balance of catchment areas in southwest Australia that remained under natural forest vegetation or had been partly cleared and developed for dryland agriculture. They showed that whereas there was close to a balance between input and output of chloride in the uncleared catchments, the ratio of output to input in partly farmed areas ranged from 3.1 to 21. Salinized land often develops in lower valley locations and at breaks of slope, however, topography alone is not sufficient to predict the location of salinized areas (Barrett-Lenard and Nulsen, 1989).

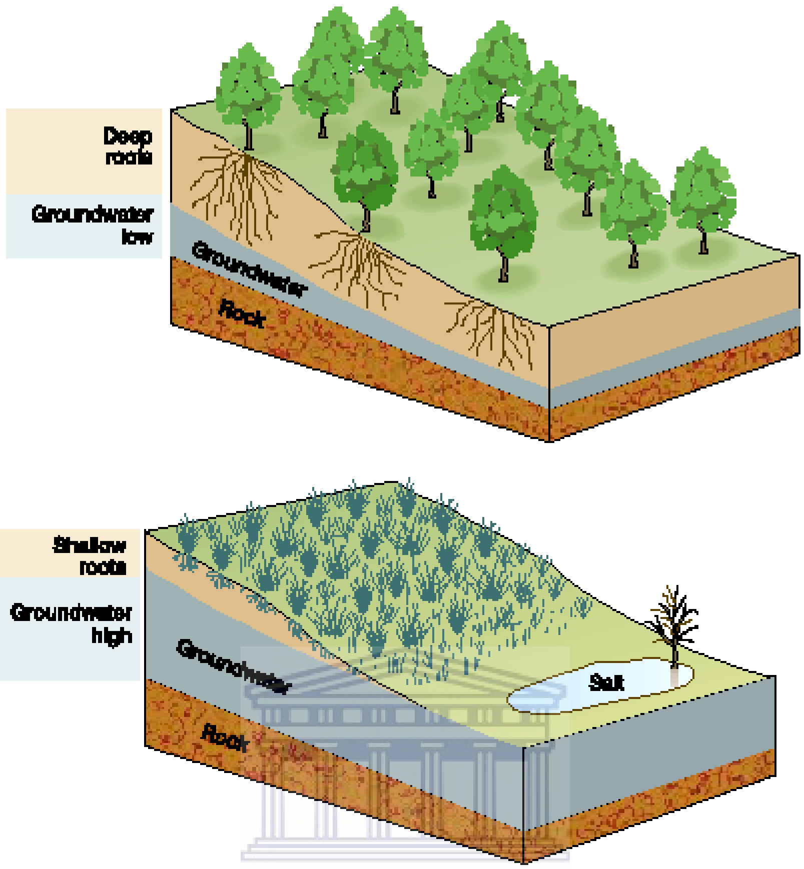


Figure 1. Replacing native vegetation with shallow rooted annual crops and pastures have led to substantial increases in the amount of water ‘leaking’ into the soil. The consequences are rising groundwater levels and dryland salinity (Gilfedder *et al*, 1999).

According to M.V Fey (personal communication), the dynamics of the process differs in the Western Cape. Evaporation from saline groundwater results in the precipitation of salts at the soil surface and consequently the formation of saline scalds. These salts are then distributed further by overland flow.

2.4 Description of the Berg River Catchment

The Berg River rises in the Franschhoek and Jonkershoek mountains and flows in a north westerly direction where it eventually discharges into the sea at Laaiplek. The river is approximately 270 km long and has a catchment size of approximately 900 km^2 (DWAF, 1993). On the eastern side a range of mountains bound the catchment, whilst on the western side it flattens out into a hilly plain. Present land cover in the catchment can primarily be sub-divided into agricultural, forestry and urban. Agricultural land use is further divided into irrigated and dryland farming activities. The latter of these make up the largest portion of the catchment (DWAF, 1993). The Berg River catchment is characterized by a Mediterranean climate with warm dry summers and cool wet winters. Mountainous areas in the southern parts of the catchment experience a Mean Annual Precipitation (MAP) in excess of 2 600 mm a^{-1}, whilst the MAP gradually decreases westwards to approximately 300 mm a^{-1} along the West Coast.

The geology of the Berg River basin (Figure 2) is dominated by the Malmesbury Group and the Table Mountain Group. Downstream of Paarl/Wellington sandstone formations are replaced by the Malmesbury Shales as one goes down the stratigraphy. Thereafter, tributaries on the eastern bank of the river drain areas that are dominated by the Table Mountain Sandstone, whilst the saline Malmesbury Shale is the dominant geological formation for tributaries draining the western bank (DWAF, 1993).

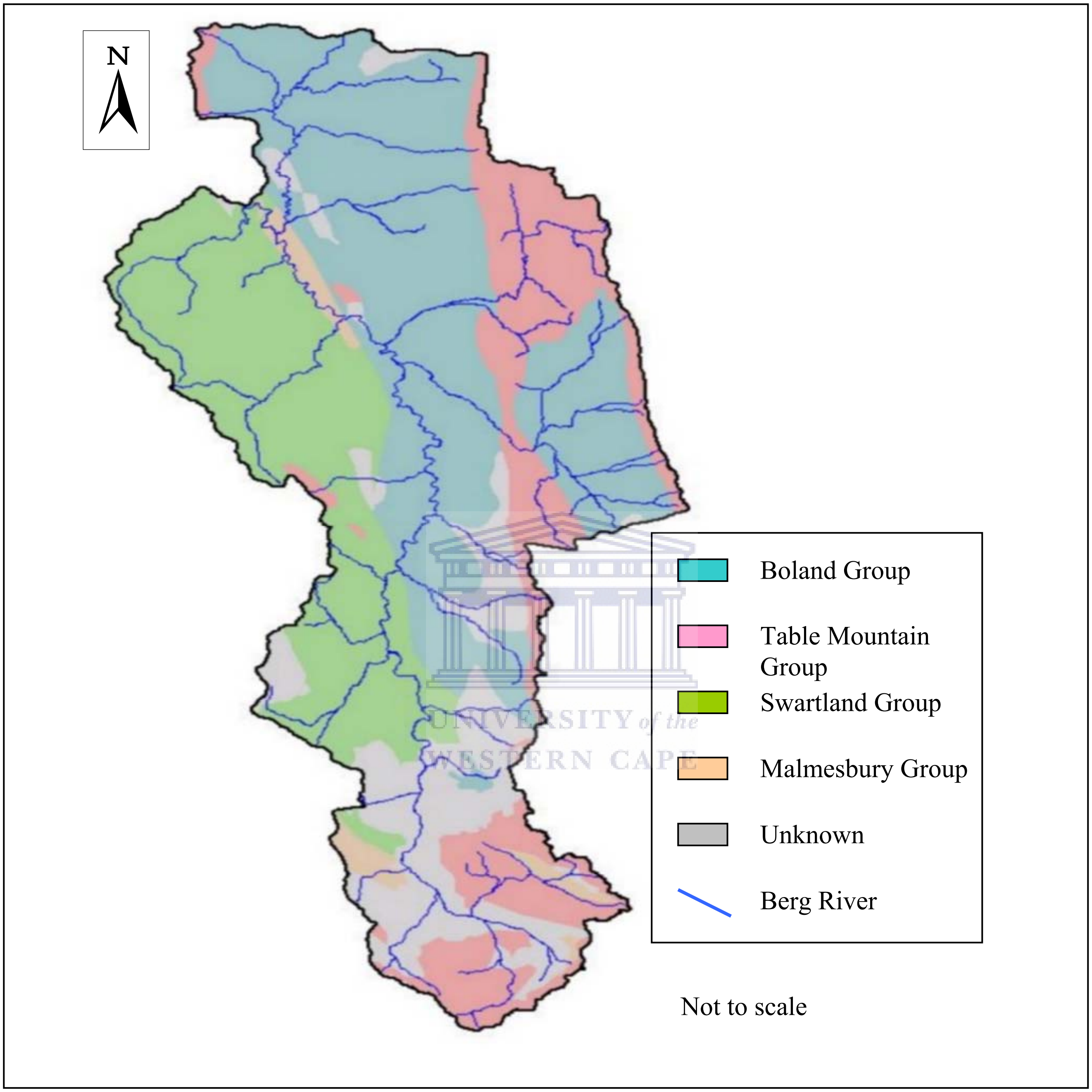


Figure 2. The Geology in the Berg River Catchment (DWAF, 1993)

2.5 Studies Conducted in the Berg River Catchment

According to Fourie (1976), the West Coast of South Africa is a semi-arid region in which dryland salinity is expected. The Department of Waters Affairs and Forestry (DWAF) has monitored Berg River water quality since the mid 1970s. Natural soil salinity has already been identified as the source of some of the salts affecting the water quality of the Berg River (Fourie and Steer, 1971; Fourie and Gorgens, 1977). Fourie assessed the salinity of the Berg River in 1976 (Figure 3) by focusing on certain Berg River tributaries on the west bank as well as on the east bank below Voëlvlei and found them to be naturally quite saline.

In 1977, Fourie and Görgens investigated the mineralization of the Berg River. It was found that the salinity increase of the river could be the result of increasing irrigation practices along the river. According to Nitsche *et al.* (2006), tributaries of the Berg River draining Malmesbury Shales possess a high salinity. High salinities were also observed in waters running off Malmesbury Shales. As a result, these waters are highly unsuitable for irrigation and thus losses in yield should be expected. Alternatively, the tributaries draining the Table Mountain Sandstones, as the dominant geological formation, show low salt levels.

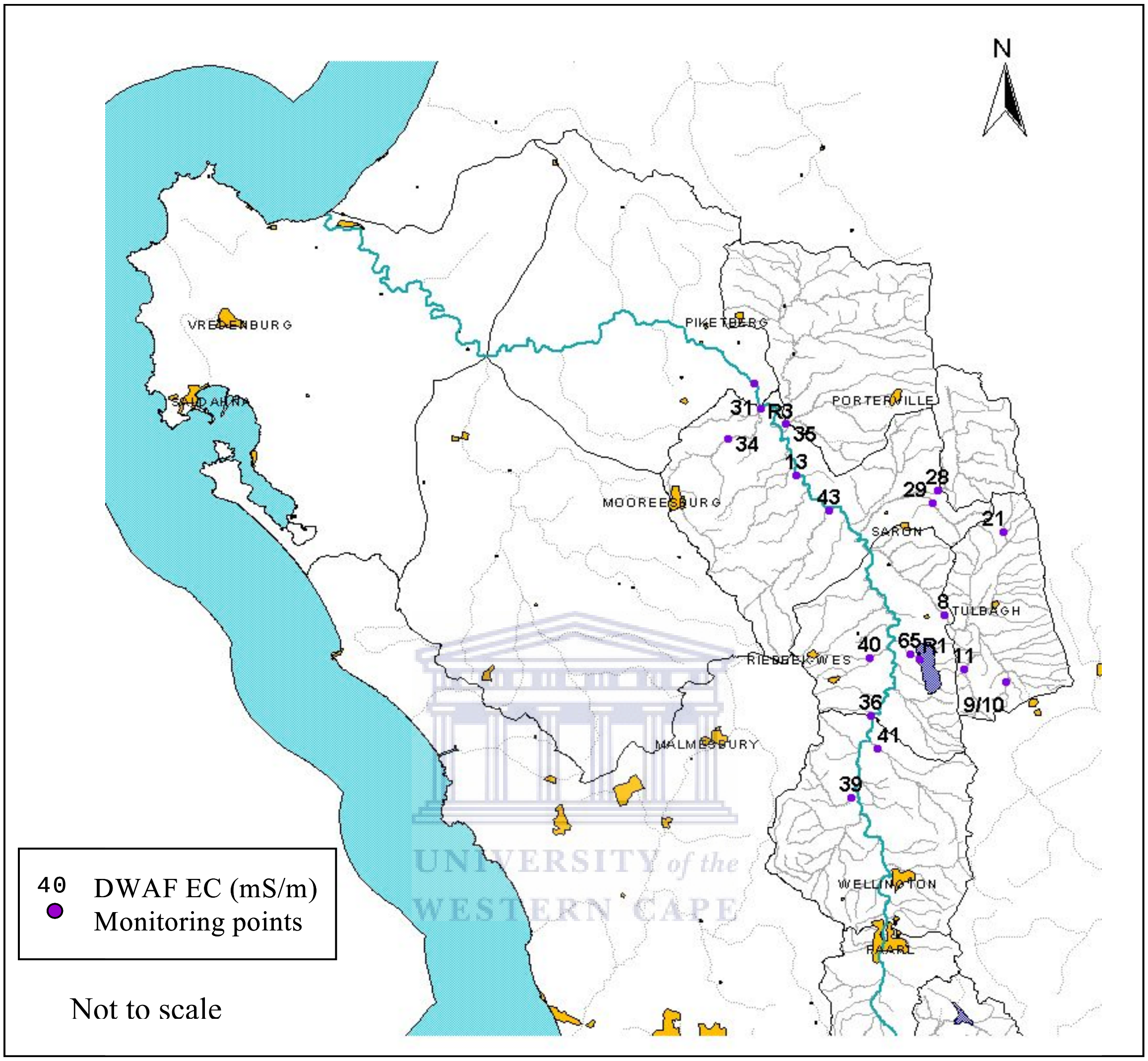


Figure 3. ArcView image of a portion of the Berg River catchment showing DWAF monitoring points in the area studied by Fourie, 1976 (Fey and de Clercq, 2004).

Nitsche *et al.* (2006) also studied the pH associated with the Berg River and its tributaries. The pH of natural waters influences the physical, chemical and biological processes in the system. It was observed that the tributaries draining the Table Mountain Sandstones tend to be more acidic, as this formation tends to erode to acidic soils. Downstream, however, the waters tend to be more alkaline.

A recent publication by Fey and De Clercq (2004) is extremely pertinent to this study. Their pilot study was undertaken to determine whether a more extensive investigation is required of dryland agricultural impacts on river salinity. Valuable results were produced. It was reported that dryland salinity is extensive and that it is likely to have a significant impact on the water quality of the Berg River. Extensive patchiness in croplands, especially in wheat fields, which dominate the land use in the Berg River catchment, has been identified. Ground truthing of these patches has consistently confirmed that they are associated with soil salinity. Modeling of runoff under different vegetation scenarios (winter wheat and renosterveld) suggested that land use changes have a potential impact on salt release from the regolith into surface water. The soils were found to be sufficiently saline to affect wheat growth. The findings of this study suggested the need for a more detailed survey of salt distribution in the soils, regolith, and ground- and surface waters coupled with a fundamental study of salt mobilization in response to climate, topography and land use practice in a small scale catchment.

Flügel (1995), extensively studied river salination due to dryland agriculture between 1985 and 1986 in the 150 km^2 catchment of the Sandspruit River, a tributary of the Berg River. All major water bodies within the basin were investigated with the aim of identifying and quantifying their salinity dynamics. Flügel reported that dryland agriculture contributed to river salination based on the findings that the bulk annual atmospheric deposition accounted for only a third of the total salt output for 1986. He stated that the remainder was delivered by groundwater and interflow from the weathered shale and the soils within the catchment.

2.6 Combating Dryland Salinity

To limit the spread of dryland salinity, a substantial change to farming systems is required (Clarke *et al.*, 2002; Gilfedder *et al.*, 1999). Restoring the native vegetation by regeneration or replanting lowers water table heights locally, but field evidence suggests that this restoration needs to be extensive for it to have regional effects. The general consensus is that alley cropping will allow the agriculture to be continued in the bays between the rows, but this method would require as much perennial, preferably deep rooted, vegetation as possible in the bays to achieve the required recharge reductions. It is also generally believed that where the asset to be preserved is valuable and an efficient method of disposal exists, then pumps and drains will form part of the salinity management system. According to Pannel and Ewing (2006), the main action to prevent groundwater tables from rising is the establishment of perennial plants, either herbaceous (pastures or crops) or woody (trees and shrubs). Where these saline water tables are already shallow, farmers still have the option of planting salt tolerant species, e.g. saltbush. Angus *et al.* (2001) suggest that lucerne pastures and improved crop management can result in greater use of rainfall than annual pastures, fallows, and poorly managed crops. The tactical use of lucerne-based pastures in sequence with well-managed crops can help with the dewatering of the soil and reduce or eliminate the risk of groundwater recharge.

2.7 Hydrosalinity Modeling

2.7.1 Hydrological Processes

Preliminary data collected on the characteristics of the study area, i.e. soil and pedology, geology, climate, topography, vegetation and land-use, were used to determine, which were the dominant water and salt balance processes in the study area, i.e. Goedertrou (Jovanovic, 2005). The processes that were identified are:

- Runoff (including stormflow, sediment yield and solute washoff)
- Vertical water and solute fluxes (including preferential flow and soil phase-water solution interactions)
- Throughflow (including subsurface lateral water and solute fluxes)

Surface Runoff

Along with leaching, solute washoff is the most direct process involved in the salinization of water resources (Wasson, 1998). This washoff is dominantly observed as concentrated flow in rills or gullies (McLaughlin *et al.*, 1998). According to Baldwin *et al.* (2002), inorganic salts may be transported, on the surface either as solutes or they may be attached to suspended particles. The solute component is influenced by precipitation and surface runoff, whilst absorbed salts are linked to sediment transport (Johanson, 1983).

Vertical Water and Solute Fluxes

According to Jovanovic (2005), a reliable estimate of water fluxes is essential for the accurate prediction of solute fluxes. These vertical water fluxes in the soil profile can be simulated using tipping bucket (cascading) models, which are based on soil-specific field capacity levels. These models, however, generally lack the capability to model the upward movement of water and salts.

Solute redistribution in the soil profile can be simulated assuming complete mixing, piston flow, convection or convection-dispersion processes. Complete mixing of infiltrating water with the soil solution is a very rough approximation of salt redistribution, as preferential flow and diffusion (salt movement within the soil solution) are not considered. Jovanovic (2005) further states that current models simulate salt fluxes based on the convection-dispersion equation. This technique includes salt movement by convection, mechanical dispersion due to variations in velocity through pores of different size, and diffusion, which is controlled by concentration gradients. The movement of contaminants in the unsaturated zone is controlled by infiltration, which is governed by large suction gradients between the wetting front and dry media.

Throughflow

According to Jovanovic (2005), throughflow along impermeable or semi- permeable layers is widespread in the study area. Throughflow can be simulated based on empirical water redistribution fractions (Schulze, 1994). Alternatively, Richard’s equation with convective-dispersive solute flux can be applied, if gradients of water pressure heads and concentrations are known.

2.7.2 Model Review

Based on the above mentioned processes, several models have been identified, which are suitable for the purpose of this study, in terms of availability and ability to simulate 2D, layered systems as well as the relevant geohydrological and geochemical processes for inorganic salts. SWAT (Soil Water Assessment Tool), SWAP (Soil-Water-Atmosphere-

Plant) and HYDRUS-2D have been identified as possibly being the most suitable. However, CHEMFLO, FEHM and STANMOD were also considered.

SWAT

SWAT (Soil and Water Assessment Tool) (Arnold *et al*., 1995) is a 2D model that predicts the effects of climate and vegetative changes, reservoir management, groundwater withdrawals and water transfer on hydrology, pesticide and nutrient cycling, erosion and sediment transport in large, complex, rural river basins. SWAT can analyze watersheds and river basins of 100 square miles by subdividing the area into homogenous parts. It uses daily time steps for continuous periods from 1 to 100 years.

The hydrology is based on the water balance, i.e. it is represented by interception, evapotranspiration, soil percolation, lateral flow and groundwater flow and river routing processes. Soil profiles can be subdivided into 10 layers. Infiltration is defined in SWAT as precipitation minus runoff. Infiltration moves into the soil profile where it is routed through the soil layers. A storage routing flow coefficient is used to predict flow through each soil layer, with flow occurring when a layer exceeds field capacity. SWAT also provides for sediment yield and size, whilst the SWAT-GIS linkage incorporates advanced visualization tools capable of statistical analysis of output data. The model simulates both the land phase of the hydrological cycle, controlling the amount of water, sediment and nutrient loadings to the main channel in each sub-basin, and the water or routing phase of the cycle through the channel network of the watershed to the outlet (Chaplot, 2005).

Inputs include information from databases and information from a GIS interface. A soil database includes information on soil type, texture, depth and hydrologic classification. Spatially distributed parameters of elevation, land use, soil types and groundwater table are used in the model. More specific information can be entered singly, for each area or for the watershed as a whole.

Main outputs are sub-basin attributes (coordinates and boundaries), topographic attributes (stream length, stream slope and geometrical dimensions, accumulation area, sediment loss), groundwater attributes (time lag of groundwater flow for each sub-basin), routing structure for sub-basins, based on the elevation map. Also, it defines the channel width and depth using a neural network that is embedded in the interface, based on the drainage area and average elevation of a sub-basin.

SWAP

SWAP (Soil-Water-Atmosphere-Plant) (Kroes and van Dam, 2003) is a 2D, transient model for water flow and solute transport in the unsaturated and saturated zones. Applications vary from irrigation and salinity studies at field scale to water flow analysis in pesticide and nutrient studies at a national scale. The various components of the model are illustrated in Figure 4.

The model is based on Richards' equation for water flow and the convection-dispersion equation for solute transport. It includes interactions between soil, plant and atmosphere, interactions between surface water, soil water and groundwater (runoff, run-on, inundation, drainage and infiltration, preferential flow, throughflow for up to five different levels, groundwater recharge and capillary rise). Concerning solutes, SWAP includes processes like non-linear adsorption, first-order decomposition, plant root uptake, leaching and drainage to drains and ditches. In this way, solute transport from the soil surface to the surface waters can be simulated. System boundaries at the top are defined by the soil surface with or without a crop and the atmospheric conditions. The lateral boundary simulates the interaction with surface water systems. The bottom boundary is located in the unsaturated zone or in the upper part of the groundwater and describes the interaction with regional groundwater (Kroes and van Dam, 2003).

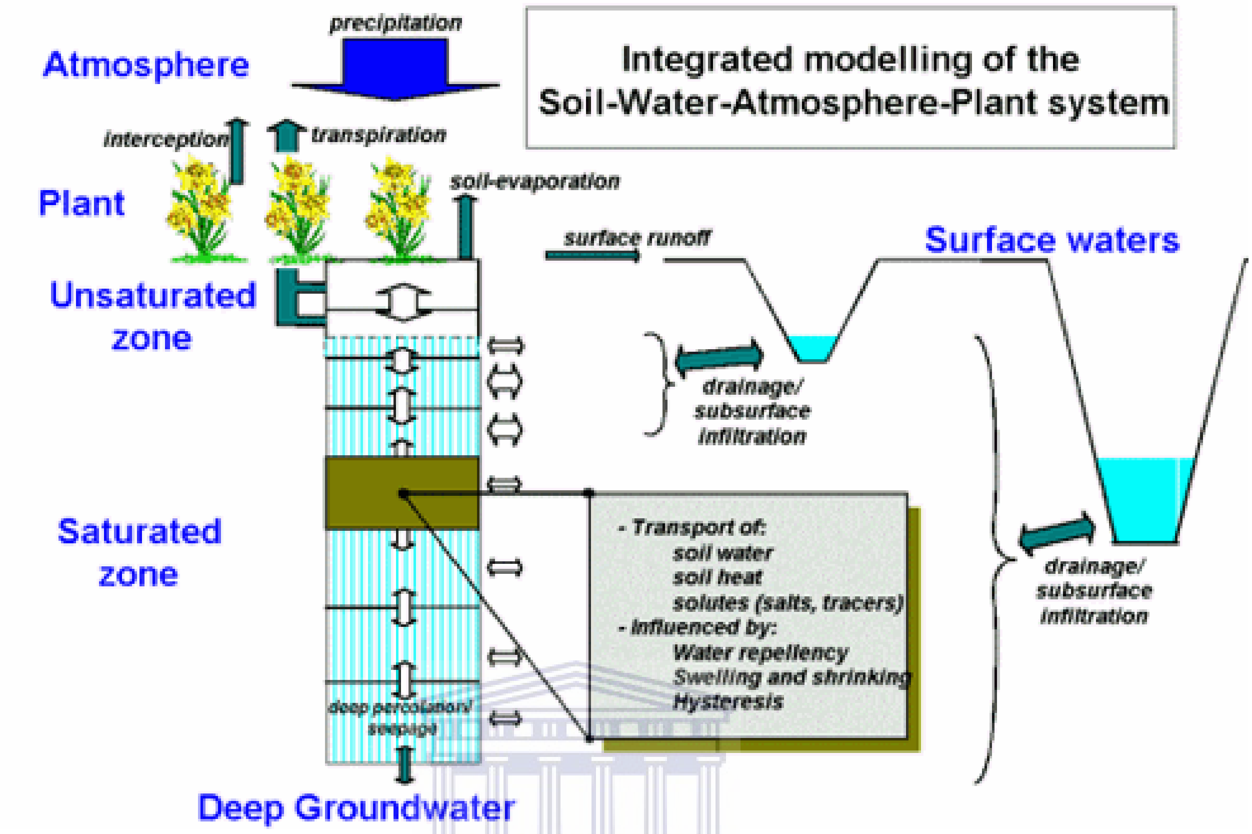


Figure 4. Conception of model SWAP after Kroes *et al*. (1998).

The SWAP model describes processes related to: soil water flow, soil heat flow, solute flow, crop growth, soil heterogeneity, interaction with surface water systems.

- **Soil water flow:** The well-known Richards' equation is applied integrally for the unsaturated-saturated zone, with possible presence of transient and perched groundwater levels.

$$C_w(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S_a(z)$$

Equation 1 (Richard's Equation; Singh *et al*., 2005), where C_W is the differential soil water capacity [L^{-1}], h the soil water pressure head [L], K the hydraulic conductivity [L T^{-1}], S_a the root water extraction rate [T^{-1}], and z the vertical coordinate [L] (positive upward).

Root water extraction at various depths in the root zone is calculated from potential transpiration, root length density and possible reductions due to wet, dry or saline conditions.

- **Soil heat flow:** Soil temperature may affect the surface energy balance, soil hydraulic properties, decomposition rate of solutes and growth rate of roots.

- **Solute flow:** The model SWAP simulates convection, diffusion and dispersion, non-linear adsorption, first order decomposition and root uptake of solutes. This permits the simulation of ordinary pesticide and salt transport, including the effect of salinity on crop growth.

$$\frac{\partial \theta C}{\partial t} = \frac{\partial}{\partial z}\left[q L_{\mathrm{dis}} \frac{\partial C}{\partial z} \right] - \frac{\partial q C}{\partial z}$$

Equation 2 (Convection-Dispersion equation, Van Genuchten and Cleary, 1979; Boesten and Van der Linden, 1991), where q is the water flux density [L T^{-1}], C the salt concentration [M L^{-3}], and L_{dis} the dispersion length [L].

- **Surface water systems:** Drainage to, or infiltration from surface water systems is calculated with Hooghoudt or Ernst drainage equations, which allow evaluation of the drainage design. The groundwater system can be modeled at the scale of a horizontal subregion with different surface water systems and options for surface water management. Drainage/subsurface water discharged towards surface water systems can be simulated with different residence times.

Input data are grouped into a general data file (main), weather, crop and lateral drainage data. The weather variables necessary for running SWAP are rainfall, minimum and maximum temperature, global radiation, air humidity and wind speed (Anuraga *et al.*, 2006). Main output data are water and solute balances, drainage fluxes, soil profiles of water and contaminants as well as final values of relevant variables. This model is especially useful in solving agricultural and hydrological problems.

HYDRUS-2D

HYDRUS-2D (Simunek *et al*., 1994) is a 2D model for modeling the movement of water, heat and multiple solutes in variably saturated porous media. The program numerically solves the Richard's equation for saturated-unsaturated water flow and the Fickian-based advection-dispersion equations for heat and solute transport. This model includes processes like sorption, degradation and several sink terms (solute uptake etc.). The program may be used to study the movement of water and solutes in unsaturated, partially saturated or fully saturated porous media. The solute transport equations consider convective-dispersive transport in the liquid phase, as well as diffusion in the gaseous phase. Transport equations include provisions for nonlinear non-equilibrium reactions between the solid and liquid phases and linear equilibrium reactions between the liquid and gaseous phases.

HYDRUS-2D can handle flow regions delineated by irregular boundaries. The flow region itself may be composed of nonuniform soils having an arbitrary degree of local anisotropy. Flow and transport can occur in the vertical plane, the horizontal plane, or in a three-dimensional region exhibiting radial symmetry about the vertical axis. The water flow part of the model can deal with prescribed head and flux boundaries, boundaries controlled by atmospheric conditions and free drainage boundary conditions. A database of soil hydraulic properties is also included in the model.

The Richard's equation (variably saturated flow) and the Fickian-based convection-dispersion equation (solute transport), can be utilized for: (a) Predicting water and solute flow in the vadose zone, (b) Analyzing specific laboratory or field experiments involving unsaturated flow and/or solute transport. Currently, HYDRUS-2D considers up to 5 solutes, which either can be coupled in a unidirectional chain or may move independently of each other.

HYDRUS-2D allows the user to design the geometry of the system to be simulated. The boundaries of the system can be described as constant or variable heads or fluxes, driven by atmospheric conditions, free drainage, deep drainage or seepage. The program includes an automatic mesh generator, MESHGEN-2D, that generates a finite element unstructured mesh fitting the designed geometry through triangulation.

The user interface is particularly suited to hydrological applications, including functions like zooming, enlargement for cross-sectional views, high-resolution colour, contouring of isolines, water content, velocity and concentrations, animations of graphic displays for sequential time steps etc.

CHEMFLO

CHEMFLO (www.epa.gov/ada/csmos/models/chemflo.html) is a one-dimensional soil water and chemical movement model. Water movement is calculated using Richards' equation, whilst movement of chemicals is simulated with the convection-dispersion equation. The model can simulate flow in any direction, regardless of layering, by specifying the orientation of the flow system.

CHEMFLO can be used to assist regulators, environmental managers, consultants, scientists and students in understanding unsaturated flow and transport processes.

The main outputs include water content, matric potential, hydraulic conductivity and flux density of water versus distance or time; concentration and flux density of a chemical as a function of distance or time; cumulative fluxes of water and chemical and total mass of chemical in the soil as a function of time. However, this model is not able to provide an integrated simulation of the system. In addition, it cannot simulate runoff of water and salt wash off.

FEHM

FEHM (Finite Element Heat and Mass transfer code) (Zyvoloski et al., 1995) is a 3D numerical model for simulation of time-dependent, multi-phase, multi-component water flow and solute transport systems.

This model accounts for both unsaturated and saturated fluxes in porous and fractured media. It can be applied to simulate flow of gas, water, oil and heat, multiple chemically reactive and sorbing tracers as well as double porosity and double permeability capabilities. Its main application area is determining the fate of contaminants in the saturated and unsaturated zones. However, its ability to simulate overland flow, solute movements and throughflow in layered environments will have to be tested.

STANMOD

STANMOD (Studio of Analytical Models) (Simunek *et al.*, 1999) is a suite of porous media solute transport models. It uses analytical solutions of the convection-dispersion equation. These models can be used for estimation of transport parameters from laboratory and field tracer experiments, calculation of solute transport with decay, estimation of equilibrium transport parameters from solute displacement experiments, non-equilibrium transport parameters from miscible displacement experiments as well as 3D equilibrium and non-equilibrium solute transport in porous media. However, this model cannot provide an integrated simulation of the system.

Chapter 3

3. Experimental Set-up

3.1 The Study Area

A suitable and representative experimental site was selected in the Goedertrou 60 ha small scale catchment (SSC). The study area is located 3 km NE of the town Riebeeck West (33° 21' 07" S & 18° 52' 03" E), which is approximately 70 km north of Cape Town in the Western Cape Province, South Africa. It is a semi-arid region, characterized by a Meditteranean climate, experiencing warm dry summers and cool wet winters. The area receives approximately 300 mm of rainfall per annum. This SSC was identified as being suitable for intensive hydro-pedological and eco-meteorological studies. The catchment was also selected on the basis that a diversity of vegetation types, land use practices and bioclimatic conditions representative of the drier, lower reaches of the Berg river basin, occur, where storage and potential discharge of salt are likely to be the greatest. Other factors such as ease of access, infrastructure, landowner commitment and supplementary funding opportunities were also considered in selecting the catchment. Site establishment started in 2005 with the installation of monitoring equipment, which are listed below. Preliminary data were collected in 2005. Additional monitoring equipment was installed in 2006, which are also listed below. In 2006, data were collected for the full winter season. The 2005 year is thus referred to as the first season of hydrosalinity fluxes and 2006 as the second.

At the experimental site, i.e. Goedertrou, shallow (<3 m thick) residual soils with differing sand, clay and gravel contents overlie the silcrete. The silcrete itself is hard, and in bulk terms, relatively massive, but no more than a few meters thick. The conditions beneath the silcrete unit are unknown, although at other sites the weathered zone of the Malmesbury Group can typically be found at depths between 5-10 m below the site surface (Bean, 2004). The Malmesbury Group itself is a Proterozoic marine deposit comprising greywacke and phyllite beds with beds and lenses of quartz schist, limestone and grit; quartz-sericite schist with occasional limestone lenses {1: 250000 Geological Series Map, Geological Survey, 1990) as cited by CSIR (2005).

Dryland wheat was planted in the first week of May 2005 at the Goedertrou SSC. The soil was shallow-cultivated to a depth of approximately 5 cm. The aim of the cultivation was to destroy weeds, provide a suitable seedbed and to break-up the surface to ensure maximum rainfall infiltration as well as to minimize wind and water erosion. In 2006, the land was left fallow, which is a common practice in the area aimed at regenerating soil fertility through the regrowth of wheat and medic grass for grazing. The experimental scheme is shown in Figure 5, on a map representing elevation levels and contours.

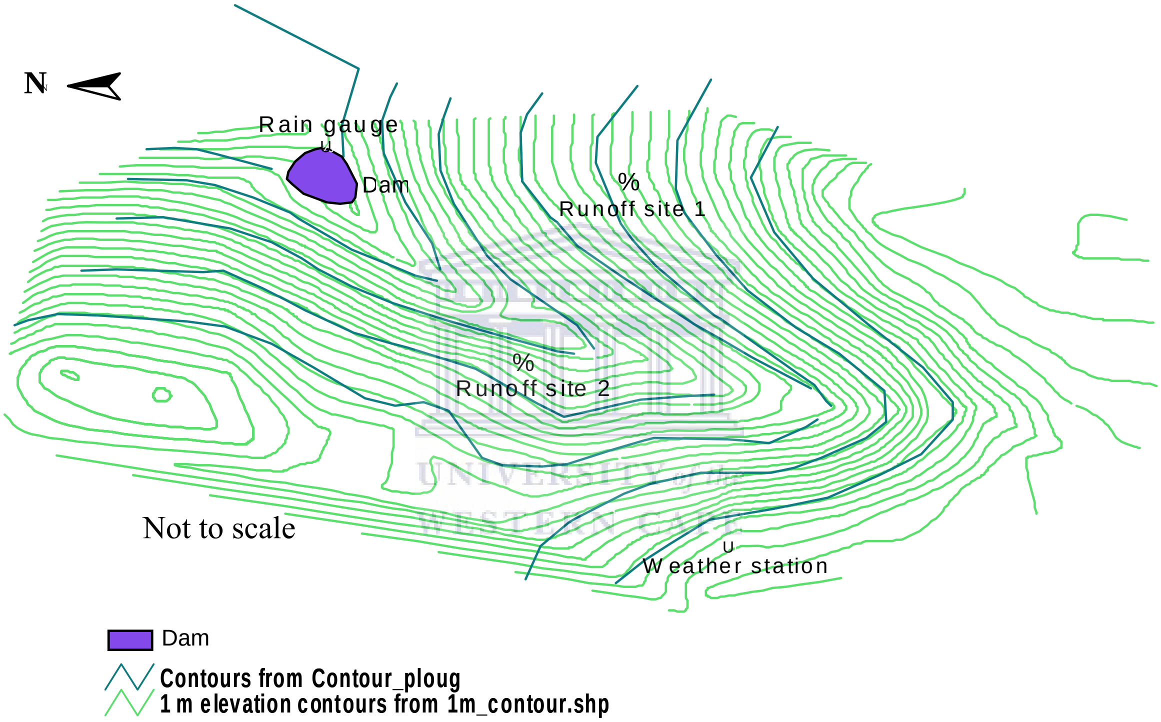


Figure 5. Experimental scheme in the Goedertrou SSC.

In 2005, two sites were established on opposing slopes (Figure 6), in the SSC. The sites represent typical but different hydrological units for modeling purposes. Runoff plots were established at sites 1 and 2 (Figure 6). Site 1 is North-oriented, whilst site 2 is South-East-oriented. The slope of site 1 is just above 9.1 %, whilst the slope at site 2 is close to 12.4 %. Both sites are representative for areas between two man-made contours. Chemical and physical analysis was performed on soil samples collected from different soil layers at site 1 and site 2, before the sites were established. The results are presented in Tables 1 and 2. These aim to give an indication of the initial conditions at the runoff plots. Chemical analysis was performed using the methods of atomic absorption and ion chromatography. The samples were prepared using the 1:5 (soil: distilled water) ratio method. The samples were analyzed for the concentrations of soluble cations and EC. The EC of the samples was also determined from the saturated paste extract (SPE).

Figure 6**.** Aerial photograph of the bare soil and Wischmeyer runoff plots at site 1 and site 2. (2005/06/06).

TABLE 1

CHEMICAL SPECIATION OF SOIL SAMPLES COLLECTED BEFORE THE RUNOFF PLOTS WERE ESTABLISHED.

Runoff Site	**Depth (cm)**	**$EC_{(SPE)}$ dS m^{-1}**	**$EC_{(1:5)}$ dS m^{-1}**	**Soluble Cations**				
				Ca^{2+} $mmol_c/l$	**Mg^{2+} $mmol_c/l$**	**Na^{+} $mmol_c/l$**	**K^{+} $mmol_c/l$**	**Sum $mmol_c/l$**
Site 1	0-20	3.18	0.47	0.26	0.32	3.99	0.06	4.62
	20-70	2.62	0.38	0.13	0.20	3.37	0.02	3.72
	70-130	1.70	0.20	0.49	0.27	0.97	0.11	1.84
Site 2	0-20	1.02	0.12	0.07	0.18	1.11	0.17	1.53
	20-100	1.08	0.15	0.16	0.21	0.92	0.10	1.39
	100+	0.87	0.16	0.05	0.19	1.34	0.14	1.72

The soil physical properties, i.e. bulk density and porosity, were determined using the soil water retention functions method (Anthony and Jovanovic, 2004). These results are presented in Table 2. The soil water retention was determined using the Eijkelkamp sand box and the Eijkelkamp sand/kaolin box. Undisturbed samples were taken at each site from each soil horizon displaying different characteristics. Water potential pressures were plotted against volumetric soil water content for each horizon. Bulk density was calculated as the ratio of air-dry soil sample and volume of the sampling cylinder ring. Porosity was assumed to be the volumetric soil water content at saturation. The results in Table 2 represent an average of 3 samples.

TABLE 2

PHYSICAL PROPERTIES OF SOIL SAMPLES COLLECTED BEFORE THE RUNOFF PLOTS WERE ESTABLISHED.

Runoff Site	Depth (cm)	Porosity (%)	Bulk Density ($g\ cm^{-3}$)	Volumetric Soil Water Content at 10 kPa
Site 1	3	36.6	1.4535	0.32
	15	41.0	1.3865	0.30
	40	38.9	1.5018	0.26
	70	33.9	1.5872	0.23
	120	28.2	1.7171	0.23
	210	33.8	1.5330	0.34
Site 2	13	40.8	1.5928	0.33
	91	20.0	1.4582	0.08

3.2 Runoff Plots

Two standard Wischmeyer runoff plots were established, the one parallel to the other, at each runoff site (Figure 7). Each runoff plot covered an area of 44.6 m^2 (22.3 m x 2 m).

In 2005 at site 1, one runoff plot was planted to wheat, i.e. plot 2, whilst the other was kept uncultivated, i.e. plot 1 (Figure 7). At site 2, both runoff plots were planted to wheat, but during the course of the season it was observed that the vegetation density was different in the two plots. In 2006 site 1, plot 2 was left fallow whilst plot 1 was kept under bare soil through the regular application of the herbicide, glyphosate. The herbicide was applied twice during the season in the months of August and September. At site 2, both plots were left fallow. As the land was used for grazing, it was required to regularly trim the wheat/medic grass on the vegetated plots to maintain a similar vegetation height as the rest of the SSC. The following measurements were carried out at each runoff plot (sites 1 and 2):

- **Runoff water volumes.** According to Dingman (2002), the terms surface runoff and overland flow may be used interchangeably and is defined as the flow of water that occurs on a sloping surface that is either saturated from above (Hortonian overland flow) or saturated from below (saturation overland flow). All runoff collected at the runoff plots may be defined in this way. A flow splitter was installed in order to divide water and sediment flow into two portions (Figure 8). The first portion from the flow splitter lead into a tipping bucket fitted with a magnetic switch, in order to record surface runoff volumes electronically. The tipping bucket was calibrated so that every tip corresponds to 1 L of water. Surface runoff volume data were collected every 10 min and stored with an MCS data logger from 5 August 2005. The first flow portion was wasted thereafter. Interruptions in logged records did, however, occur as a result of trampling by cattle and severe storms.

- **Runoff Sampling.** The second flow portion from the splitter lead into two surface runoff traps (Figure 8). These traps were used to collect overland flow samples for laboratory analysis, i.e. salinity and chemical speciation. Two tanks were used in order to trap coarser particles in the first tank and finer particles in the second. This was done to establish whether salinity was influenced by the coarseness of the sediment particles and thus by the adsorbed ions on the sediment particles. These samples were collected during field visits which were undertaken after major rainfall events (every week on average) during the 2005 and 2006 winter seasons. Sampling was done by scratching the bottom of the tanks with a clean spade, thereby mixing the water, and collecting water samples in plastic bottles. The flow splitter was calibrated on a regular basis to maintain an approximate 50 % split between the tipping buckets and runoff traps. Surface runoff volumes were also measured during field visits by measuring the height of the water column collected in the tanks (runoff traps), of known volume, from June 2005. When both tanks overflowed the maximum capacity of the tanks was recorded. The tanks were emptied and washed after sampling, during each field visit.

- **Runoff water quality.** The water samples collected during field visits were used to determine the quality of the surface runoff. Electrical conductivity was measured on all samples collected. Water samples collected on 13/04/05,10/06/05 23/06/05, 11/08/05, 30/08/05, 8/09/05, 14/10/05 and 3/11/05 were analyzed for inorganic ions (Ca, Mg, K, Na, Cl, NO_2, NO_3, SO_4) with ion chromatography and atomic absorption. On 8 June 2006, an Eijkelkamp CTD-Diver and BaroDiver were installed in the first tank of the bare soil runoff plot at site 1 with the aim of monitoring salinity, temperature and water level changes in the tank during single runoff events. Readings were recorded with the built-in logger at time intervals varying between 2 and 10 min. The measurements were taken at different time intervals in order to establish at which interval more accurate (higher resolution) changes in water level and salinity may be recorded. The CTD-Diver was coupled to a BaroDiver in order to correct the measurements of water level in the tank for atmospheric pressure.

- **Rainfall.** Since 5 August 2005, rainfall at sites 1 and 2 was recorded every 10 min with a tipping bucket rain gauge and data were stored with an MCS data logger. The data loggers were enclosed in a box and powered via battery and solar panel. The outlet of the rain gauges was fitted with a tube leading to a plastic bottle. The bottles were housed in a box to minimize evaporation. Each tip corresponded to 0,2 mm of rainfall. Rain water was collected in the plastic bottles and analyzed in the laboratory. Electrical conductivity of rain water was measured on samples collected during field visits.

- **Soil water content.** Soil water content was measured gravimetrically by sampling during field visits, which was generally after major rainfall events. The soil samples were taken at the top and bottom of each runoff plot. Sampling was done outside the runoff plots to avoid disturbance, at sites representative of the conditions inside the plots. Sampling depths were at 10 cm and 40 cm (at the top of the weathered layer) at runoff site 1. At runoff site 2, sampling was at 10 cm and 50 cm soil depth. The samples were weighed, placed in the oven at 105 ^{0}C, for at least 24 hours, and weighed again afterward to determine the gravimetric soil water content. The volumetric soil water content was then calculated using bulk density. From 3 November 2005, volumetric soil water content at site 2 was measured electronically with four Echo sensors connected to an Echo logger (Decagon Devices Inc.). The Echo sensors are 20 cm long capacitance probes. Two sensors were installed vertically close to the top of the runoff plots, and the other two sensors close to the bottom of the runoff plots. Measuring depths were 0-20 cm and 40-60 cm. On 9 December 2005, four Echo sensors were also installed vertically at site 1 and connected to an Echo data-logger. Two sensors were installed close to the top and the other two sensors close to the bottom of the runoff plots. Measuring depths were 0-20 cm and 20-40 cm. All electronic measurements of volumetric soil water content were done on an hourly basis and data were downloaded during field visits. The sensors' readings were calibrated using the calibration for mineral soil supplied by the manufacturer. The purpose of the electronic measurement of soil water content was to quantify throughflow using water retention curves, hydraulic conductivities and the HYDRUS-2D model.

- **Soil chemical properties.** The soil samples collected to measure water content were also used to measure soil salinity. A 1:5 soil to distilled water ratio method was used (Hesse, 1971). 15 g of fine soil and 75 ml distilled water were used. Once the two substances were mixed in a test tube, the sample was placed on a shaker at an intermediate speed for 30 minutes. Thereafter, it was left to stand for 15 minutes and then placed in a centrifuge at an intermediate speed for 10 minutes. The mixture was left to stand overnight and the EC of the 1:5 soil/water solution was measured the following day. The 1:5 water extracts of soil samples collected on 13/04/05, 4/07/05, 22/07/05, 23/08/05, 8/09/05 and 14/10/05 were analyzed for inorganic ions (Ca, Mg, K, Na, Cl, NO_2, NO_3, SO_4, F, PO_4) with ion chromatography and atomic absorption.

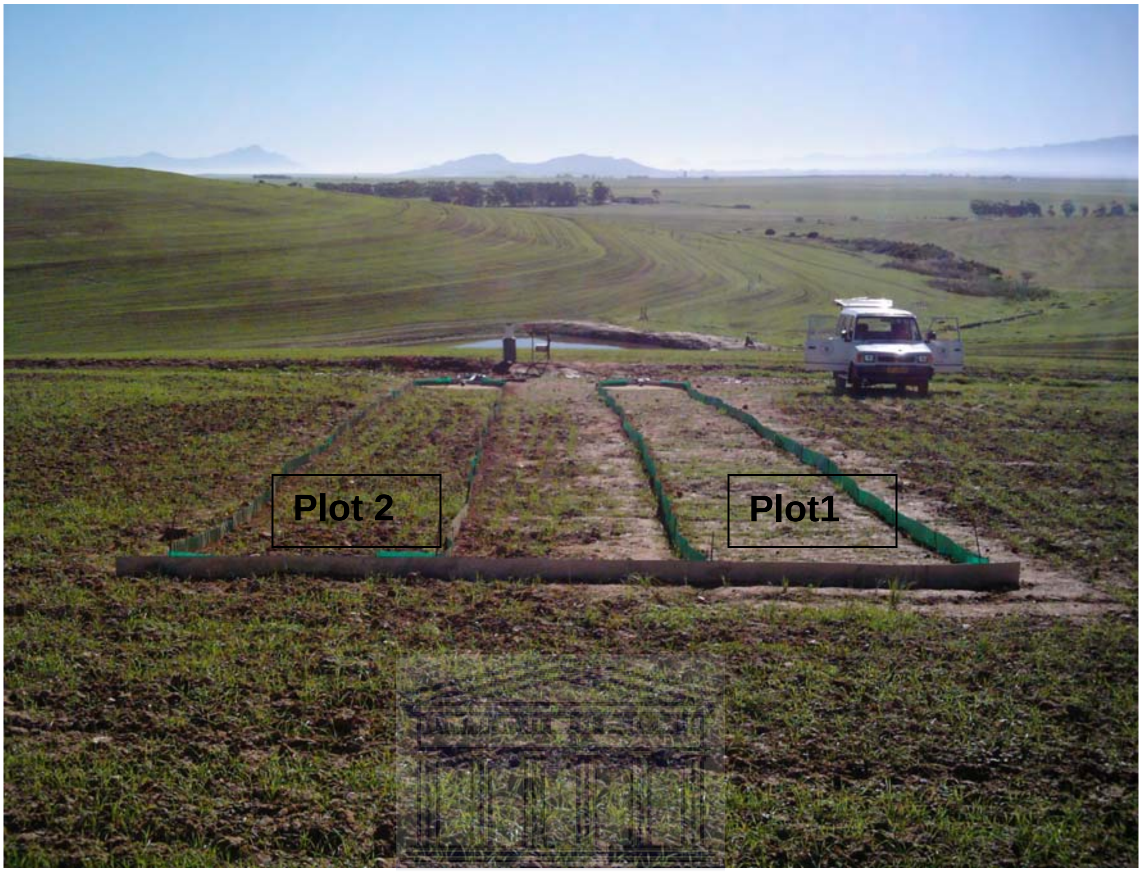


Figure 7. Runoff site 1.

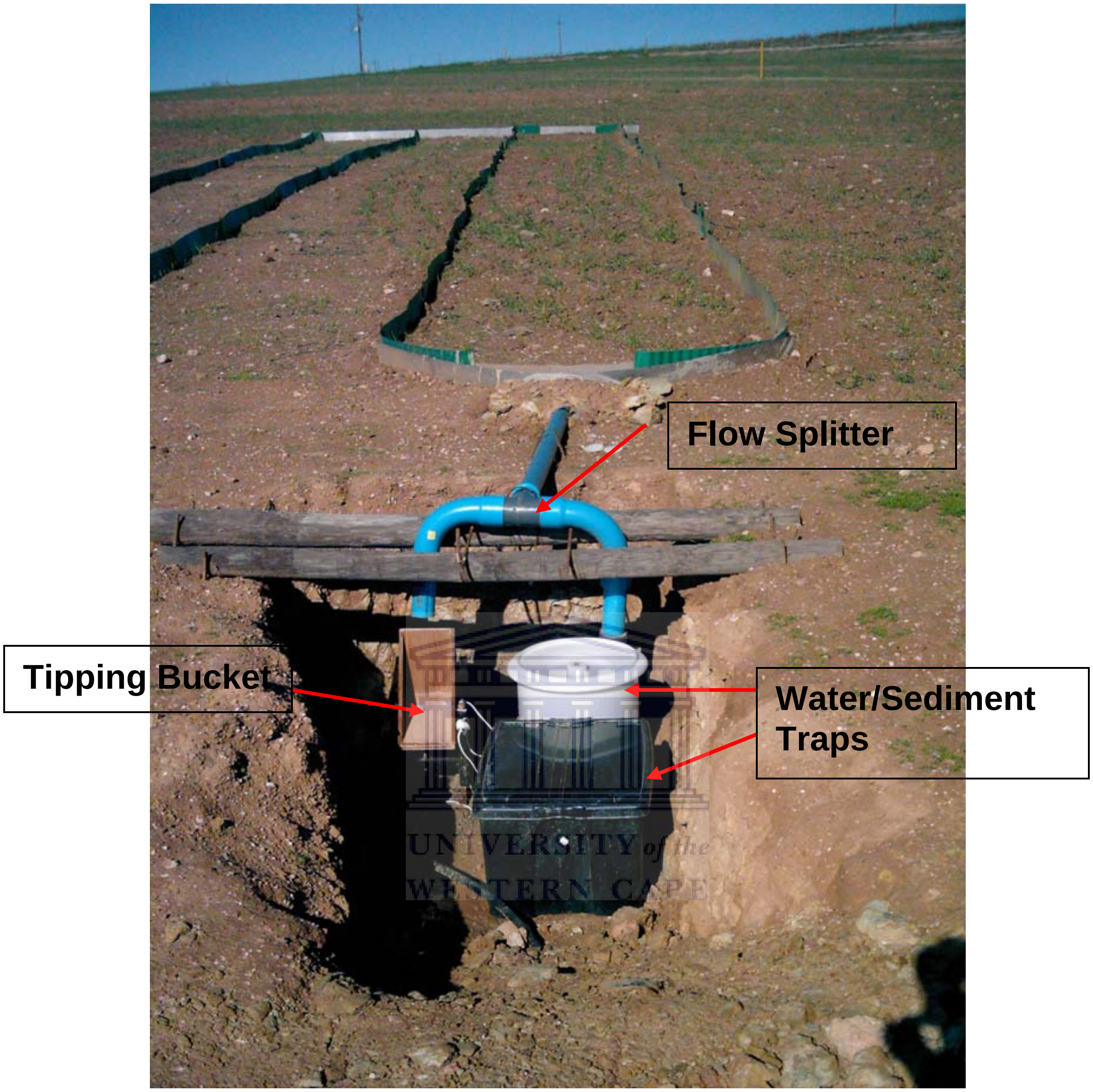


Figure 8. Flow splitter, tipping bucket for measurement of runoff and two plastic tanks for water and sediment sampling (Site 1).

3.3 Contour Weir

Contour furrows were constructed in the SSC to minimise erosion. It was expected that runoff and, to a certain extent, throughflow would be diverted out of the catchment from the area between the two contours where runoff site 1 is located (Figure 5). The following measurements were carried out in the contour furrows just below each runoff site:

- **Water level.** Pressure sensors were installed at the beginning of August 2005 to measure the water level in the contours every 10 min. Data were collected and stored with an MCS data logger.

- **Water quality.** Surface runoff collects in the contour furrows during and after rainfall events. This water was sampled and its electrical conductivity measured. Water samples collected on 13/04/05, 10/06/05, 23/06/05, 11/08/05, 30/08/05, 8/09/05, 14/10/05 and 3/11/05 were analyzed for inorganic ions (Ca, Mg, K, Na, Cl, NO_2, NO_3, SO4) with ion chromatography and atomic absorption.

3.4 Dam

The water collecting in the dam (Figures 5 and 6) originates both from overland flow and throughflow. The following measurements were carried out at the dam:

- **Water quality.** Water samples were collected from the dam during field visits. Electrical conductivity was measured on all samples collected. Water samples collected on 13/04/05, 10/06/05, 23/06/05, 11/08/05, 30/08/05, 8/09/05, 14/10/05 and 3/11/05 were analyzed for inorganic ions (Ca, Mg, K, Na, Cl, NO_2, NO_3, SO_4) with ion chromatography and atomic absorption.

3.5 Automatic weather station

An automatic weather station (Figure 9) was installed in the catchment on 25 April 2005. The following weather variables were measured and stored on an hourly basis:

- Solar radiation.
- Temperature.
- Relative humidity.
- Leaf wetness
- Wind speed and direction.
- Rainfall

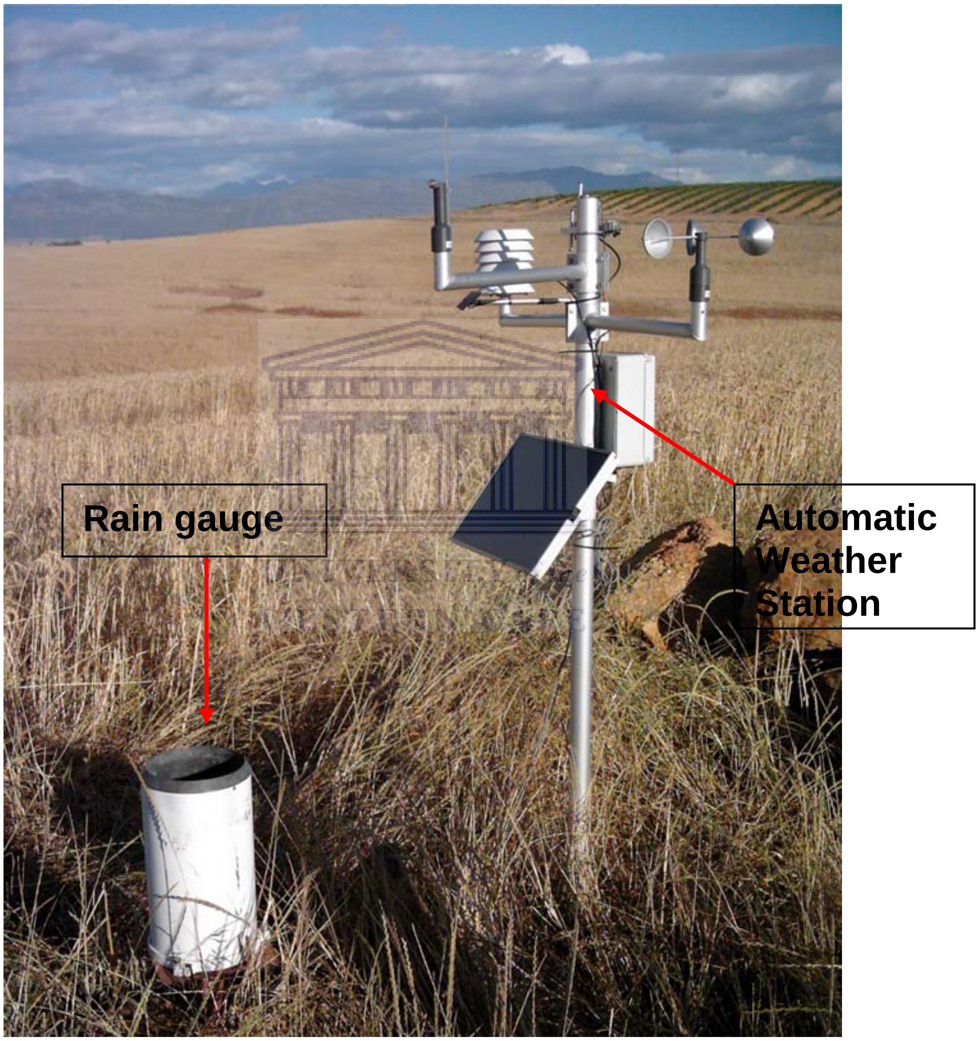


Figure 9. Automatic Weather Station and Rain gauge.

3.6 Hydrosalinity Modeling

Taking all the models reviewed in the literature review into consideration, it was decided that HYDRUS-2D, would be suitable in this study to simulate hillslope hydrology and solute fluxes along the runoff plots. The HYDRUS-2D model (Simunek *et al.*, 1994) includes state-of-the-art algorithms for water and solute fluxes and it is able to simulate important processes like root water uptake, water movement and salt fluxes. In addition, it allows the user to construct irregular geometries of the system, which is to be simulated. It also automatically generates nodes for the calculation of these fluxes in an unstructured triangular mesh, and it allows the user to assign preferred boundary conditions, e.g. constant or variable heads and fluxes. These features were taken into consideration when examining HYDRUS-2D’s suitability to simulate the conditions at Goedertrou.

Chapter 4

4. Results and Discussion

In this Chapter, the results representing the first and second season of measurements regarding the hydrosalinity fluxes are presented.

4.1 Meteorological Results

Figure 10 shows the seasonal rainfall measured with the automatic weather station during 2005 and 2006. The data indicate that rainfall events were generally prolonged with peaks of intensity up to almost 8 mm h^{-1} in 2005 and 7 mm h^{-1} in 2006. The maximum daily rainfall recorded in 2005 was 20 mm, whilst in 2006 it was 26 mm. In 2006 the area also received considerably more rainfall. An approximate total of 442 mm was recorded at the weather station in 2006, whilst it was 262 mm in 2005. It should be noted that data for the periods when the weather station was not operational, were obtained from the raingauge on the south facing slope. In 2005 the temperatures ranged from a minimum of 1,84 ^{o}C to a maximum of 37,9 ^{o}C. The average temperature, measured from April to December was 14,9 ^{o}C. In 2006, a minimum temperature of 4,2 ^{o}C was measured and a maximum of 36,7 ^{o}C. The average temperature, measured between February and September was 14,1 ^{o}C. A similar pattern in temperature variations was observed between the two seasons. An average wind speed of 2,4 m s^{-1} was measured in 2005 and 2,7 m s^{-1} in 2006. A similar seasonal pattern was also observed in wind speed variations. These variables, i.e. temperature, wind speed as well as relative humidity are illustrated on graphs in Appendix A and Appendix B.

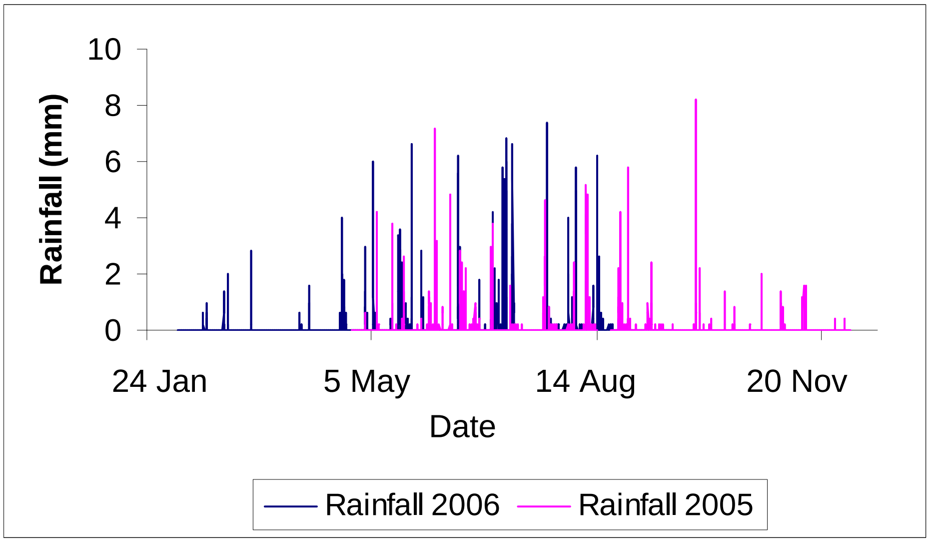


Figure 10. Rainfall data for 2005 and 2006.

4.2 Surface Runoff Measurements

4.2.1 Manual Runoff Measurements

Runoff data recorded manually by measuring the liters of water collected in the runoff traps are shown for site 1 (North-oriented) in Figure 11 and site 2 (South-oriented) in Figure 12. The data were converted into mm runoff for ease of comparison with Figure 10. Surface runoff events matched major rainfall events. It should be noted that rainfall data were not available for the period from 12 August 2005 (DoY 225) until 18 August 2005 (DoY 231), due to problems with the electronics. Rainfall data from the weather station for the period of 5 July 2006 (DoY 186) to 11 August 2006 (DoY 222) were also lost as a result of the weather station being trampled by cattle. Data for this period were obtained from the MCS logger at site 2. It should also be noted that field visits were planned 1 to 3 days after major rainfall events, so there was a lag in time between rainfall events and manual runoff measurements. As a result of the limited capacity of the runoff collection tanks, accurate measurements of runoff volumes, in this manner, could not be obtained during large rainfall events because both collection tanks overflowed. Together, both tanks could only hold 1.5 mm of runoff ,corresponding to 65.3 L. It should be noted that all measurements of runoff volumes were doubled to account for the 50:50 split of runoff water.

Figure 11 represents runoff events from the two plots at site 1, the one uncultivated (plot 1) and the other planted to wheat in 2005 and then left fallow during 2006 (plot 2). It is evident from the data that more runoff occurred from the uncultivated plot compared to the vegetated plot in 2005 and 2006. During the period of the study an approximate total of 2 300 L plot^{-1} of runoff was recorded at site 1, plot 1 compared to 850 L plot^{-1} at site 1, plot 2. This indicates that wheat cropping and shallow cultivation practices like those applied at Goedertrou could be beneficial in terms of containing water in the catchment and reducing runoff. During 2006 it was observed that the regrowing wheat and medic grass were also effective in reducing runoff. A total of 1 400 L plot^{-1} was recorded at site 1, plot 1 compared to 400 L plot^{-1} at site 1, plot 2 during 2006. This gives an indication of the importance of vegetation in terms of soil conservation practices. It was also observed that salt transport was reduced as a result of reduced surface runoff. Evidence for this will be provided in Chapter 4.3.

Figure 12 represents runoff events from two plots at site 2, both planted to wheat (2005) and left fallow in 2006. It was observed that these plots exhibit different spatial vegetation densities. Plot 1 was less densely vegetated, toward the bottom of the plot, and presented evidence of higher runoff values compared to plot 2, which was densely vegetated toward the bottom of the plot. The lower runoff values recorded from plot 2 were due to higher evapotranspiration, higher infiltration of rainfall and better containment of water by the denser vegetation at the downslope end of plot 2. This behaviour of the system was evident during the entire 2005 winter season, even after full canopy cover was reached. The system behaved similarly in 2006. It should also be noted that it was observed that the sheets demarcating the two plots at site 2 were unintentionally inserted to different depths. This may have resulted in water movement underneath these sheets. Differences in runoff values measured at site 1 (plot 2) (Figure 11) and site 2 (Figure 12) were mainly due to differences in soil properties and slope.

Table 3 shows the average plant densities measured at Goedetrou on 28 October 2005, while the SSC was under wheat cropping. Random areas of each plot were selected.

Plants were counted from three areas of 1 m^2 in each plot and the results represent an average of the three readings.

TABLE 3 AVERAGE PLANT DENSITIES MEASURED ON 28 OCTOBER 2005 AT GOEDETROU SSC.	
Runoff Plots	**Average Plant Density (no. of plants m^{-2})**
Site 1, Runoff Plot 2	40
Site 2, Runoff Plot 1	39
Site 2, Runoff Plot 2	39

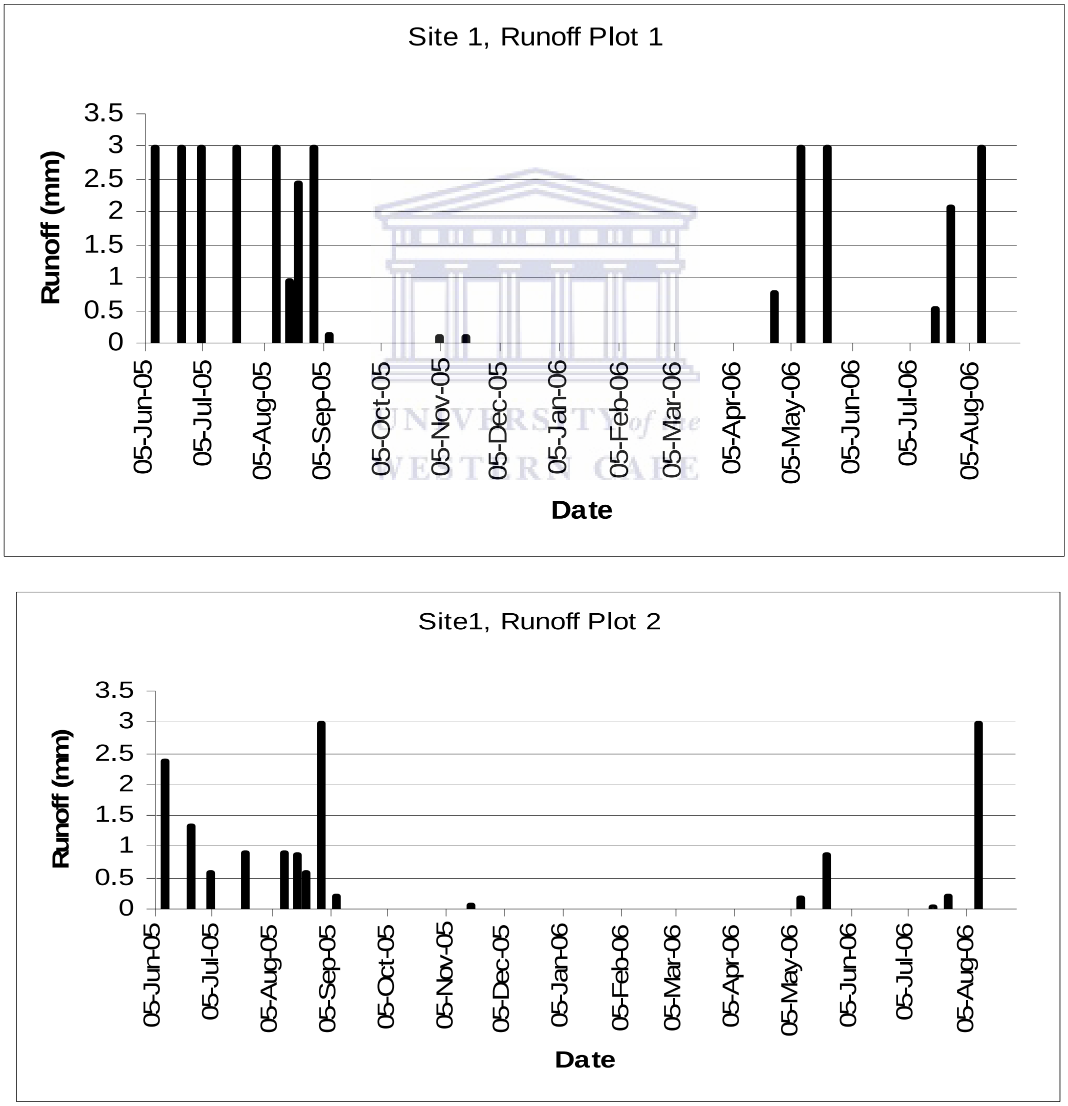


Figure 11. Runoff data at site 1. Where runoff reached the 3 mm level, both tanks overflowed and thus runoff was >3 mm.

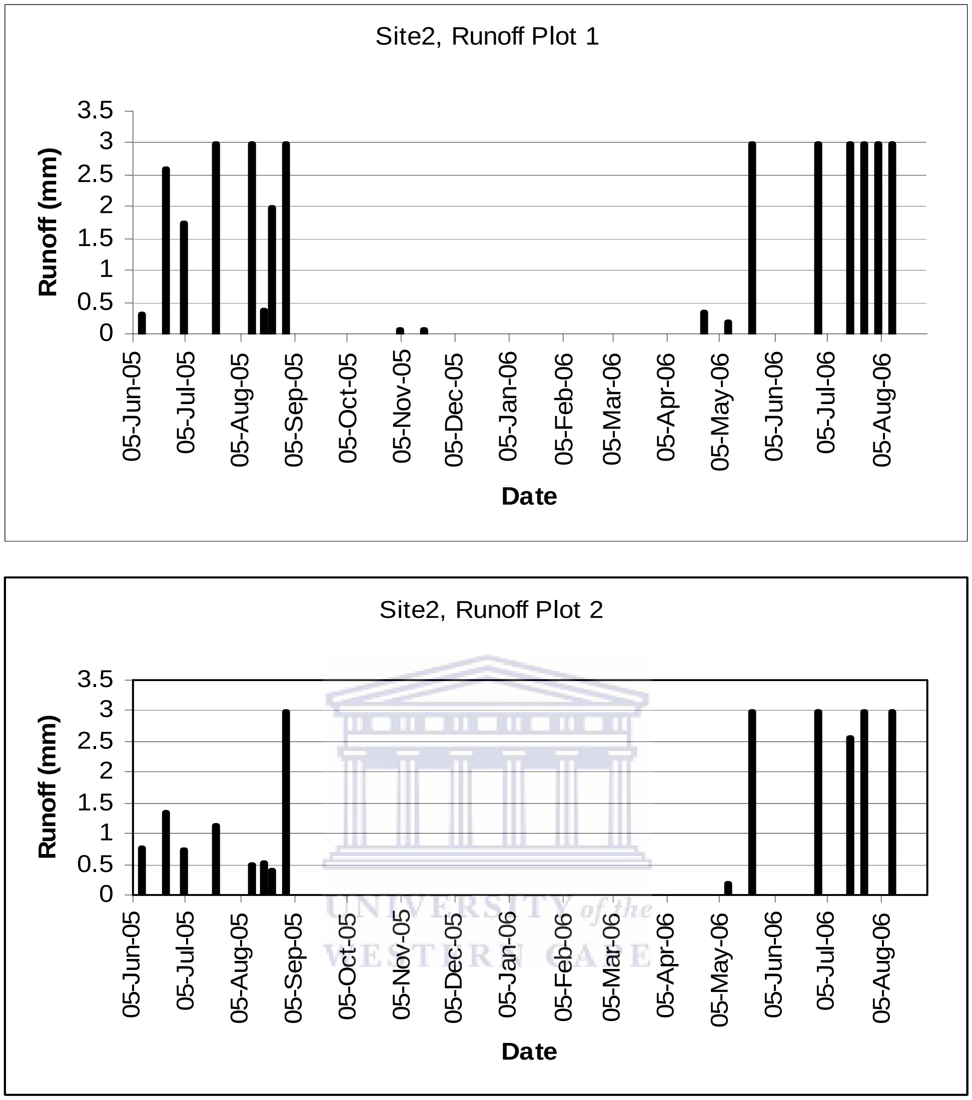


Figure 12. Runoff data at site 2. Where runoff reached the 3 mm level, both tanks overflowed and thus runoff was >3 mm.

4.2.2 Automatic Runoff Measurements

From 5 August 2005, logging systems were installed at both runoff sites to record rainfall and runoff with tipping buckets as well as to automatically record the fluctuations in water level in the contours. However, during 2005 the logger at site 1 was not operational due to problems with the electronics. The logger at site 2 functioned well. In 2006, both systems were operational for most of the season. Output data from these logging systems are presented in the following sections and in Appendix C.

4.3 Soil Water Contents

Volumetric soil water contents for the 2005 season are shown in Figure 13 for site 1 and site 2. Variation in volumetric water content of between 0.1 m m^{-1} and 0.4 m m^{-1} was observed. In general, the values were higher in the top soil when compared to deeper layers, due to the relatively low infiltration capacity of the soil (de Clerq *et al*., 2005). The values showed a general tendency to increase during July 2005 due to rainfall. As the root depth of wheat increased thereafter, dynamic trends were observed depending on rainfall and root water uptake, both in the top soil and in the deeper layer.

The logged records of volumetric soil water content, obtained with the use of Echo soil moisture sensors in 2006 are shown in Figure 14. The soil moisture content tended to decrease in summer as a result of increased evapotranspiration demand and lack of rainfall, and increase in winter due to increased rainfall. The Echo sensors illustrated that under the re-growth of wheat/medic grass vegetation types, the deeper soil layers tended to consistently have higher moisture contents when compared to the shallow soil layers. This was evident at both site1 and site 2. This is most likely a result of differences in evaporation rates between shallow soil layers and deeper soil layers. Differences in the water contents recorded at the top and bottom of the plots were dynamic and thus no trends could be observed. It should be noted that the sensor installed at a depth of 10 cm at the bottom end of site 1 was damaged during June 2006 and thus logged no further readings. Other data were not available due to poor contact between the soil and the sensors during the season. After wetting events, contact was re-stored and the sensors kept logging data.

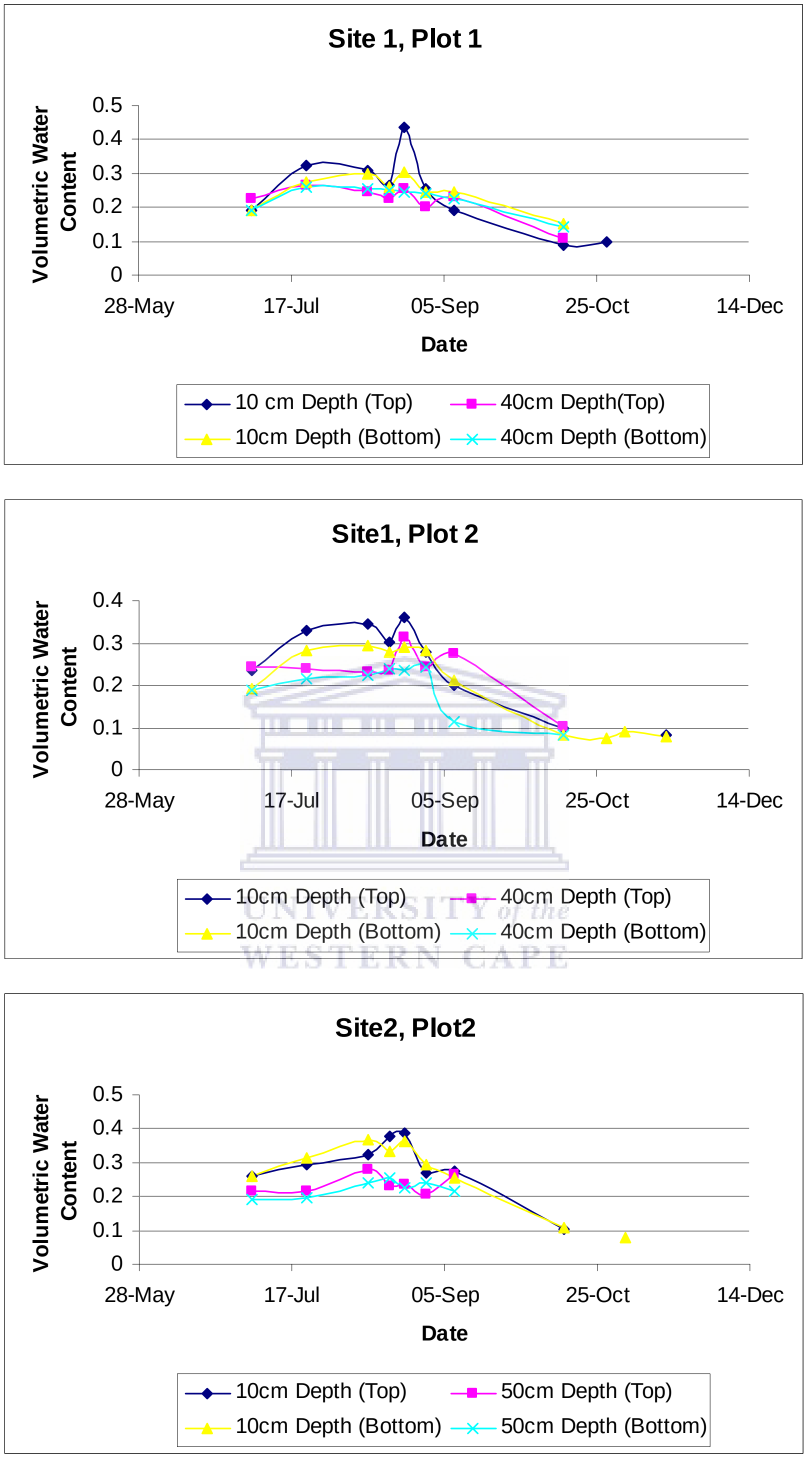


Figure 13. Volumetric soil water contents for soil samples collected at runoff sites 1 and 2 during 2005.

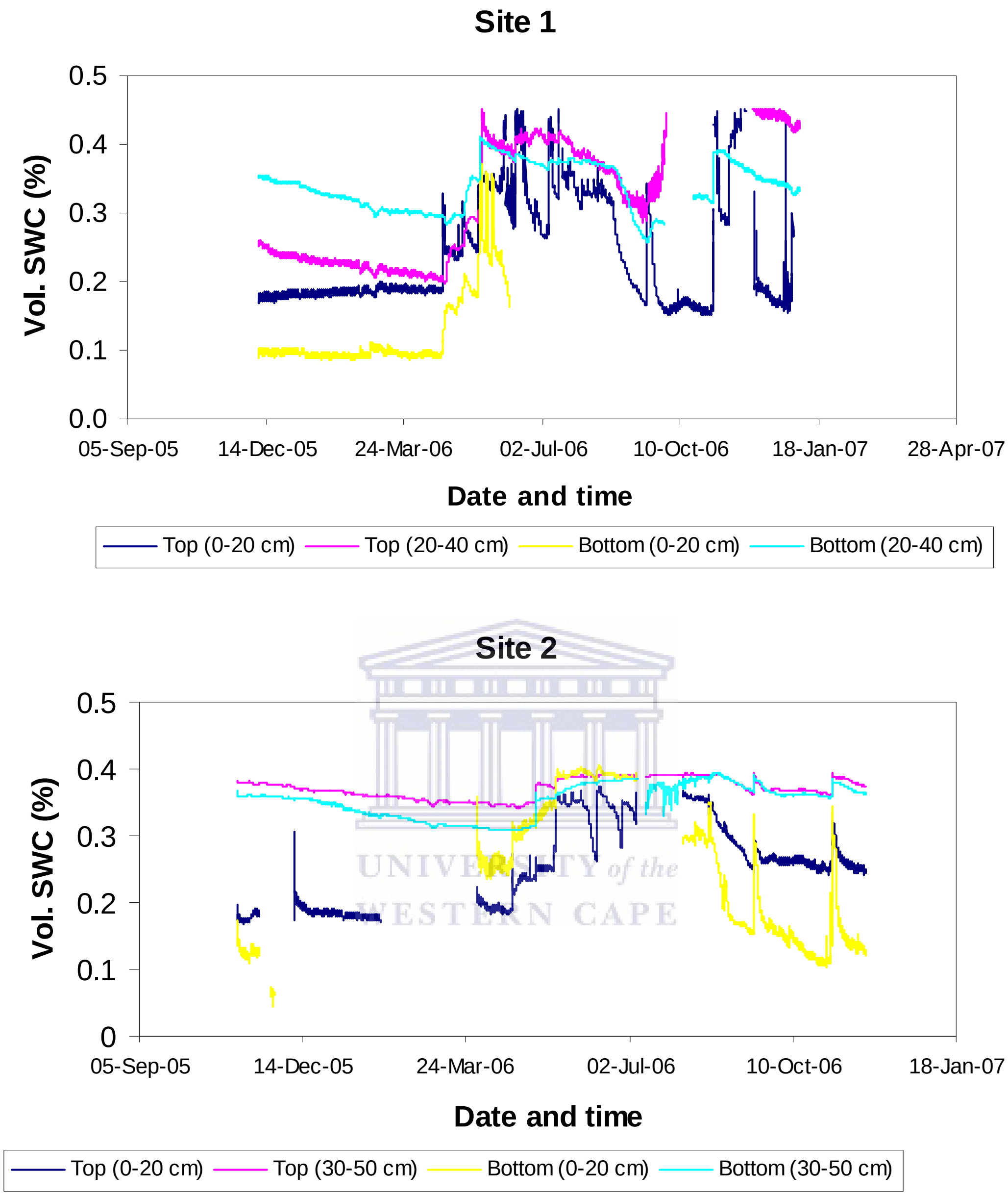


Figure 14. Volumetric (Vol.) soil water contents (SWC) at runoff sites 1 and 2 measured with Echo soil moisture sensors.

4.4 Salinity

Figures 15 and 16 show electrical conductivity (EC) values measured on water samples collected at runoff sites 1 and 2. The samples were collected from both sediment tanks, where tank 1 was the first in the sequence. In 2005, EC values generally ranged between 0.5 and 1.5 dS m^{-1}, with a minimum of 0.12 dS m^{-1} recorded at site 1, plot 2 (Figure 15), and a peak of 2.75 dS m^{-1} at site 2, plot 1 (Figure 16). In 2006, EC values generally ranged between 0.3 dS m^{-1} and 1.0 dS m^{-1}. A maximum of 1.24 dS m^{-1} was recorded at site 1, plot 1 (Figure 15) and a minimum of 0.1 dS m^{-1} at site 2, plot 2 (Figure 16). At site 1, the unvegetataed plot generated more saline runoff, in terms of the total salt load, when compared to the grassed plot. An approximate total of 900 g plot^{-1} of salts were mobilized from site 1, plot 1 compared to 160 g plot^{-1} from site 1, plot 2 during the period of the study. A peak in salinity (2.5 dS m^{-1}) was observed at site 2, at the start of winter (June), and a clear decrease therafter. This was evident from both 2005 and 2006 data. Salinity of runoff water was dynamic depending on local processes, but no clear trend in the values over time and between tanks could be observed. The differences in salinity between the two tanks at the same runoff plot were negligible. In general, the plots that yielded less runoff generated less saline runoff water. This may have implications with total salt load under different land uses because different land uses influence runoff amounts differently and consequently also salt loads.

Figure 17 represents the salinity of water samples collected in the contours just below the runoff plots at sites 1 and 2, as well as the salinity of the water in the dam. The salinity of water collected both in the contours and in the dam was in the range of that measured in runoff water. A maximum of 2 dS m^{-1} was measured in contour waters. The salinity levels in the contours between measurements showed fluctuations to a certain extent but the extremes were less pronounced compared to those measured in runoff water (Figures 15 and 16). The extremes were even less pronounced for salinity in the dam. This indicates that less fluctuations and a lessening of the effects of extreme events can be expected by increasing the scale of observation. During the summer months of November 2005 to March 2006 the dam water showed a drastic increase in EC, with it almost rising to as high as 7 dS m^{-1} (Figure 17). This was a result of increased evaporation from the dam during these months and thus a concentration of the salts in the dam. However, salinity of the dam water decreased rapidly with the onset of the 2006 winter season.

Figure 18 represents the EC of rain water measured during the season. The data represent the average of measurements taken on rain water samples collected at sites 1 and 2, with standard deviations. The data show that the highest average EC recorded was 0.41 dS m^{-1}. However, most samples had an EC below 0.1 dS m^{-1}. From this, one can deduce that rainfall alone cannot account for the quantities of salts being measured in overland flow and soil layers. This strongly suggests that geological controls are playing a major contributing role to salt input. According to M.V. Fey (personal communication) salts of marine origin (transported by rain and wind) occur in abundance in the regolith in the study area. The periods during the deposition of these salts are interpreted to be drier than present and hence the change in the water balance has resulted in the mobilization of these salts trapped in the regolith.

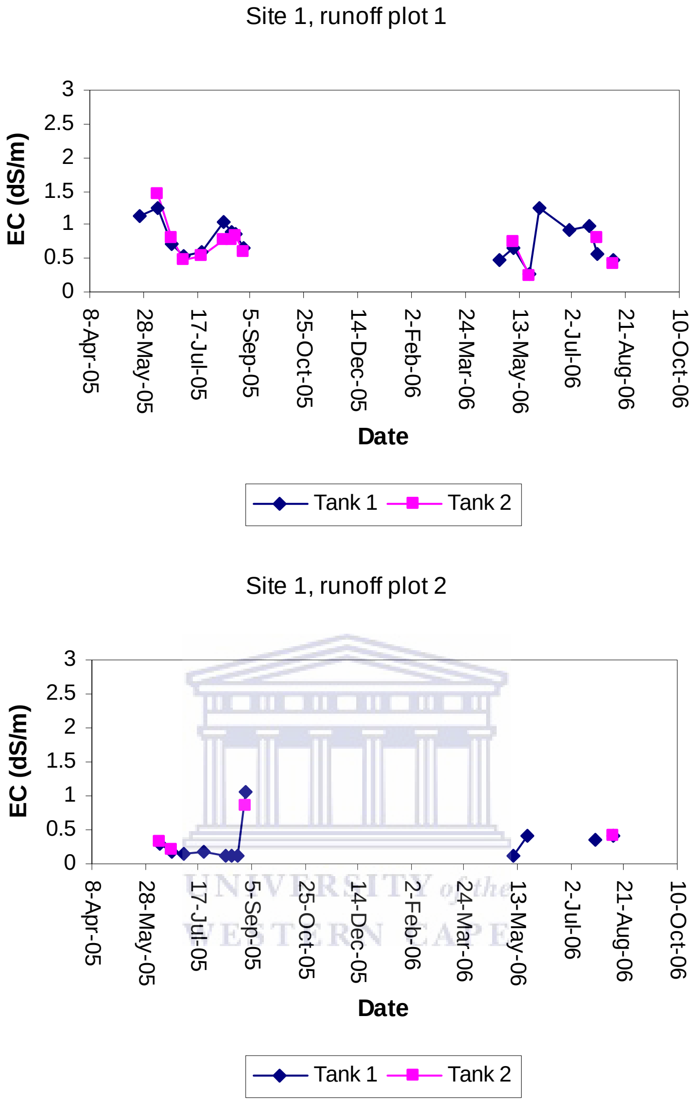
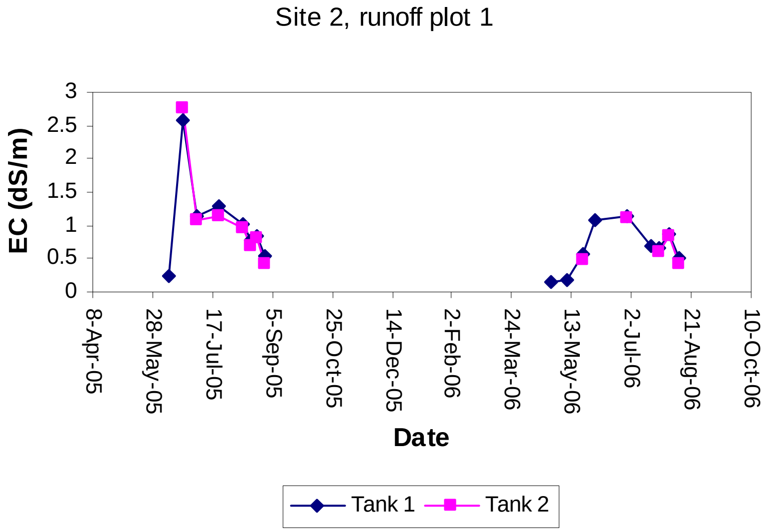


Figure 15. Electrical conductivity (EC) of runoff water at site 1



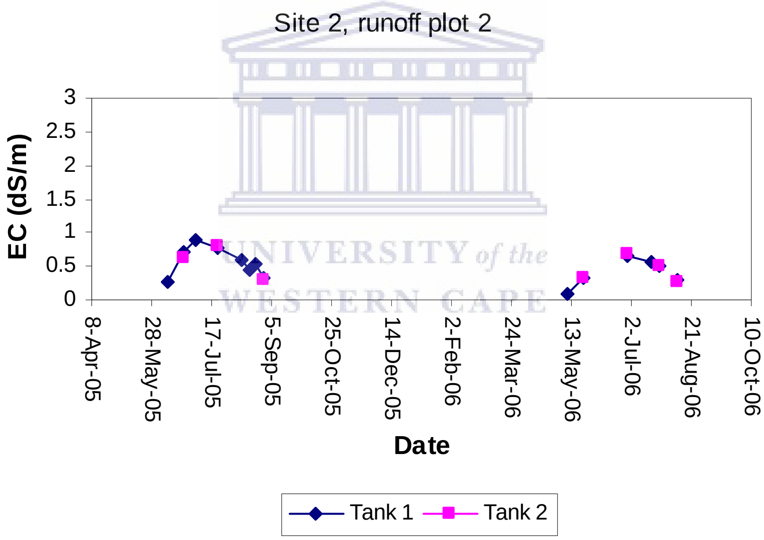


Figure 16. Electrical conductivity (EC) of runoff water at site 2

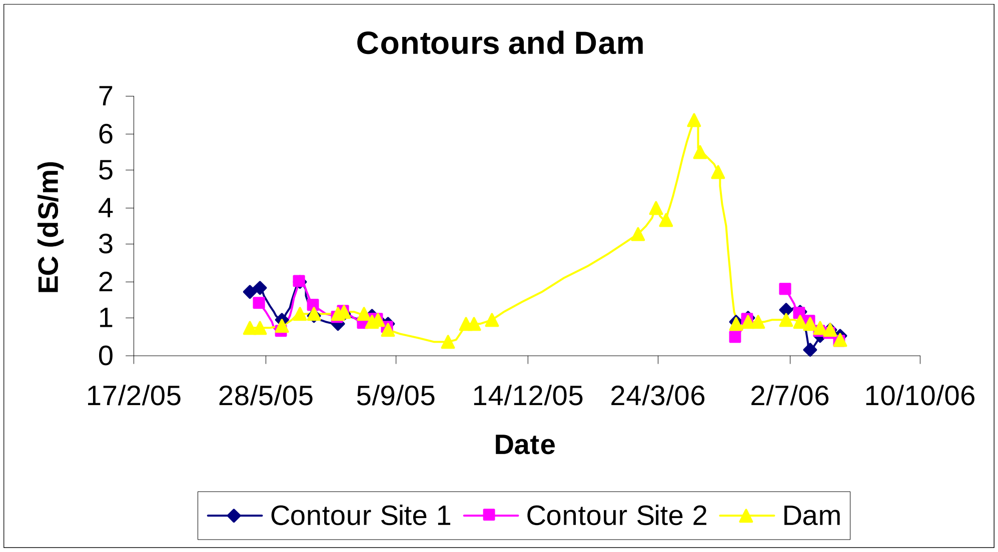


Figure 17. Electrical conductivity (EC) of water collected in contours and dam

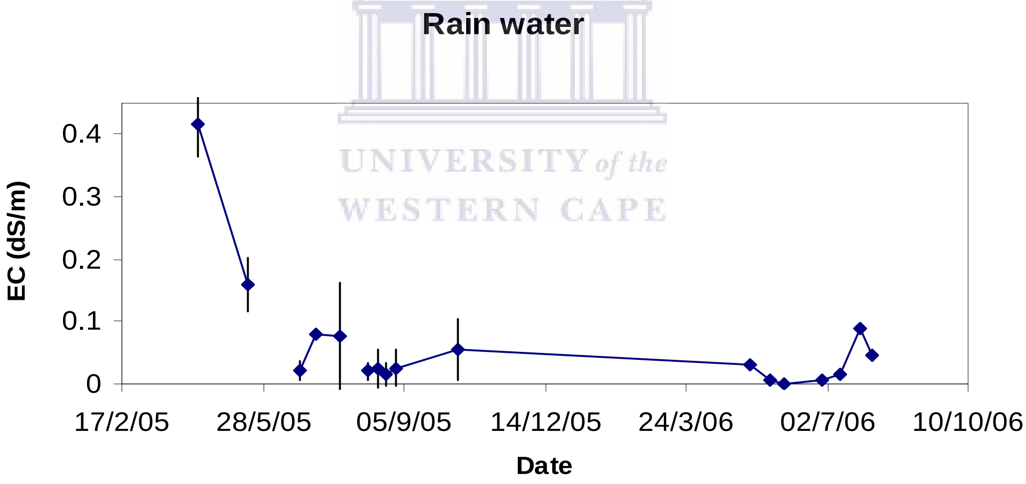


Figure 18. Average electrical conductivity (EC) of rain water at sites 1 and 2 with standard deviations.

The Electrical Conductivity (EC) of 1:5 soil/water ratio extracts of soil samples collected at site 1 and site 2 are shown in Figure 19. The EC values generally ranged between 0-1.5 dS m^{-1} at site 1 and 0-0.4 dS m^{-1} at site 2. The higher values at site 1 could be a result of the fact that site 1 is located on a saline patch with a bulk soil electrical conductivity of approximately 1.6 dS m^{-1}. Plot 1 at site 1, however, showed higher EC values when compared to plot 2. Plot 1 exhibited an average EC of 0.51 dS m^{-1} at the top of the plot and 0.46 dS m^{-1} at the bottom of the plot. Plot 2 exhibited an average EC of 0.33 dS m^{-1} at the top and 0.21 dS m^{-1} at the bottom of the plot. This is most likely as a result of the vegetation on plot 2, which minimizes evaporation of soil water and consequently the precipitation of salts near the soil surface. Alternatively, the vegetation reduces the amount of water reaching deeper layers, through root water uptake. The water reaching deeper layers acts as a salt mobilizing agent. The vegetation at site 2 may have a similar effect on soil salinity. In general, higher EC values were observed in 2006. At site 2 an average EC of 0.21 dS m^{-1} was measured in 2005 and 0.35 dS m^{-1} in 2006. This difference in EC between 2005 and 2006 could be a result of the different land use or differences in rainfall patterns. The data illustrate that the type of vegetation cover could influence the amount of salts being precipitated at the soil surface and consequently being available for mobilization by runoff. However, no temporal or spatial trends could be observed.

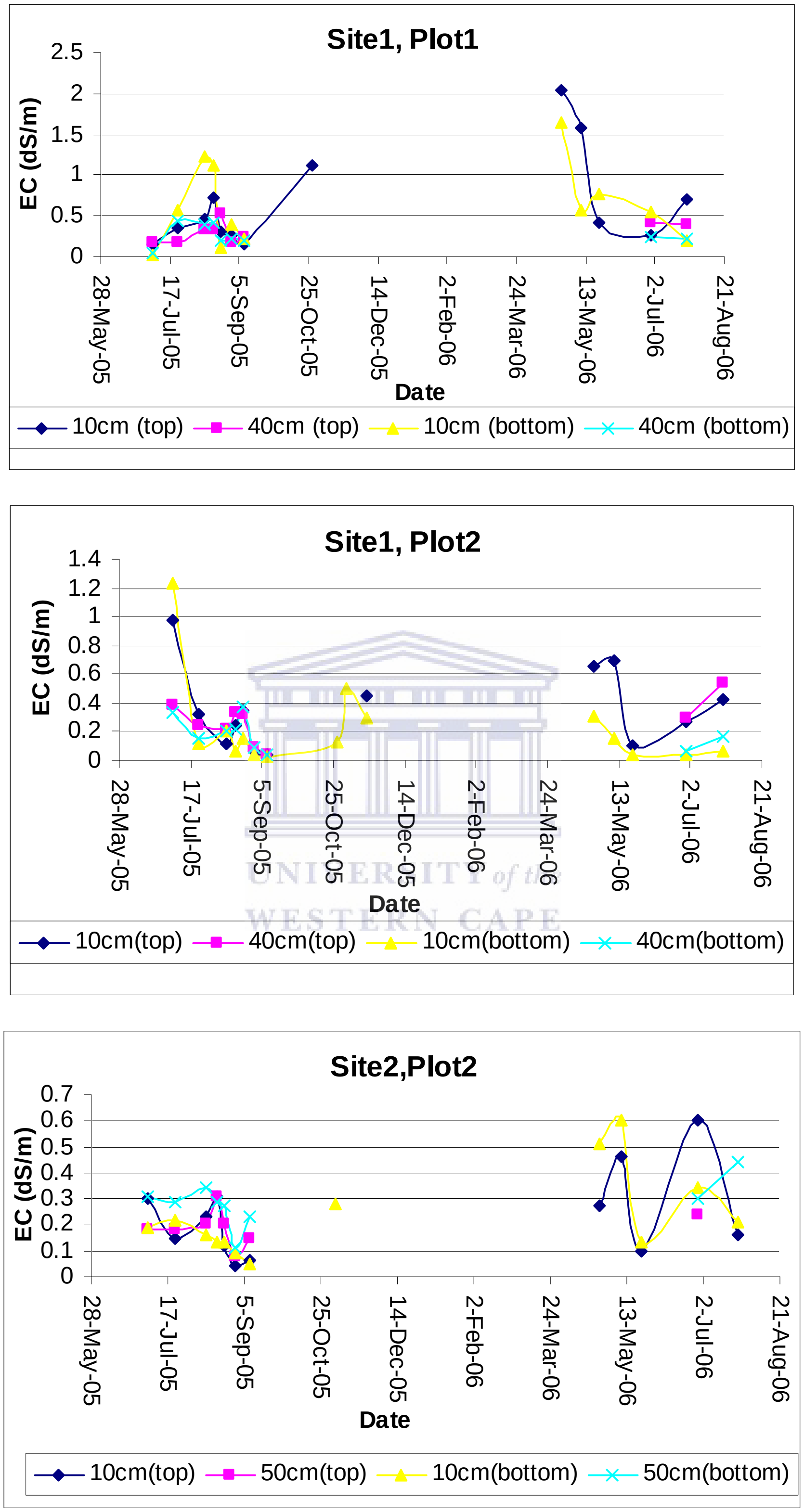


Figure 19. Electrical Conductivity (EC) of soil samples collected at site 1 (plot 1 and 2) and site 2 (plot 2).

4.5 Soil and Water Chemical Speciation

Water and soil samples collected during 2005 were analyzed for inorganic ions to establish the dominant ions in the SSC. The methods of atomic absorption and ion chromatography were used. The results of the laboratory analysis indicate that Na^+ and Cl^- are the most dominant inorganic ions, both in the soil solution and runoff. The results were also used to study the relationships between the various ions, and between the ions and variables such as EC, pH and TDS. The TDS was calculated as the sum of the anions and cations that were analyzed in mg L^{-1}. The correlation between EC and TDS is shown for runoff (Figure 20) and for 1:5 soil/water ratio extracts (Figure 21). The high R^2 values of the correlations indicate that we can infer TDS from EC using the derived equation for surface water, subsurface water and soil, and that the system is conservative in terms of ionic speciation. High R^2 values were also obtained for the correlations of EC vs. Na and Cl (Figure 22). All other results are presented in the form of graphs in Appendix D.

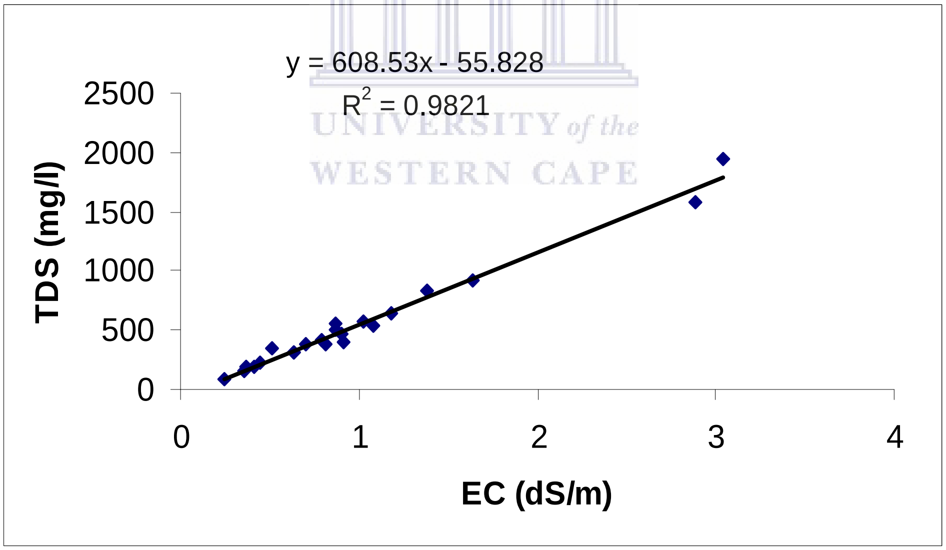


Figure 20. Correlation between electrical conductivity (EC) and TDS (total dissolved solids) in runoff water.

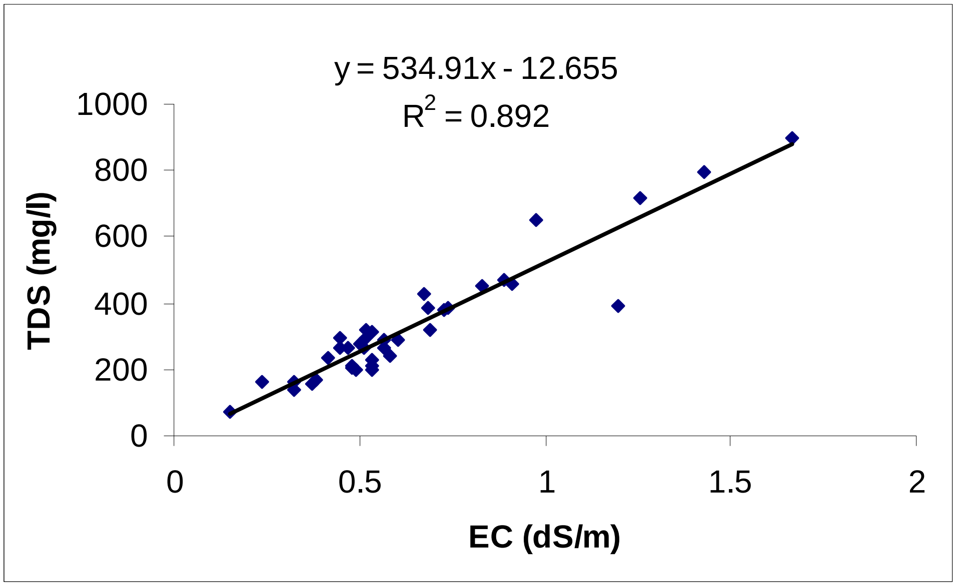


Figure 21. Correlation between electrical conductivity (EC) and TDS (total dissolved solids) in 1:5 soil/water ratio extracts

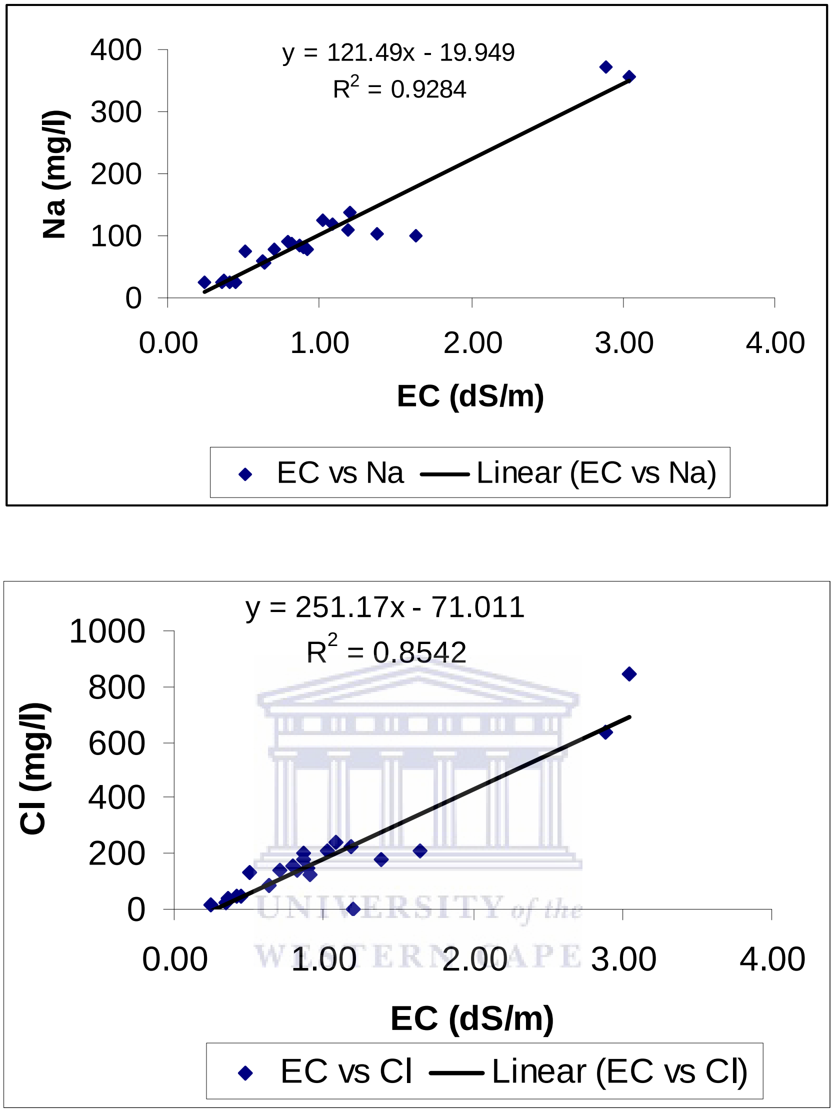


Figure 22. Correlation between electrical conductivity (EC) and Na and Cl in runoff water.

4.6 Dynamics of Salinity during Individual Runoff Events

From June to September 2006, an Eijkelkamp CTD-Diver and Baro-Diver were installed at plot 1 of site 1 (bare plot). The Divers were suspended in the first sediment collection tank, i.e. tank 1. The aim of installing these Divers was to study the dynamics of the movement of salts during individual runoff events. The CTD-Diver measured EC (dS m^{-1}), temperature and the height of water. The BaroDiver measured atmospheric pressure. The readings of water pressure taken with the CTD-Diver were normalized for atmospheric pressure using the Baro-Diver readings and the software provided by the manufacturer. The CTD-Diver sensor was always kept submerged in a few centimeters of tap water to keep it wet and to avoid damage. Figure 23, shows the results obtained for a runoff event that occurred on 21 July 2006 (DoY 202). A sudden increase in water level and salinity is observed due to saline runoff water discharging into the tank. As the event progressed, the water level of the tank reached a maximum level and overflow into the second tank occurred, whilst the salinity remained constant indicating an influx of runoff water with steady salinity. This contradicts an initial theory that suggested that there would be an initial peak in salinity, followed by a decrease in salinity as the runoff event progressed. Similar results were obtained for other runoff events in the period from July to September 2006. This indicated that, at least during the runoff events studied, salinity in runoff water stayed constant and a steady mobilization of salts occurred during the runoff process. This is due to the nature of rainfall in the area, where events are typically steady, of long duration and generally relatively low intensity. Results for all other runoff events recorded during the period of July to September 2006 are presented in Appendix E.

Due to constraints associated with the CTD-Diver, the EC values shown in Figure 23 and Appendix E are not a true representation of EC. This is due to the fact that the CTD-Diver’s resolution is not adequate to measure fluctuations in water level less than 30 mm, i.e. it will only detect changes in water level when they are greater than approximately 30 mm. Different recording intervals, i.e. 2 minutes and 10 minutes, were also used in order to test the dynamics of the system for different time resolutions. It was observed that where water levels are concerned, the interval of 10 minutes showed less dramatic fluctuations in water height. Accurate water level measurements were required to compensate for the initial quantity of tap water placed in the tank, to submerge the CTD-Diver, resulting in a mixing between the fresh water and runoff and a subsequent dilution of salts. An attempt was, however, made to determine the actual EC of runoff water using the Diver EC measurement, the initial depth of tap water and the increase in water level in the tank due to the incoming runoff water. However, the compensation of EC during the initial period of the runoff event (when mixing of the initial tap water and the incoming runoff water occurred) was not possible due to the irregular water level readings. It was also observed that fluctuations in temperature between night and day followed variations in water level measurements. The installation of these instruments has however provided a good understanding of the dynamics of the process.

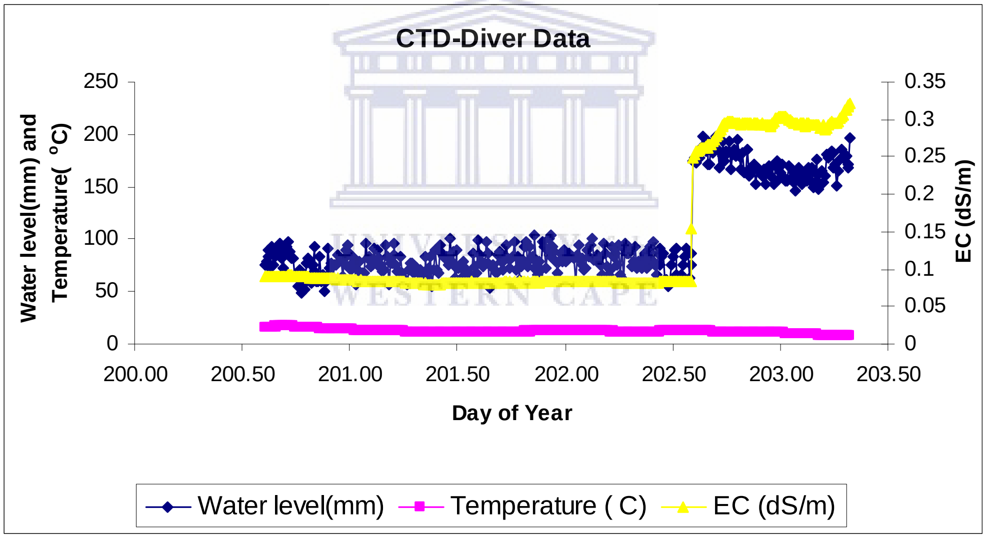


Figure 23. Water level, temperature and electrical conductivity (EC) in the first tank of the bare soil runoff plot at site 1, during the runoff event that occurred on 21 July 2006 (day of year 202)

Table 4 compares EC values measured with different instruments in tank 1 of site 1, plot 1. The EC values obtained from the calibrated portable EC-meter taken during field visits, which generally were after major rainfall events, were assumed to represent the average EC of individual runoff events. This assumption was based on the EC data collected with the Diver, which generally showed there is little variation in runoff water salinity during individual runoff events. The probe was lowered into the runoff collection tank and the results represent an average EC of the runoff from a particular rainfall event. The average EC obtained from the CTD-diver is the average of the EC values measured during runoff events. The final EC measured with the CTD-Diver is the last reading that was taken before the diver was removed and the tank emptied. Data from the divers were downloaded during field visits. The table shows that the EC-meter consistently recorded higher readings than the average and final reading of the CTD-Diver. This reading should essentially be very similar to the average reading of the CTD-Diver as they are measuring the same variable. The general feeling was that the CTD-Diver readings are more accurate and that this instrument should be used as reference. However, a trend in the proportion with which the EC-meter readings were larger than the average or final CTD-Diver readings could not be observed, and thus we did not compensate for this difference.

TABLE 4

A COMPARISON OF EC VALUES MEASURED WITH A PORTABLE EC-METER AND AN EIJKELKAMP CTD-DIVER.

Date	**Average EC ($dS\ m^{-1}$) - measured with an EC-meter.**	**Average EC ($dS\ m^{-1}$) -measured with a CTD-Diver.**	**Final EC ($dS\ m^{-1}$) - measured with a CTD-Diver**
29 June 2006	0.91	0.47	0.74
18 July 2006	0.97	0.49	0.77
25 July 2006	0.55	0.14	0.38
17 August 2006	0.4	0.25	0.29

4.7 Salt Fluxes in Runoff

Manual runoff measurements, runoff data recorded with the MCS loggers and the salinity of runoff water collected in the tanks were used to determine the total amounts of salts mobilized by overland flow in 2005 and 2006. The volumes of runoff water in L/plot and L m^{-2} are summarized in Tables 5 to 8 for events occurring during winter 2005 and 2006. For ease of comparison it should be noted that 1 L m^{-2} of runoff equates to 1 mm of runoff. EC readings for the individual runoff events are also reported in the Tables. The average EC from the tanks for each event was converted into TDS (total dissolved solids) using the equation in Figure 21. The values of TDS were then multiplied by the litres of runoff to obtain the salts mobilized in g plot^{-1} and g m^{-2}. The total volumes and masses of salts represent the seasonal runoff and the amount of salts mobilized through overland flow (Tables 5 to 8).

The asterisks marking some events indicate that manual readings of runoff were taken by measuring the liters of water collected in the tanks during field visits, as logged data were not available due to malfunction of loggers caused by severe storms, damage by grazing cattle or the loggers were simply not installed yet. For the events when logger data were not available and both collection tanks overflowed, a value of 131 L plot^{-1} was reported, corresponding to the maximum capacity of the tanks. Both logger values of runoff and those obtained through manual readings were doubled to account for the 50:50 split between the tipping bucket and collection tanks.

At site 1, it was observed that more runoff (935 L plot^{-1} in 2005 and 1 398 L plot^{-1} in 2006) and consequently more salt (424 g plot^{-1} in 2005 and 486 g plot^{-1} in 2006) was mobilized from the bare soil plot (Table 5) compared to the plot where wheat was cropped in 2005 (464 L plot^{-1} and 92 g plot^{-1}) and re-growth of wheat/medic grass occurred in 2006 (385 L plot^{-1} and 71 g plot^{-1}, Table 6). At site 2, large differences in runoff and salt mobilization were recorded, possibly due to uneven growth of vegetation. At plot 1 a total of 891 L plot^{-1} and 508 g plot^{-1} was recorded in 2005 and 2740 L plot^{-1} and 1050 g plot^{-1} in 2006. Plot 2 exhibited totals of 628 L plot^{-1} and 139 g plot^{-1} in 2005 and 939 L plot^{-1} and 214 g plot^{-1} in 2006. The plots at site 2 produced more runoff and salts compared to the vegetated plot at site 1, possibly due to wetter conditions on the South facing slope, more clayey soil and a steeper slope.

The data in the tables were also used to quantify the approximate percentage of rainfall that became overland flow in 2006. At site 1, plot 1, 20 % of recorded rainfall was partitioned into runoff, and at site 1, plot 2, this was calculated to be in the region of 8 %.

This discrepancy was expected as site 1, plot 1 was unvegetated. The total runoff was calculated to be approximately 19 % of the total recorded rainfall at site 2, plot 1, and 9 % at site 2, plot 2. This difference was interpreted to be a function of the difference in spatial vegetation cover density.

TABLE 5
ELECTRICAL CONDUCTIVITY (EC), RUNOFF VOLUMES AND SALTS MOBILIZED FROM RUNOFF PLOT 1 (BARE SOIL) AT SITE 1

Date	**EC (dS m^{-1})**			**Rainfall (mm)**	**Runoff**		**TDS**	
	Tank1	**Tank2**	**Average of tanks**		**L/plot**	**L/m^2**	**g/plot**	**g/m^2**
10-Jun-05	1.24	-	1.24	-	131*	2.94*	91.54	2.08
23-Jun-05	0.7	1.45	1.06	-	131*	2.94*	77.19	1.75
4-Jul-05	0.54	0.79	0.67	-	131*	2.94*	46.10	1.05
22-Jul-05	0.58	0.47	0.53	-	131*	2.94*	34.94	0.79
11-Aug-05	1.05	0.53	0.79	-	131*	2.94*	55.66	1.27
18-Aug-05	0.88	0.78	0.83	-	42*	0.95*	18.87	0.43
23-Aug-05	0.85	0.78	0.82	-	107*	2.43*	47.42	1.08
30-Aug-05	0.66	0.83	0.75	-	131*	2.94*	52.47	1.19
Total (2005)	**-**	**-**	**-**	**-**	**935**	**21.02**	**424.19**	**9.64**
25-Apr-06	0.48	-	0.48	22	22	0.49	5.20	0.12
9-May-06	0.65	0.74	0.70	24.4	100	2.24	37.01	0.83
23-May-06	0.27	0.23	0.25	46.4	131*	2.94*	12.62	0.28
1-Jun-06	1.24	-	1.24	12.2	24	0.54	16.77	0.38
29-Jun-06	0.91	-	0.91	-	456	10.22	227.06	5.09
18-Jul-06	0.97	-	0.97	-	23*	0.52*	12.29	0.28
25-Jul-06	0.55	0.81	0.68	29	250	5.61	89.49	2.01
3-Aug-06	0.15	-	0.15	17	14	0.31	0.50	0.01
10-Aug-06	0.49	0.43	0.46	13.8	378	8.48	84.71	1.90
Total (2006)	**-**	**-**	**-**	**-**	**1398**	**31.35**	**485.65**	**10.89**
Combined Total	**-**	**-**	**-**	**-**	**2333**	**52.37**	**909.84**	**20.53**

* Manual measurement

TABLE 6
ELECTRICAL CONDUCTIVITY (EC), RUNOFF VOLUMES AND SALTS MOBILIZED FROM RUNOFF PLOT 2 AT SITE 1

Date	EC (dS m^{-1})			Rainfall (mm)	Runoff		TDS	
	Tank1	**Tank2**	**Average of tanks**		**L/plot**	**L/m^2**	**g/plot**	**g/m^2**
10-Jun-05	0.3	0.31	0.31	-	105*	2.38*	13.95	0.32
23-Jun-05	0.19	0.2	0.2	-	59*	1.34*	3.89	0.09
4-Jul-05	0.16	-	0.16	-	25*	0.58*	1.04	0.02
22-Jul-05	0.18	-	0.18	-	40*	0.90*	2.15	0.05
11-Aug-05	0.13	-	0.13	-	39*	0.89*	0.91	0.02
18-Aug-05	0.12	-	0.12	-	39*	0.88*	0.67	0.02
23-Aug-05	0.13	-	0.13	-	26*	0.59*	0.61	0.01
30-Aug-05	1.06	0.86	0.96	-	131*	2.97*	69.22	1.57
Total (2005)	**-**	**-**	**-**	**-**	**464**	**10.53**	**92.42**	**2.10**
25-Apr-06	-	-	-	-	-	-	-	-
9-May-06	0.11	-	0.11	24.4	10	0.22	0.11	0.00
23-May-06	0.42	-	0.42	46.4	38*	0.85*	7.51	0.17
1-Jun-06	-	-	-	-	-	-	-	-
29-Jun-06	-	-	-	-	-	-	-	-
18-Jul-06	-	-	-	-	1*	0.02*	-	-
25-Jul-06	0.34	-	0.34	29	12	0.27	1.79	0.04
3-Aug-06	-	-	-	-	-	-	-	-
10-Aug-06	0.42	0.40	0.41	13.8	324	7.26	62.08	1.39
Total (2006)	**-**	**-**	**-**	**-**	**385**	**8.63**	**71.49**	**1.60**
Combined Total	**-**	**-**	**-**	**-**	**849**	**19.16**	**163.91**	**3.7**

* Manual measurement

TABLE 7
ELECTRICAL CONDUCTIVITY (EC), RUNOFF VOLUME AND SALTS MOBILIZED FROM RUNOFF PLOT 1 AT SITE 2

Date	EC (dS m^{-1})			Rainfall (mm)	Runoff		TDS	
	Tank1	Tank2	Average of tanks		L/plot	L/m^2	g/plot	g/m^2
10-Jun-05	0.241	-	0.24	-	13*	0.30*	1.17	0.03
23-Jun-05	2.59	2.75	2.67	-	114*	2.60*	178.86	4.06
4-Jul-05	1.15	1.08	1.12	-	76*	1.73*	47.56	1.08
22-Jul-05	1.29	1.14	1.22	-	131*	2.97*	89.94	2.04
11-Aug-05	1.02	0.96	0.99	-	131*	2.97*	71.61	1.63
18-Aug-05	0.78	0.7	0.74	-	16*	0.37*	6.31	0.14
23-Aug-05	0.85	0.82	0.84	22.6	82	1.86	37.34	0.85
30-Aug-05	0.53	0.41	0.47	21	328	7.45	75.50	1.72
Total (2005)	**-**	**-**	**-**	**-**	**891**	**20**	**508.29**	**11.55**
25-Apr-06	0.15	-	0.15	15.2	8	0.18	0.28	0.01
9-May-06	0.19	-	0.19	24.4	8	0.18	0.47	0.01
23-May-06	0.57	0.48	0.53	46.4	131*	2.94*	34.59	0.78
1-Jun-06	1.08	-	1.08	-	-	-	-	-
29-Jun-06	1.15	1.12	1.14	122.6	752	16.86	475.41	10.66
18-Jul-06	0.69	-	0.69	34	131*	2.94*	47.24	1.06
25-Jul-06	0.65	0.61	0.63	25	432	9.69	140.14	3.14
3-Aug-06	0.87	0.83	0.85	24.6	292	6.55	133.49	2.99
10-Aug-06	0.51	0.41	0.46	31.6	986	22.11	218.69	4.90
Total (2006)	**-**	**-**	**-**	**-**	**2740**	**61.43**	**1050.31**	**23.55**
Combined Total	**-**	**-**	**-**	**-**	**3631**	**81.43**	**1558.6**	**35.1**

* Manual Measurement

TABLE 8
ELECTRICAL CONDUCTIVITY (EC), RUNOFF VOLUME AND SALTS MOBILIZED FROM RUNOFF PLOT 2 AT SITE 2

Date	EC (dS m^{-1})			Rainfall (mm)	Runoff		TDS	
	Tank 1	Tank 2	Average of tanks		L/plot	L/m^2	g/plot	g/m^2
10-Jun-05	0.26	-	0.26	-	34*	0.76*	3.48	0.08
23-Jun-05	0.72	0.61	0.67	-	58*	1.33*	20.41	0.46
4-Jul-05	0.88	-	0.88	-	33*	0.74*	15.83	0.36
22-Jul-05	0.76	0.79	0.78	-	50*	1.13*	20.94	0.48
11-Aug-05	0.58	-	0.58	-	21*	0.48*	6.24	0.14
18-Aug-05	0.45	-	0.45	-	22*	0.50*	4.80	0.11
23-Aug-05	0.53	-	0.53	22.6	82	1.86	21.87	0.50
30-Aug-05	0.33	0.31	0.32	21	328	7.45	45.56	1.04
Total (2005)	**-**	**-**	**-**	**-**	**628**	**14.25**	**139.13**	**3.16**
25-Apr-06	-	-	-	-	-	-	-	-
9-May-06	0.10		0.10	24.4	8	0.18	0.04	0.00
23-May-06	0.33	0.34	0.34	46.4	131*	2.94*	19.57	0.44
1-Jun-06	-	-	-	-	-	-	-	-
29-Jun-06	0.66	0.69	0.68	122.6	244	5.47	86.52	1.94
18-Jul-06	0.57	-	0.57	34	112*	2.51*	32.28	0.72
25-Jul-06	0.50	0.51	0.51	25	174	3.90	43.84	0.98
3-Aug-06	-	-	-	24.6	-	-	-	-
10-Aug-06	0.29	0.28	0.29	31.6	270	6.05	32.18	0.72
Total (2006)	**-**	**-**	**-**	**-**	**939**	**21.05**	**214.42**	**4.81**
Combined Total	**-**	**-**	**-**	**-**	**1567**	**35.3**	**353.55**	**7.97**

* Manual measurement

4.8 Detailed Event Analysis

An example of logger output data from 5 to 31 August 2005 (DoY 218 to 244) is shown in Figure 24 for site 2. The data were logged at hourly intervals until 18 August 2005 (DOY 231), and in 10 minute intervals thereafter. Six major rain events were recorded during this period (Figure 24, top graph). Water level in the contour is expressed in mV. Some of the water level data were lost during the night due to a shortage in power supply. However, it is evident that the sensor responded well during the last two rain events. Runoff data from plot 1 (Figure 24, middle graph) and plot 2 (bottom graph) were comparable with rain events in terms of the time of the event and its intensity. The logging system at site 1 was being installed and tested in 2005.

Two snapshots in time were extracted in order to get better insight of the processes occurring for two rain events on DoY 230 and 239 in 2005 (Figure 25). Rainfall and runoff data for both plots at site 2 are represented in mm h^{-1} (DoY 230) and mm $10min^{-1}$ (DoY 239) in Figure 25. The time lag of runoff depended on antecedent moisture conditions, rainfall intensity and duration. Higher runoff values were again recorded on plot 1, when compared to plot 2.

In 2006 the electronics functioned for most of the winter season. The only disturbances in data records were caused by large rainstorms and trampling by cattle. MCS logger data for site 1 and 2, for 12 June 2006 (DoY 163) to 13 June 2006 (DoY 164), are presented in Figures 26 and 27. It was observed that runoff is largely influenced by the intensity of rainfall events and by antecedent moisture conditions. Site 1, plot 2 generally produced very little runoff during the 2006 season. Fluctuations in the water levels in the contours measured by the pressure sensors also generally followed the rainfall pattern. A time lag occurred between the start of a rainfall event and the increase in water level. This could be a result of the time required for the rainfall intensity to exceed the soil's infiltration rate or for the soil to reach saturation. All other available logger data, for both site 1 and site 2, for the 2006 winter season is presented in Appendix C.

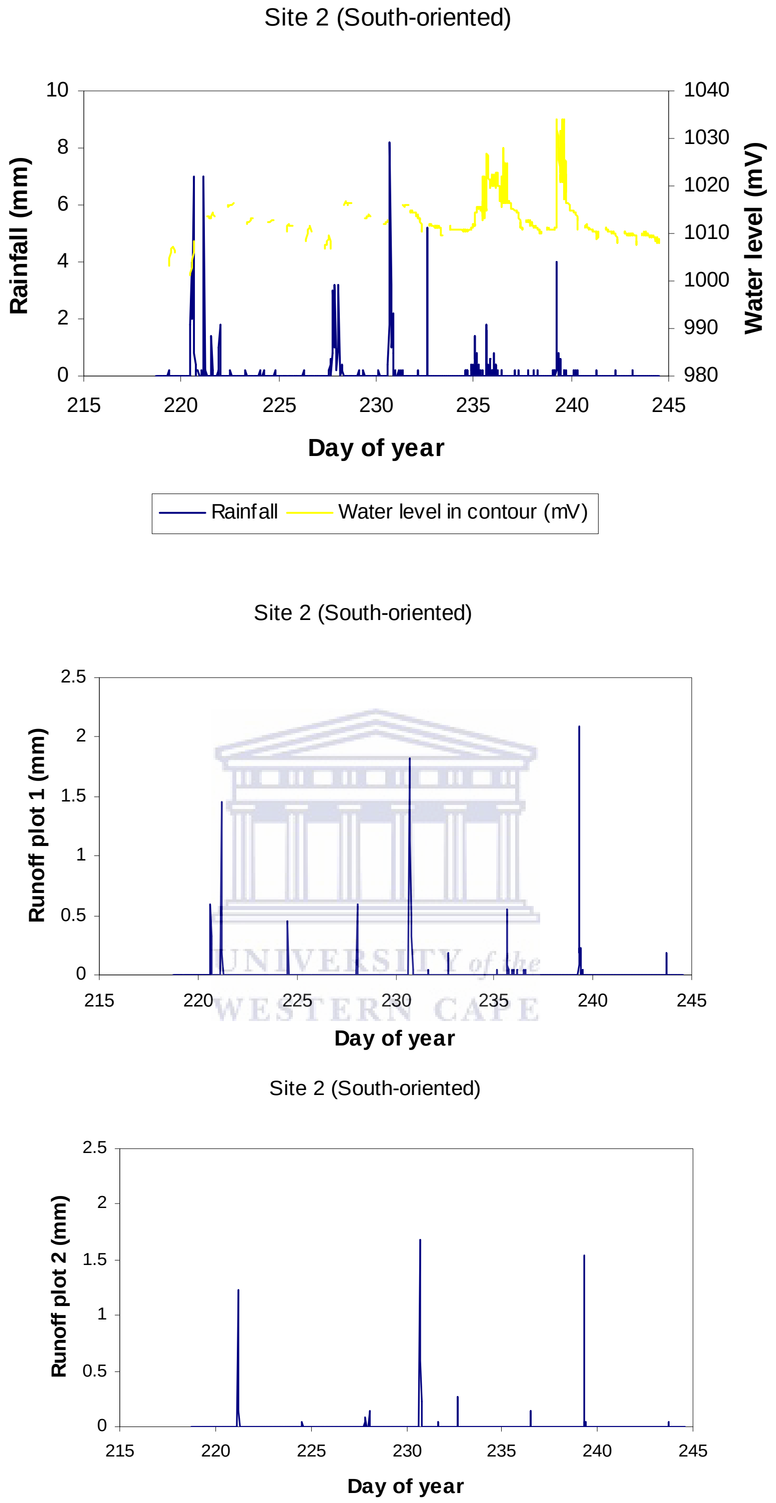


Figure 24. Logged records of rainfall and water level in the contours in mV (top graph), and runoff data from plot 1 (middle graph) and plot 2 (bottom graph) for site 2 in 2005.

Figure 28 shows logged records of total runoff as a function of total rainfall for rainfall events at site 1, plot 2 and at site 2, plot 1 and 2. The runoff data for site 1, in 2005, were obtained via manual measurements, i.e. by measuring the water heights in the collection tanks (excluding the events when both collection tanks overflowed). The rainfall data were obtained from the automatic weather station. The data for site 2 were obtained via manual measurements and from the data logger on the south-facing slope. In 2006, all data were obtained from the MCS loggers. It is clear from the graphs that there is no correlation between total runoff and total rainfall, as these are influenced by many other factors, like for example, type of vegetation and stage of crop growth, interception, water uptake by plant roots, and the antecedent moisture conditions. The intensity of the rainfall event also influenced runoff amounts.

The relationship between the amount of runoff produced by a rainfall event and the antecedent moisture conditions, represented by the soil water content, is shown in Figure 29. Typical events are shown for both site 1 and site 2. The average soil water content, obtained from two Echo sensors, is plotted against the total runoff produced by rainfall events. Data from the shallow, i.e. 10 cm, Echo sensors were used. The data indicates that during low intensity rainfall events, the antecedent moisture conditions mainly govern the amount of runoff being produced. However, the antecedent moisture condition’s influence is drastically minimised during high intensity rainfall events. There was thus two types of overland flow occurring in the SSC. During low intensity storms it was mainly saturation excess overland flow, i.e once saturation is reached, overland flow commences. On the other hand, during high intensity storms, infiltration excess overland flow occurs, i.e. once the rainfall intensity exceeds the infiltration rate, overland flow occurs. All other available data are shown in Appendix F.

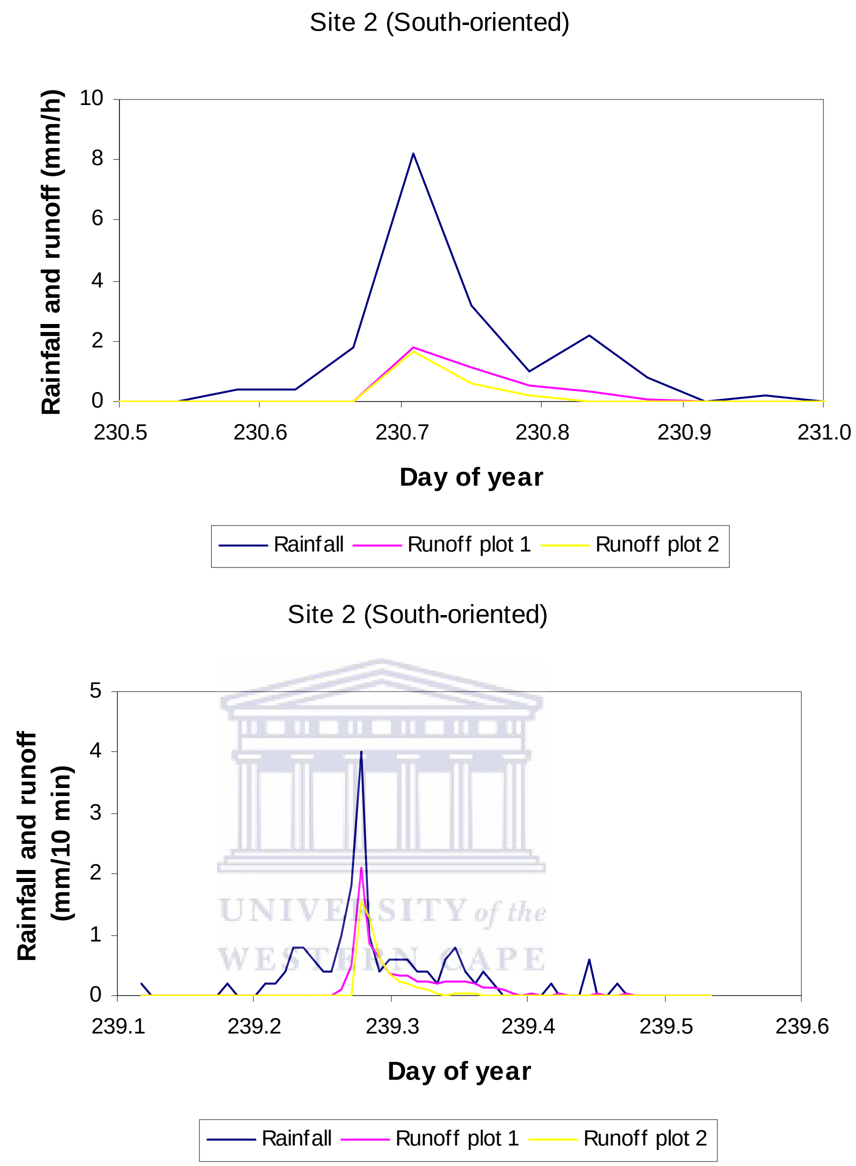
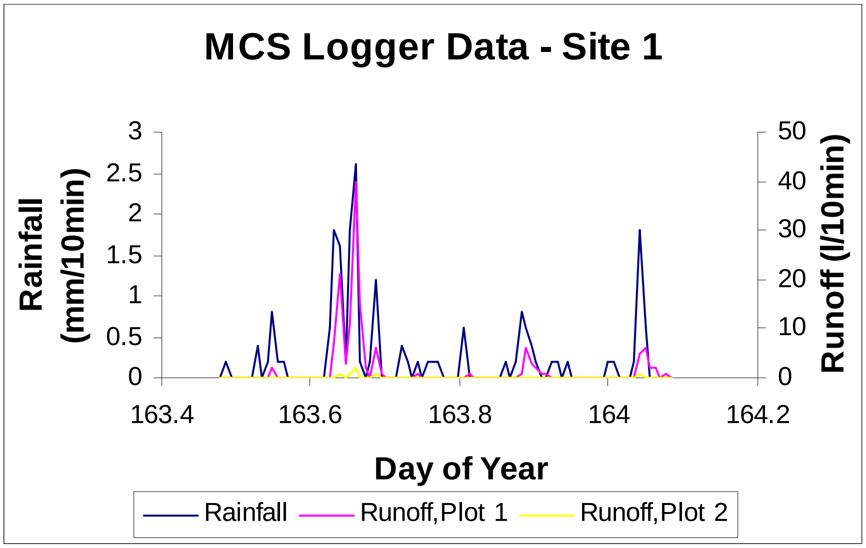


Figure 25. Snapshot of logged records of rainfall and runoff for two rain events at site 2 in 2005.



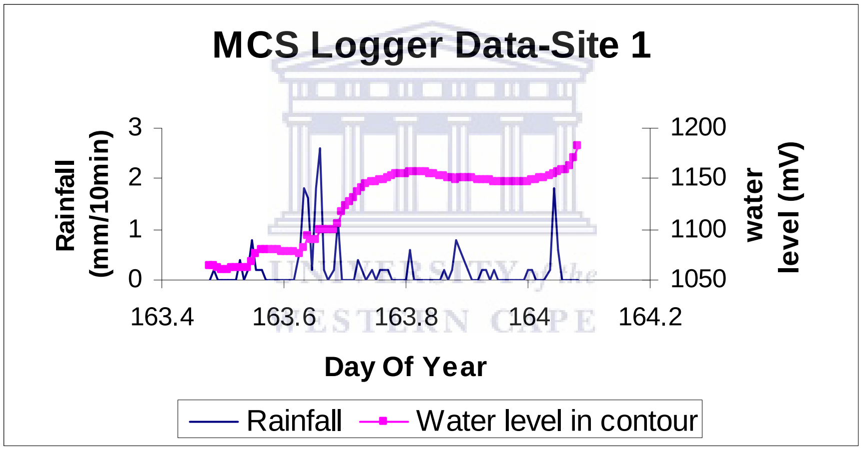
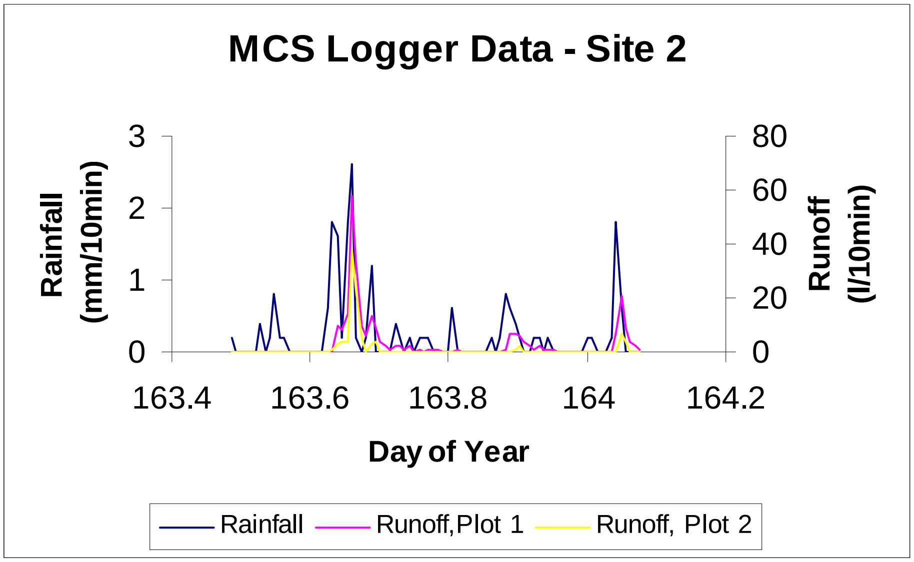


Figure 26. MCS Logger data for 12 and 13 June 2006 (Site 1).



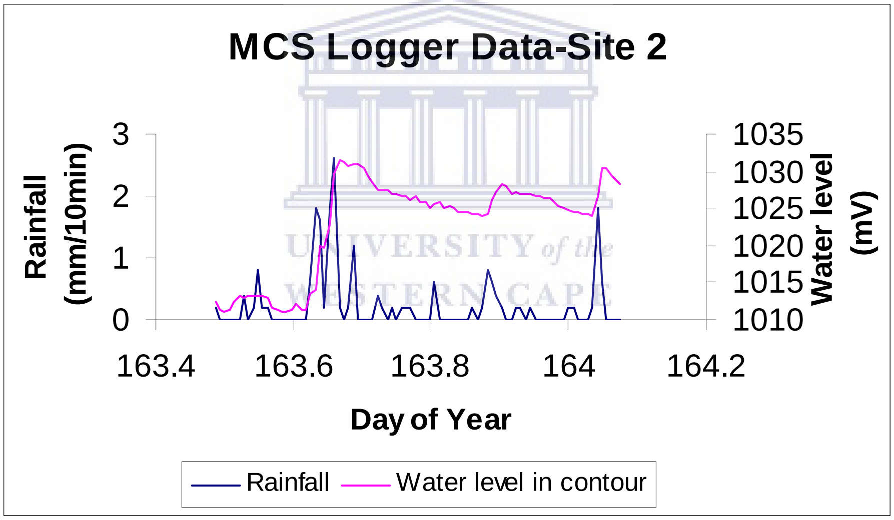
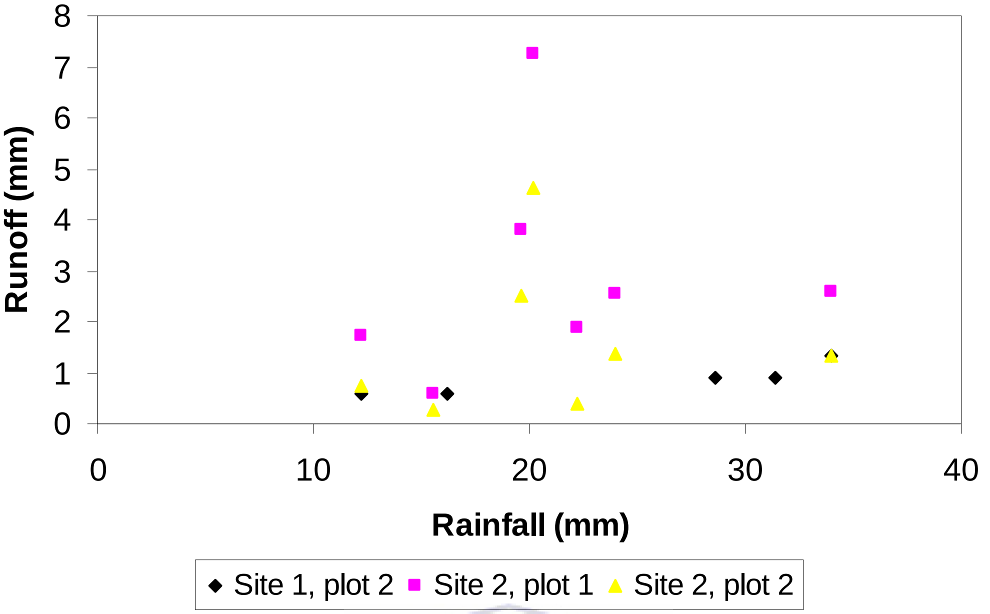


Figure 27. MCS Logger data for 12 and 13 June 2006 (Site 2).



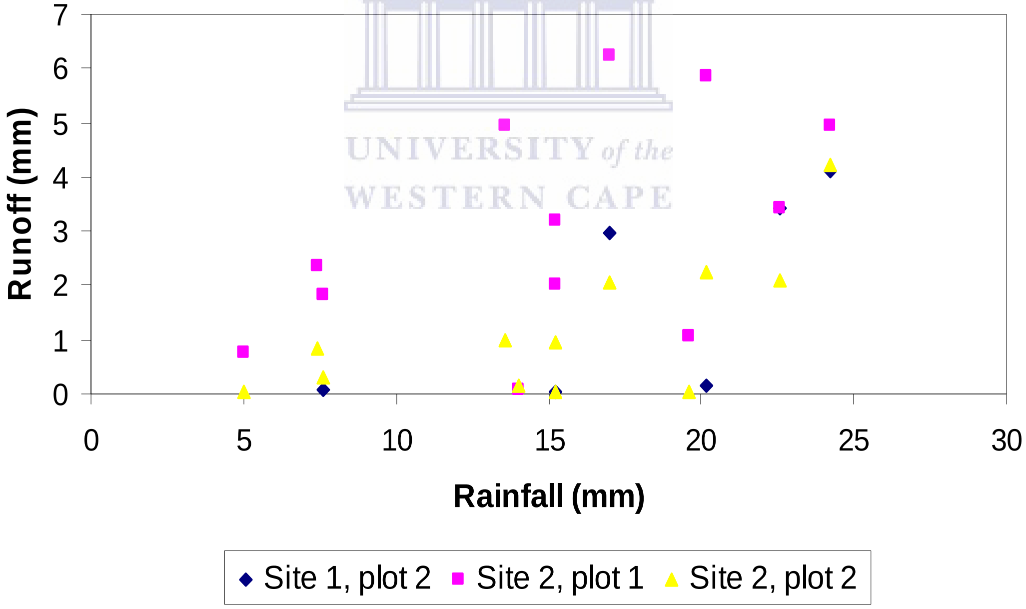
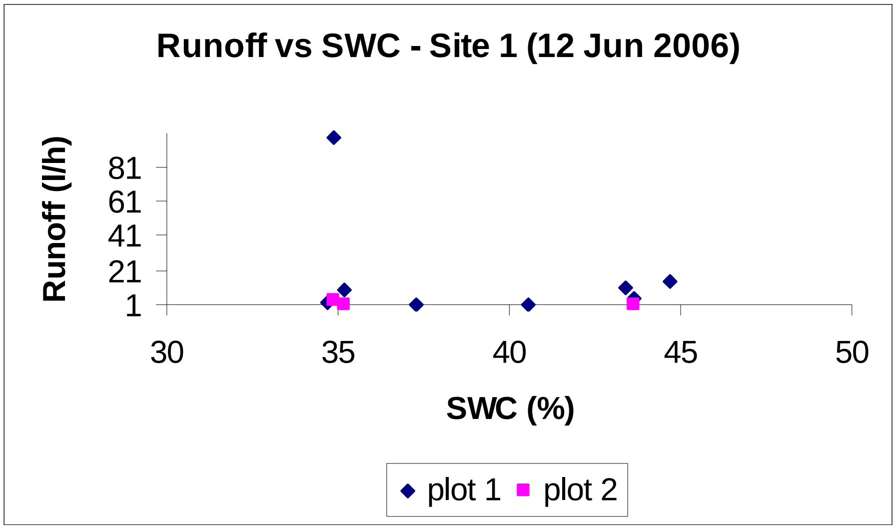


Figure 28. Total runoff as a function of total rainfall per event, for the three runoff plots planted to wheat in 2005 (top graph) and left fallow in 2006 (bottom graph).



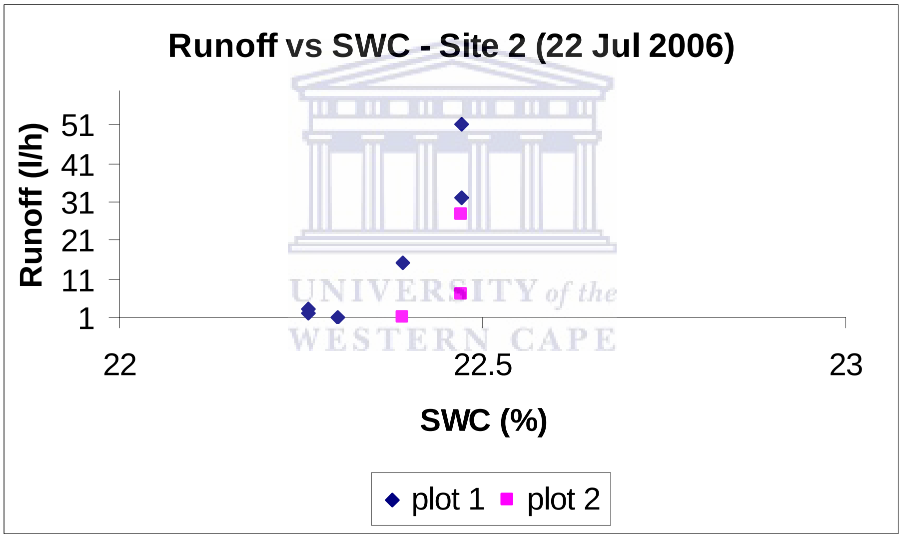


Figure 29. The relationship between the Soil Water Content (SWC) and the amount of runoff produced by a rainfall event.

Figure 30 illustrates the relationship between the total runoff produced by a rainfall event and the product of the total amount of rainfall and the peak intensity of events. The events are plotted for the three vegetated runoff plots. The graph shows that a clear relationship between these variables was not discernable, i.e. low R^2 values were obtained. However, the correlation was better, compared to the relationships in Figures 28 and 29. It is therefore concluded that amount and peak intensity of rainfall may be the main factors affecting runoff in the particular environment.

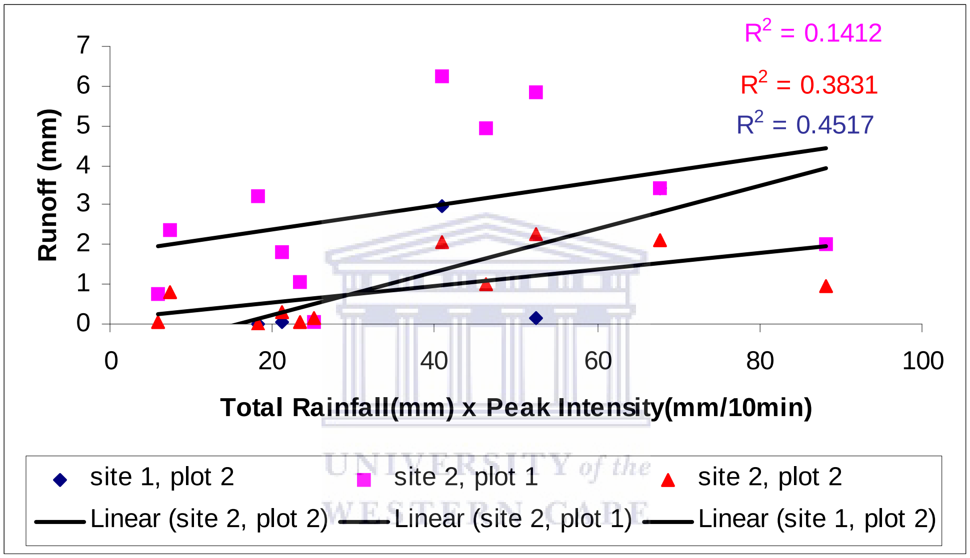


Figure 30. The relationship between runoff and the product of the total rainfall and peak intensity of rainfall events (2006).

4.9 Comparison of Measured Runoff Data and SCS Curve Number Method

Table 12 and 13 present the results of a comparison made between the runoff data obtained with the MCS Loggers and an estimation of runoff calculated using the Soil Conservation Service (SCS) Curve Number (CN) Method. According to Hudson (1993), the SCS Curve Number Method is a means of quantifying probable rates of runoff. It is based on the fact that runoff will vary according to the amount of rainfall during the storm, and according to the amount of moisture which can be absorbed by the soil. The equation is (USDA-SCS, 1985):

$$Q = (P-0.2S)^2 / (P+0.8S)$$

Where:

Q – runoff in mm or inches

P – total rainfall in mm or inches

S – amount of rainfall in mm or inches which can soak into the soil during the storm.

According to Hudson (1993), the runoff potential can be calculated using two approaches. Method 1 calculates the runoff potential, taking into account the number of days since the last rainfall event, i.e. the antecedent moisture conditions. According to Hudson (1993), this method results in more accurate estimates of runoff when compared to method 2, which is described below. Method 1 is further described in Table 9.

TABLE 9

VALUES OF S (mm), TAKING INTO ACCOUNT THE NUMBER OF DAYS SINCE THE LAST RAINFALL EVENT AND THE DIFFERENT STORAGE CAPACITIES OF DIFFERENT SOILS (USDA-SCS 1964).

Soil type	**Number of days since last storm which caused runoff**		
	More than 5	2-5	Less than 2
Good permeability, for example, deep sands	150	75	50
Medium permeability, for example, sandy clay loams and clay loams	100	50	25
Low permeability, for example, clays	50	25	25

Site 1 at Goedertrou is best described as a soil type with medium permeability and site 2 as a soil type with low permeability.

An alternative approach, i.e. Method 2, assumes a constant value of S for a given catchment. It takes into account variables such as land use, soil conservation practices and the hydrologic condition of the catchment. According to Hudson (1993), the procedure would be to first describe the area according to soil group, then according to land use, then obtain the curve number for each treatment and condition. Soils are assigned to one of four hydrologic soil groups (A-D) based on their infiltration capacity. “A” soils possess a high infiltration capacity and resultantly a low potential to produce runoff, while “D” soils have a low infiltration capacity and thus a high runoff potential (Viessman and Lewis, 2003). Table 10 outlines the various hydrologic soil groups.

TABLE 10
HYDROLOGIC SOIL GROUPS (USDA-SCS 1964).

Hydrologic soil group	Runoff potential	Infiltration when wet	Typical soils
A	Low	High	Excessively drained sands and gravels
B	Moderate	Moderate	Medium textures
C	Medium	Slow	Fine texture or soils with a layer impeding downward drainage
D	High	Very slow	Swelling clays, clay pan soils or shallow soils over impervious layers

Site 1 is best described by hydrologic soil group C and site 2 by soil group D. The hydrologic condition essentially reflects on the quality and management of a particular land use. The potential for runoff is minimized by a good hydrologic condition. An area possessing a good condition is typically characterized by a dense land cover. Alternatively, a poor condition is characterized by sparse land cover and extensive use and thus possesses a high potential for runoff. According to Hudson (1993), for arable land, the hydrologic condition reflects whether the rotation will encourage infiltration and promote a good tilth. For grassland, it is assessed based on the density of the vegetative cover, and more than 75 % cover is 'good', while less than 50 % is 'poor'. For forest lands, the criteria are the depth of litter and humus, and the compactness of the humus. Once all these variables have been determined, a runoff curve number (CN) is assigned using Table 11.

TABLE 11
ESTIMATION OF RUNOFF CURVE NUMBERS FOR AVERAGE ANTECEDENT MOISTURE CONDITIONS. (USDA-SCS 1964).

Land use or cover	**Treatment or practice**	**Hydrologic condition**	**Hydrologic soil group**			
			A	**B**	**C**	**D**
Fallow	Straight row	-	77	86	91	94
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	75	82	86
	Terraced	Poor	66	74	80	82
	Terraced	Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Terraced	Poor	61	72	79	82
	Terraced	Good	59	70	78	81
Close seeded legumes or rotation meadow	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Good	55	69	78	83
	Terraced	Poor	63	73	80	83
	Terraced	Good	51	67	76	80
Pasture or range	Contoured	Poor	68	79	86	89
	Contoured	Fair	49	69	79	84
	Contoured	Good	39	61	74	80
		Poor	47	67	81	88
		Fair	25	59	75	83

		Good	6	35	70	79
Meadow (permanent)		Good	30	58	71	78
Woods (farm wood-lots)		Poor Fair Good	45 36 25	66 60 55	77 73 70	83 79 77
Farmsteads		-	59	74	82	86
Roads		-	74	84	90	92

The CN is then used to calculate S, using the following equation (USDA-SCS, 1965):

$S = 1000/CN - 10$ (units are expressed in inches)

$S = 25400/CN - 254$ (units are expressed in mm)

The results of the comparison is presented in Tables 12 and 13. The land use at Goedertrou in 2006 is best described as pasture (Table 11). The SCS Curve Number Method constantly underestimated the amount of runoff that would occur from plot 1 at site 1 (Table 12). This might be because the bare plot, strictly speaking, does not fall into the pasture category (Table 11). However, utilizing the land uses given in Table 11, it was decided that pasture was the most suitable for this plot. For the other runoff plots (Tables 12 and 13) the results varied. This might result from over –or under-compensation of some processes (for e.g. infiltration, interception, evaporation or antecedent moisture conditions) by the SCS Curve Number Method. The small scale of observation represented by the runoff plots might also not be suitable for application of the SCS Curve Number Method. Based on the results obtained application of the SCS Curve Number Method would not be suitable for similar investigations.

TABLE 12
A COMPARISON OF RUNOFF VALUES OBTAINED FROM THE MCS LOGGER WITH VALUES CALCULATED USING THE SCS CURVE NUMBER METHOD AT SITE 1.

Site 1					
Date	**Rainfall (mm)**	**Runoff (L/m^2) – MCS Logger Data**		**Runoff (L/m^2) – SCS Curve Number Method**	
		Plot 1	**Plot 2**	**Method 1**	**Method 2**
12 & 13 Jun 2006	20.2	6.36	0.27	1.73	5.72
13 Jun 2006	7.6	3.23	0.14	0.24	0.24
21 & 22 Jul 2006	15.2	5.66	0	2.95	2.94
31 Jul 2006	13.4	0.32	0.05	0.22	2.10
3 & 4 Aug 2006	13.2	8.27	5.91	2.03	2.01
11 Aug 2006	15.2	8	8.23	0.49	2.94
14 Aug 2006	22.6	9.36	6.82	7.27	7.24

TABLE 13
A COMPARISON OF RUNOFF VALUES OBTAINED FROM THE MCS LOGGER WITH VALUES CALCULATED USING THE SCS CURVE NUMBER METHOD AT SITE 2.

Site 2

Date	**Rainfall (mm)**	**Runoff (L/m^2) – MCS Logger Data**		**Runoff (L/m^2) – SCS Curve Number Method**	
		Plot 1	**Plot 2**	**Method 1**	**Method 2**
21 Apr 2006	14	0.14	0.27	0.3	4.29
1 Jun 2006	5	1.5	0.09	0.56	0.17
12 & 13 Jun 2006	20.2	11.68	4.5	5.75	8.67
13 Jun 2006	7.6	3.63	0.59	0.24	0.92
6 Jul 2006	19.6	2.14	0.09	1.55	8.22
21 & 22 Jul 2006	11.8	4.05	1.91	1.45	2.96
31 Jul 2006	15.2	6.41	0.05	2.96	5.08
3 Aug 2006	17	12.45	4.14	3.89	6.32
8 Aug 2006	13.6	9.91	2	2.20	4.04
11 & 12 Aug 2006	24.2	9.86	8.45	8.34	11.82
14 Aug 2006	22.6	6.82	4.18	7.27	10.54

4.10 Modeling of Subsurface Fluxes

The movement of water and solutes in the vadose zone during 2006, at both runoff sites, was simulated using HYDRUS-2D. The simulated results were compared to field data, to assess the suitability of the model as well as to estimate the subsurface lateral fluxes of water and in particular salts. This model was selected because of its ability to simulate fluxes for irregular geometries, i.e. hill slopes, and because of its strong theoretical background.

HYDRUS-2D has an interactive user interface, which includes (i) a project manager for managing and creating new data, (ii) a pre-processing tab for entering the required input data, and (iii) a post-processing tab for viewing the output data. The software runs in Microsoft Windows 95, 98, and NT. The package requires a MS-DOS compatible system, 16 Mb of RAM memory, and at least 10 Mb of available disk space. Extensive on-line context-sensitive help is available through the interface.

4.10.1 Input Data

The input data required to successfully run the model are selected/entered in the pre-processing tab. The input data are arranged as follows:

- Main processes (processes to be simulated, e.g. water flow, solute transport, root water uptake, etc.)
- Geometry information (details on the geometry of the system to be designed by the user)
- Time information (time units and discretization)
- Print information (output print details)
- Iteration criteria
- Soil hydraulic model
- Water flow parameters
- Solute transport – General information
- Solute transport – Transport parameters
- Solute transport – Reaction parameters
- Solute transport – Temperature dependence

- Heat transport parameters
- Root water uptake model
- Root water uptake model (parameters) – Pressure head reduction (water stress parameters)
- Time-variable boundary conditions
- Geometry and mesh editor
- Boundary conditions editor

4.10.2 Output Data

After a simulation is completed, the results can be viewed in the post-processing tab in various formats. They may be displayed as two-dimensional X-Y graphs, contour and spectral maps, velocity vectors or as an animation of both contour and spectral maps. Output data are arranged as follows:

- Graphical display of results in contour or spectral maps
- Observation points
- Pressure heads
- Water boundary fluxes
- Cumulative water boundary fluxes
- Solute fluxes
- Soil hydraulic properties
- Run time information
- Mass balance information
- Conversion of output into ASCII files

4.10.3 HYDRUS-2D Simulations

HYDRUS-2D was used to run simulations of water and solute movement in the vadose zone, at the two intensive monitoring sites where the runoff plots were installed. These simulations were run for the 2006 season, when the Goedertrou SSC was left fallow. The results were compared to field measurements to assess the suitability of the model and to estimate subsurface lateral fluxes of water and salts due to the formation of temporary water tables, in particular at site 1 where the Malmesbury shale restricts free drainage.

The simulations were run from DoY 1 (1 January 2006) to DoY 241 (30 August 2006). When designing the geometry of the system, variables such as the length of the profile and its slope were taken into account to construct the system to scale. The runoff plots are 22 m in length with a slope of 9.1 % at site 1 and 12.4 % at site 2. Two different soil types are also represented at each site, i.e. Glenrosa at site 1 and Swartland at site 2. The soil at site 1 is approximately 0.5 m deep, overlying Malmesbury shale, whilst the soil at site 2 is a deep clay loam. HYDRUS-2D provides a soil catalogue accompanied by the parameters that influence water flow in that particular soil type. From that catalogue, sandy clay loam was chosen for site 1 and clay loam for site 2. The average bulk density for both soil profiles was 1.53 g cm^{-3}. In order to describe the geometric shape of the profile, rhomboids were drawn and MESHGEN-2D was used to generate the finite element mesh (Figure 31). HYDRUS-2D also provides a number of different boundary conditions to assign to the system being designed. The boundary conditions chosen are shown in Figure 31.

The boundary conditions were (Figure 31):

i) Atmospheric at the top side of the rhomboid (green boundary nodes)

ii) No flux at the vertical upper side of the rhomboid (white boundary nodes) and Variable Pressure (blue boundary nodes). The variable pressure was calculated from measurements of volumetric soil water content obtained with the Echo sensors. The measurements were converted into pressure values using soil water retention curves determined before the experiment started.

iii) Seepage face at the vertical lower side of the rhomboid (dark green boundary nodes).

iv) The lower side of the rhomboid represented a constant flux boundary condition at site 1 (purple boundary nodes). A constant flux of 0.00048 m day^{-1}, calibrated against soil water content data, was assigned to this boundary due to the relatively low hydraulic conductivity of the Malmesbury shale. At site 2, the lower side of the rhomboid represented a free drainage boundary condition (red boundary nodes).

The variable pressure boundary node essentially forces a point in the soil profile to exhibit a specified water content as moisture is either added to, or removed from this node. These water contents are however derived from field measurements obtained with the Echo sensors and thus the forced water content is interpreted to reflect field conditions. The contribution of water to the profile from this node proved to be essential in simulating realistic subsurface lateral water and solute fluxes along the profile.

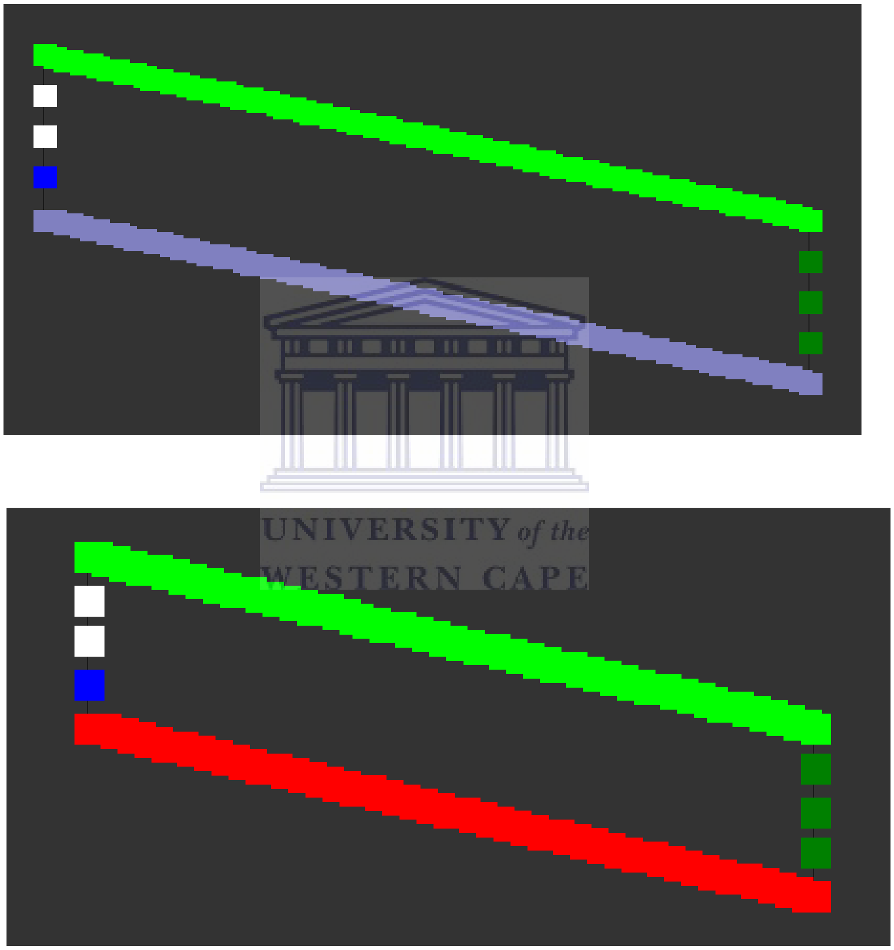


Figure 31. Printout of the geometries of the system with boundary conditions for site 1 (top) and site 2 (bottom). The dimensions of the shapes are not proportional.

At site 1, salts were added to the profile from 3 sources, i.e. rainfall, the underlying Malmesbury shale and throughflow. Throughflow was accounted for by the variable pressure boundary node (upper vertical boundary). This node also contributed water to the profile. At site 2 salt and water were contributed to the profile by rainfall and via the variable pressure boundary node. An average EC of 0.12 dS m^{-1} (rounded off) was calculated for all rainfall in 2006. This was converted to TDS using the equation in Figure 20, yielding a result of 14.38 g m^{-3}. Thus rainfall in 2006 contributed 14.38g m^{-3} of salts per rainfall event, at site 1 and site 2. The amount of salts contributed by the underlying geology and from the variable pressure boundary node was calculated using the results obtained from 1:5 soil to water ratio analysis performed in 2006. An average EC of 0.18 dS m^{-1} was calculated from samples collected at site 1 and 0.29 dS m^{-1} at site 2. These values, however, are not a true representation of field conditions due to the diluting effect of the added water in the preparation of the 1:5 soil:water extracts. As the amount of water is 5 times the amount of soil, the soil sample is said to have a water content of 500 % in gravimetric terms. The gravimetric water content is thus 5g water per 1g soil. If this is converted into volumetric water content, using the measured bulk density of 1.53 g cm^{-3}, a value of 7.65 or 765 % is obtained. Assuming the soil water content at the runoff plots was on average 0.2 or 20 % (in volumetric terms, obtained from field measurements), the concentrations of 1:5 soil:water ratio analysis were diluted by a factor of 38.25. When the diluting effect was taken into account, an average of 6.89 dS m^{-1} was calculated from samples collected at site 1 and 11.1 dS m^{-1} from samples collected at site 2. These figures were then converted to TDS using the equation in Figure 21. A value of 3673 g m^{-3} was obtained for site 1 and 5925 g m^{-3} at site 2. These concentrations represent the sources of salts, from the underlying geology (site 1) and from the variable pressure boundary node (site 1 and site 2).

The parameters for the Feddes' root water uptake model were selected for grass, from the database included in the Hydrus-2D model, in order to simulate re-growth of wheat and medic grass (crops grown in previous seasons) under fallow conditions.

The time variable boundary conditions were entered on a daily time step:

i) Rainfall obtained from the weather station, as well as the associated salt concentration (described above).

ii) Evaporation and transpiration. Weather data were used to calculate the FAO Penman-Monteith reference evapotranspiration ETo (Allen *et al*. 1998).

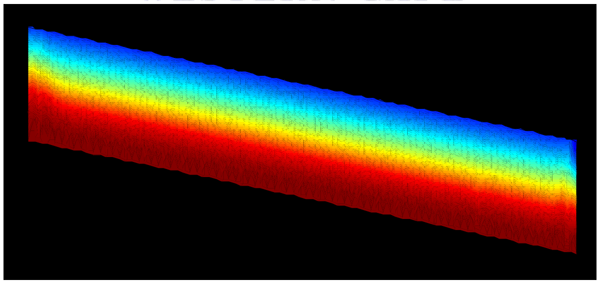
iii) The amount of salts contributed from the Malmesbury shale and from the variable pressure boundary node (described above).

A linear density distribution was set for the root system (1 at the soil surface and 0 at the bottom of the soil profile).

4.10.4 Simulation results

In testing the HYDRUS-2D model, the first step was to get an acceptable simulation of the soil water fluxes and contents. The model's soil water content followed the measured trends of soil moisture during winter (from June to August 2006). The simulated soil water content values also proved to be sensitive to rainfall events and water uptake by the crop. Four snapshots in time are presented in Figures 32 (site 1) and 33 (site 2). The soils were subject to drying and wetting processes during winter 2006. Site 2 (more clayey soil) was generally wetter than site 1.

DoY 125



DoY 191

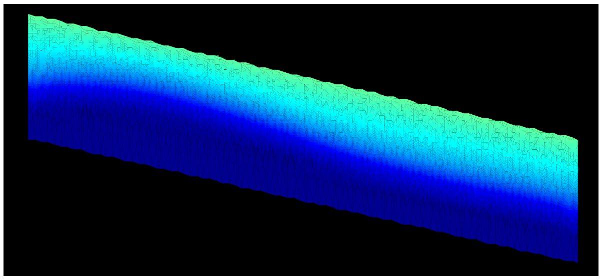


Figure 32. Simulation of volumetric soil water content on the hill slope profile at site 1.

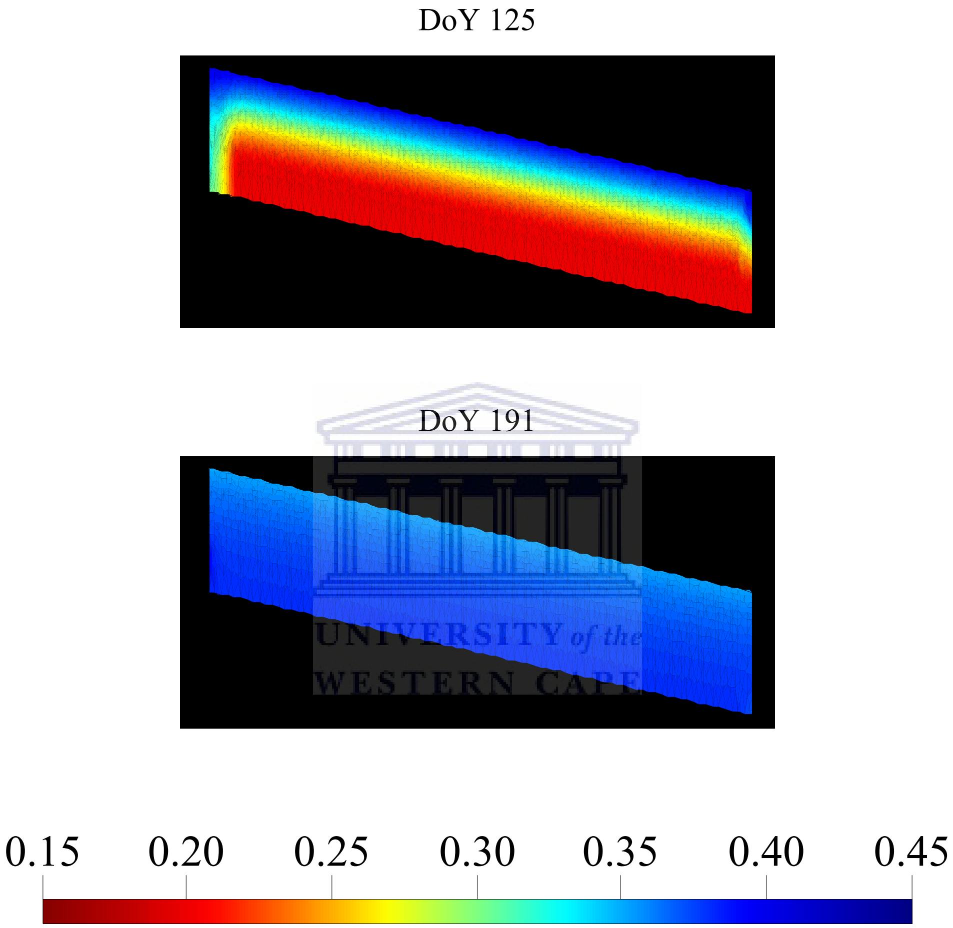


Figure 33. Simulation of volumetric soil water content on the hill slope profile at site 2.

The comparison between measured and simulated volumetric soil water contents is shown in Table 14. Water contents were measured with Echo sensors, whilst the simulated values represent the average of the cross section at the given depth. The simulated and measured values were very closely related during the winter months. It should be noted that HYDRUS-2D assumes that the distribution of the root system is constant over time.

TABLE 14
VOLUMETRIC SOIL WATER CONTENTS MEASURED WITH ECHO SENSORS AND SIMULATED WITH HYDRUS-2D (AVERAGE VALUES OF CROSS-SECTIONS) DURING WINTER 2006

Soil depth			40 cm	
Site	**Date**	**Day of Year (DoY)**	**Measured**	**Simulated**
1	22/06/2006	172	0.38	0.37
	30/06/2006	180	0.37	0.39
	17/07/2006	197	0.38	0.39
	30/07/2006	210	0.37	0.39
	4/08/2006	215	0.38	0.39
	14/08/2006	225	0.37	0.39

Soil depth			50 cm	
Site	**Date**	**Day of Year (DoY)**	**Measured**	**Simulated**
2	22/06/2006	172	0.38	0.36
	30/06/2006	180	0.38	0.35
	17/07/2006	197	0.37	0.35
	30/07/2006	210	0.36	0.36
	4/08/2006	215	0.38	0.36
	14/08/2006	225	0.39	0.37

Concentrations of salts in the soils were then simulated. The results are shown in Figures 34, 35 and 36 (site 1) and Figures 37 and 38 (site 2). The results are shown in the form of snapshots in time of salt concentrations along the hill slope soil profiles as well as in graphs illustrating the results for the entire simulation period. The salt concentrations are in g m^{-3}. The simulations show that as winter progresses, more and more salts are flushed out of the profile. The salts which are contributed from the Malmesbury shale and via throughflow are replaced by the salts which are contributed from rainfall. The overall salt concentration of the profile thus decreases. It should be noted that only the profile at site 1 receives salts from the underlying geology. This was not simulated at site 2, as the free drainage bottom boundary condition was set. Both profiles (site 1 and 2) receive water and salts from the variable pressure boundary node. The graphs (Figures 35 and 38) also show how the salt concentrations in the profile vary with depth over time, where the observation nodes were set on the seepage vertical boundary, and N1 represents a depth of 1 m, N2 a depth of 75 cm, N3 a depth of 50 cm and N4 a depth of 25 cm. The deeper layers remain more saline for longer as infiltrating rainfall and throughflow will first mobilize salts stored in the shallow soil layers. Figure 36 shows the total amount of salts that were flushed out of the soil profile at site 1 from the seepage face boundary. For the simulation period a total of 695,56 g m^{-1} was calculated. The salts only started flushing out of the profile toward DoY 190, when the profile neared saturation. It should be noted that salts were also lost from this profile at the constant flux bottom boundary. The results of the simulation at site 2 show that no salts were flushed from the soil profile, at the seepage face boundary. Salts were lost from the profile at the free drainage bottom boundary. From this, one can deduce that the presence of restricting layers, as is the case at site 1, influences the movement of water and salts.

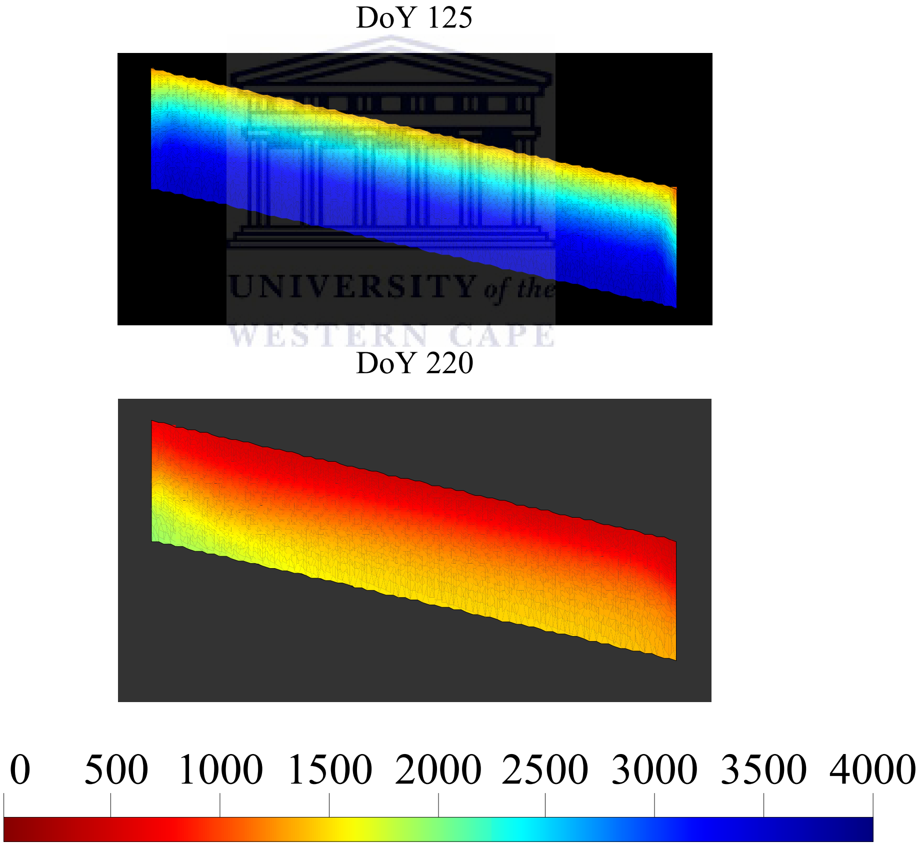


Figure 34. Simulated concentrations of salts (g m^{-3}) on the hillslope profile at site 1.

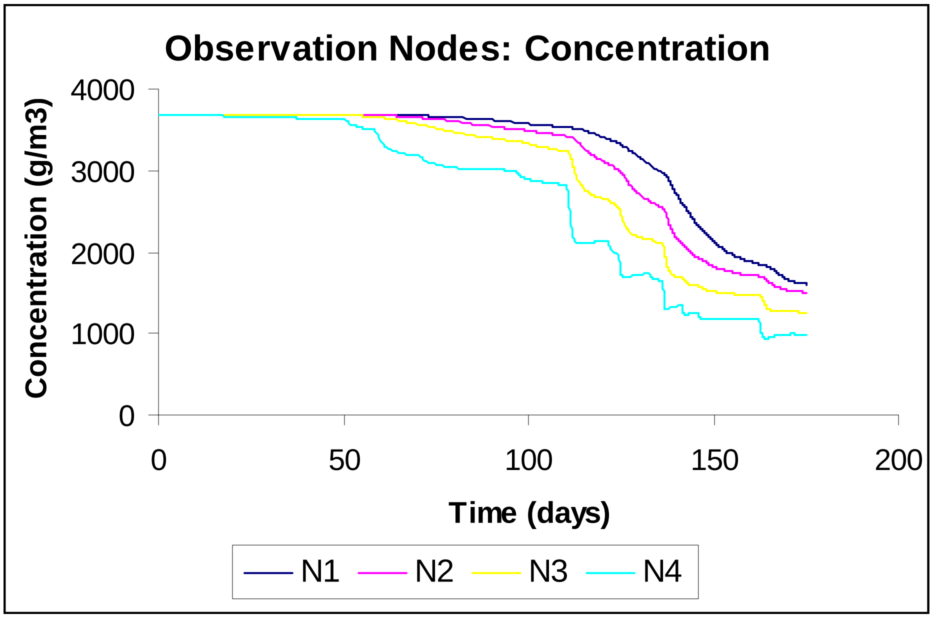


Figure 35. Simulated concentrations of salts in the soil profile at site 1 at varying depths.

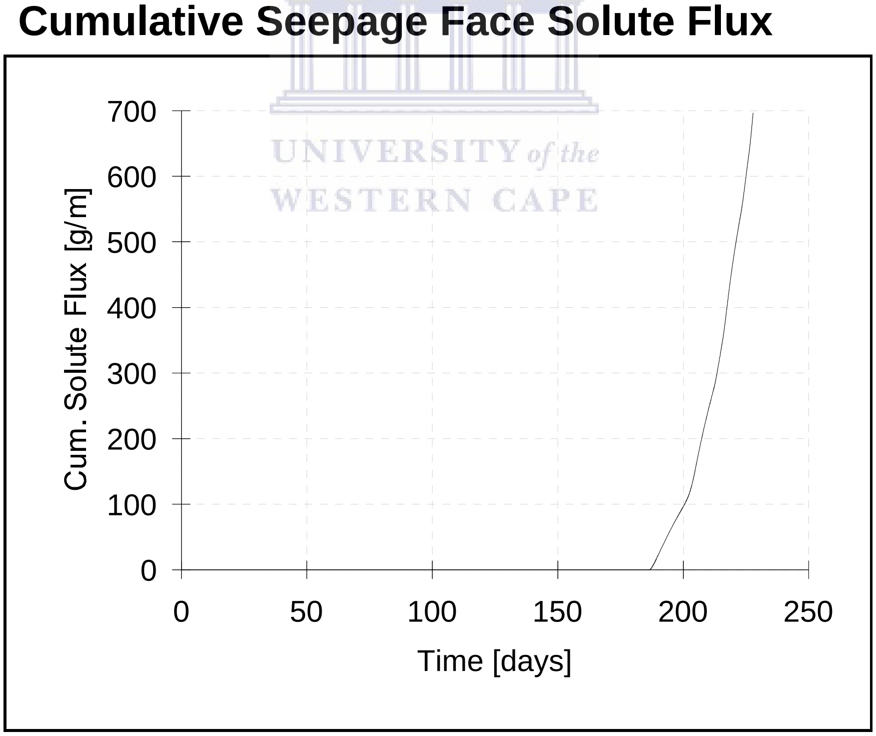


Figure 36. Simulation results representing the amounts of salts flushed from the soil profile (through subsurface flow and the seepage face) at site 1.

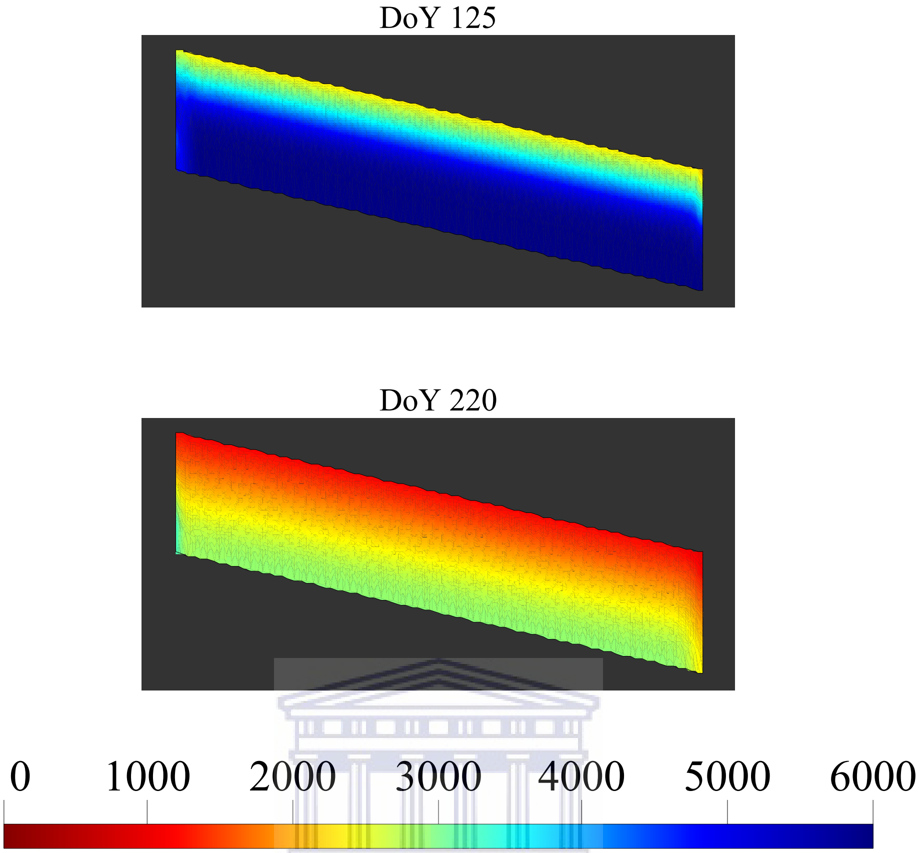


Figure 37. Simulated concentrations of salts (g m^{-3}) on the hill slope profile at site 2.

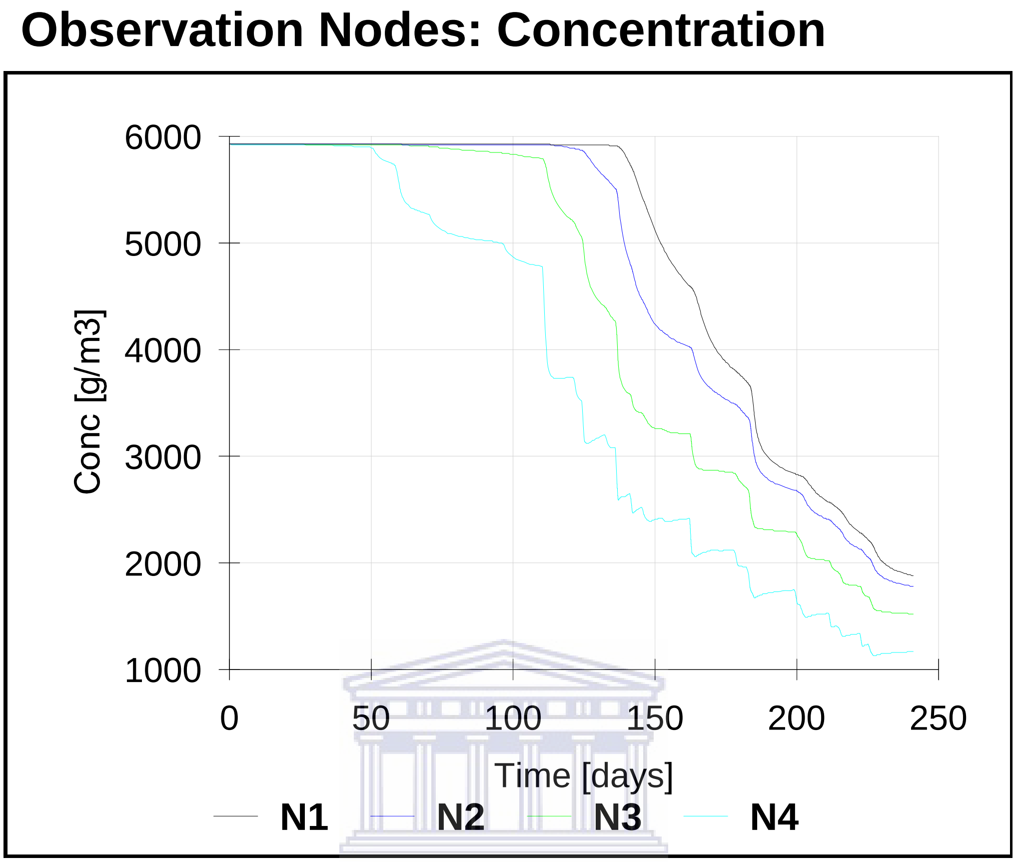


Figure 38. Simulated concentrations of salts in the soil profile at site 2 at varying depths.

Table 15, shows the comparison between salt concentrations that were measured in 2006 (1:5 soil to water ratio), and salts simulated with HYDRUS-2D. The diluting effect of the 1:5 ratio method was taken into account. Measured and simulated values were in the same order of magnitude and they followed the same trends in some instances. The observed discrepancies may have been due to spatial variability of the measurements, and the assumptions made in the model on the constant sources of salts originating from rainfall, throughflow and underlying geology. From the results of the simulations one can deduce that salts are mainly flushed into water bodies during winter, when the area receives most of its rainfall, i.e. from DOY 150 to DOY 250. In summer, the profile is then concentrated with salts as evaporation is the dominant salt mobilizing agent. It should be noted that observations and insight gained from the HYDRUS-2D simulations is restricted to the 22 m long soil profile.

TABLE 15
EC (dS m^{-1}) MEASURED USING THE 1:5 SOIL TO WATER RATIO AND SIMULATED USING HYDRUS-2D.

Site	Date	Day of Year (DoY)	Measured	Simulated
1	25/04/2006	114	8.18	6.57
	9/05/2006	128	3.36	6.04
	23/05/2006	142	0.77	4.77
	29/06/2006	179	1.24	2.98
	25/07/2006	205	3.34	2.85
Site	**Date**	**Day of Year (DoY)**	**Measured**	**Simulated**
2	25/04/2006	114	11.48	11.09
	9/05/2006	128	13.12	11.09
	23/05/2006	142	2.69	10.64
	29/06/2006	179	5.89	7.09
	25/07/2006	205	9.1	5.09

Chapter 5

5. CONCLUSIONS

The first winter season of the experiment (2005) was used to install and test equipment. It was not therefore possible to fully quantify the seasonal water and salt fluxes using the data collected in this period. Additional equipment was installed and additional measurements were taken during 2006 for this purpose. The data collected in 2006 therefore provided a good idea of the volumes of water and amounts of salts mobilized from the runoff plots established on different soil types, under different land uses and slopes. The data collected in 2005 and 2006 allowed us to draw some important conclusions:

- Different land uses caused different volumes of runoff and different amounts of salt mobilization. Uncultivated (bare) soil and less densely planted soil produced more runoff when compared to densely planted plots, under the same conditions. Consequently larger volumes of salt were mobilized from the plots that produce more runoff.
- Different soil properties, slopes, rainfall intensity and duration as well as antecedent moisture conditions caused different volumes of runoff. From the comparison of measured data and predictions with commonly used runoff models, it transpired that further investigation needs to be undertaken in order to develop a predictive runoff model for the specific site. This would aid in the efficient use of water resources as well as in the understanding of non-point source pollution problems, like for example transport of sediments, nutrients and pesticides.
- A time lag occurred between a rain event and increase of water level in the contour, depending on antecedent moisture conditions and rainfall intensity, especially at the beginning of the rain event.
- A time lag occurred between the start of a rain event and runoff from the plot, depending on antecedent moisture conditions, rainfall intensity and duration.
- Fluctuations in salinity due to local processes are less pronounced at a catchment scale. The largest fluctuations in salinity were recorded in runoff water, followed by

water collected in contours. The lowest fluctuations in salinity were observed in dam water due to the mixing of water and the longest residence times at this scale.

- Salinity and soil water content fluctuations are greatly influenced by seasonality. The salinity of water in the dam showed a dramatic increase during summer. This was a consequence of increased evaporation rates and thus a concentration of salts. Fluctuations in soil water content were more evident in the winter months, when the area receives the majority of its rainfall.
- The fluxes of salts during individual runoff events are constant, i.e. runoff water has a steady salinity throughout an event, mainly due to the nature of rainfall and source of salts. This contradicts the initial theory that there would be an initial peak in salinity and that the salinity would decrease as runoff progressed.
- The largest amounts of salts were mobilized overland from site 2; plot 1, where the largest amounts of overland flow were also recorded. An approximate total of 1559 g plot^{-1} were mobilized in 2005 and 2006.
- The chemical speciation of water and soil in the catchment is conservative, with Na^+ and Cl^- being the dominant ions.
- Overland flow depends on slope and slope orientation, type of soil, as well as land use. Between 9 and 61 mm of runoff were recorded during the period of measurement in 2006. At site 1 the total runoff amounted to 20 % (plot 1) and 8 % (plot 2) of the recorded rainfall. At site 2 this relationship ranged from 19 % (plot 1) to 9 % (plot 2). An accurate comparison of overland flow volumes could not be made between the two seasons as the logging system was not installed for the full 2005 season. However, it is evident that more overland flow occurred from site 2 when compared to the vegetated plot at site 1. This was a result of the larger slope at site 2 and also the soil at site 2 retaining moisture better than the soil at site 1.
- HYDRUS-2D was able to simulate water and salt fluxes along the hillslope profiles at site 1 and site 2, with acceptable accuracy as the simulations compared well with field observations.
- Salts are concentrated close to the soil surface during summer when evaporation is the dominant salt mobilizing agent. In winter, the salts associated with rainfall gradually replace the salts contributed to the profile via throughflow and from the

geology, thereby decreasing the overall salt concentration of the profile, as rainfall generally has a low salt concentration.

- HYDRUS-2D calculated that a total of approximately 700 g m^{-1} of salts were flushed out of the 22 m long and 0.5 m wide soil profile at site 1 through lateral subsurface flow. This was calculated at the seepage face boundary. At site 2, however, the simulation showed that no salts were flushed from this boundary, given the bottom boundary was set to be free-draining and limited lateral subsurface flux was predicted. The presence of restricting layers (site 1) thus influences the movement of water and solutes.

Chapter 6

6. Recommendations

The monitoring of hydrosalinity fluxes in the Goedertrou SSC has provided insight into the salinity patterns in the area. However, more seasons of monitoring are required to identify trends and typical characteristics of the study area. This will in turn allow for extrapolation of data to similar environments.

One of the main aims of the project commissioned by the WRC (Land use impacts on salinity of Western Cape waters) was to use the intensive data gathered at runoff plot and SSC scale during this project to allow for extrapolation to a quaternary catchment scale. The inclusion of additional monitoring, especially at the dam would allow for the better extrapolation to the quaternary catchment scale. This monitoring should include monitoring the fluctuations of the dam levels and the discharge of overflows from the dam. This would allow for the better of the fluctuations in the effect of hydrological events at different scales of observation.

The inclusion of different types of land cover in the experimental setup would also allow more informed decisions to be made in terms of management. A possible remediation measure would be to allow the re-establishment of Renosterveld, which is the indigenous vegetation of the area. Practices that combine Renoserveld with cultivated land, e.g. alternate strips, need to be investigated as management options to reduce the salinisation of cultivated land and water resources.

HYDRUS-2D has provided insight into the subsurface processes in the SSC. However, the extent of observation made during this project may essentially be limited to the 22 m long soil profiles. It is recommended that additional soil moisture and soil salinity measurements be undertaken at strategic positions so as to allow for the accurate simulation of subsurface fluxes in the SSC.

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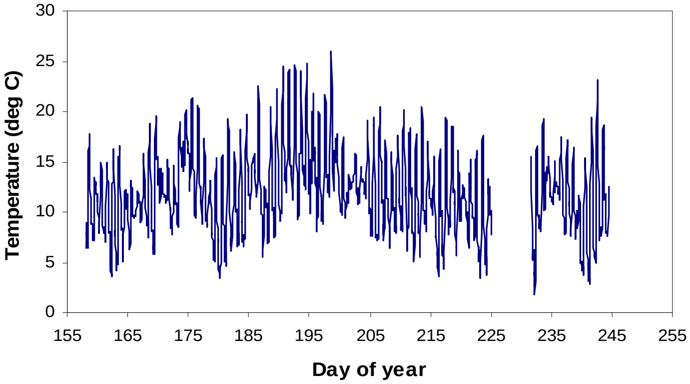
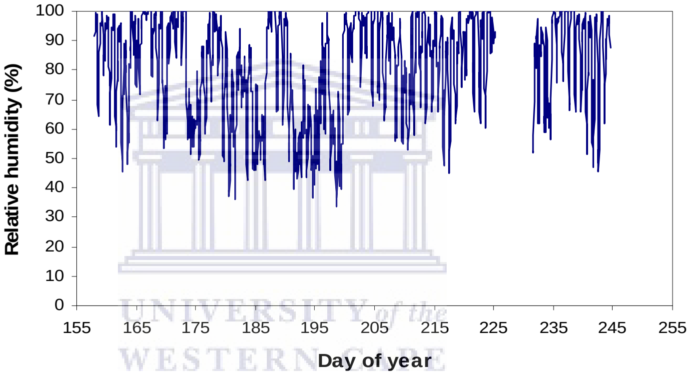
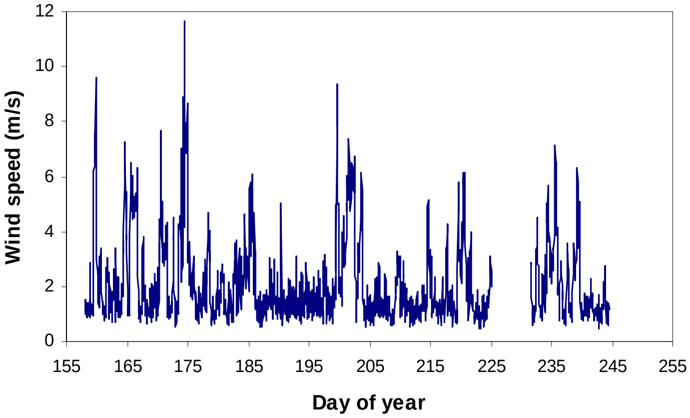
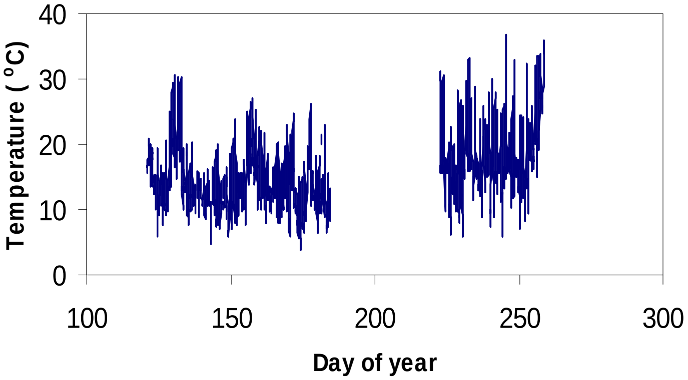
Appendix A. The 2005 winter season weather data

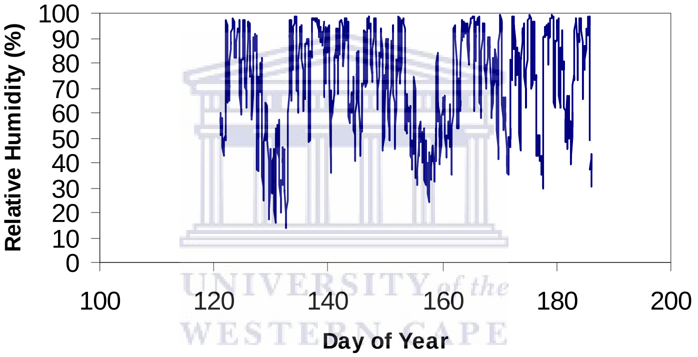


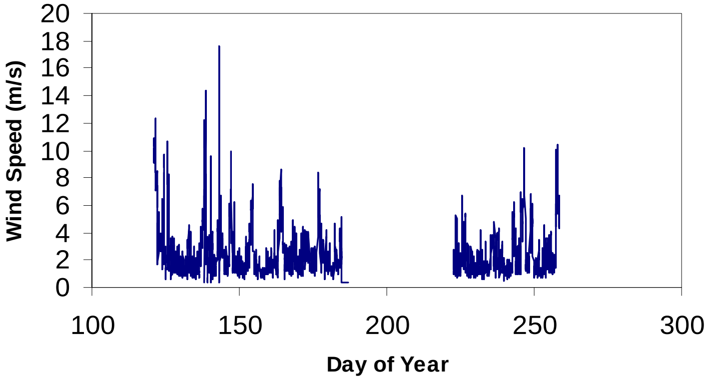




Appendix B. The 2006 winter season weather data.



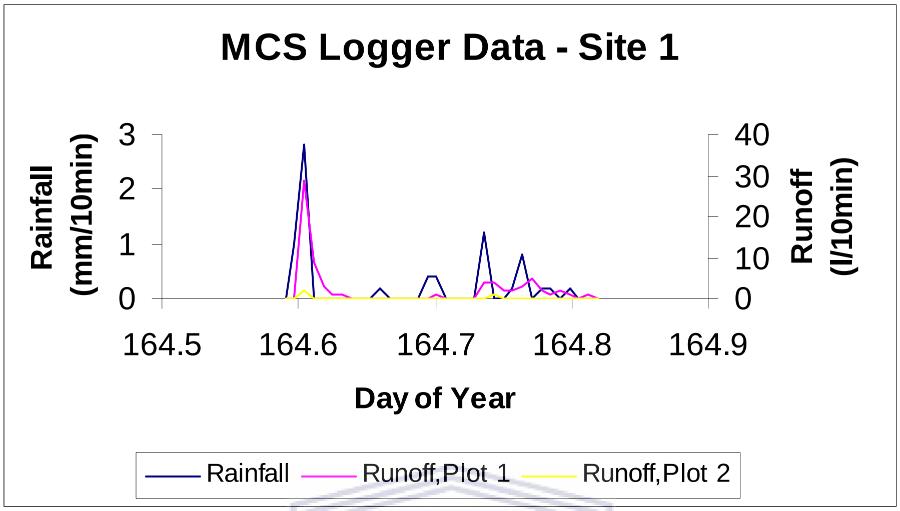


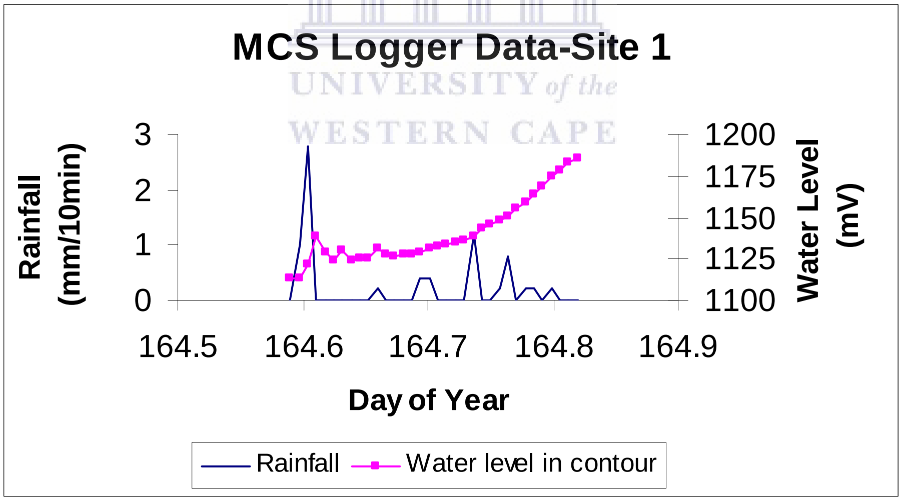


Appendix C. 2006 MCS Logger Data.

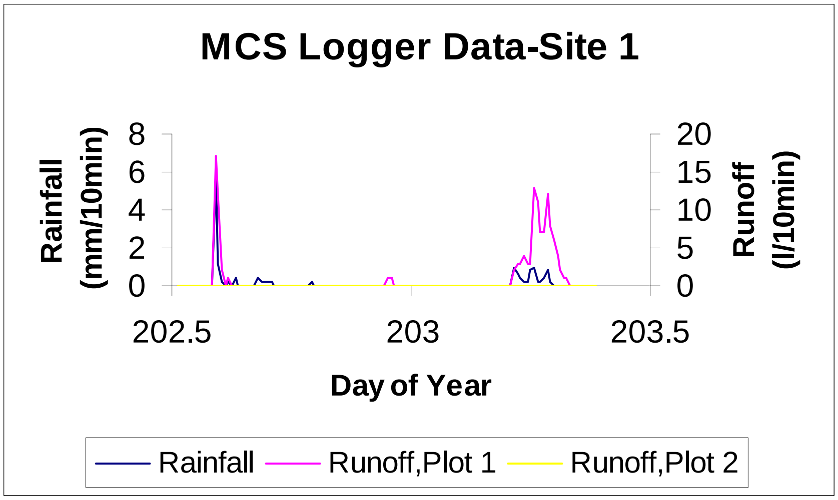
Site 1

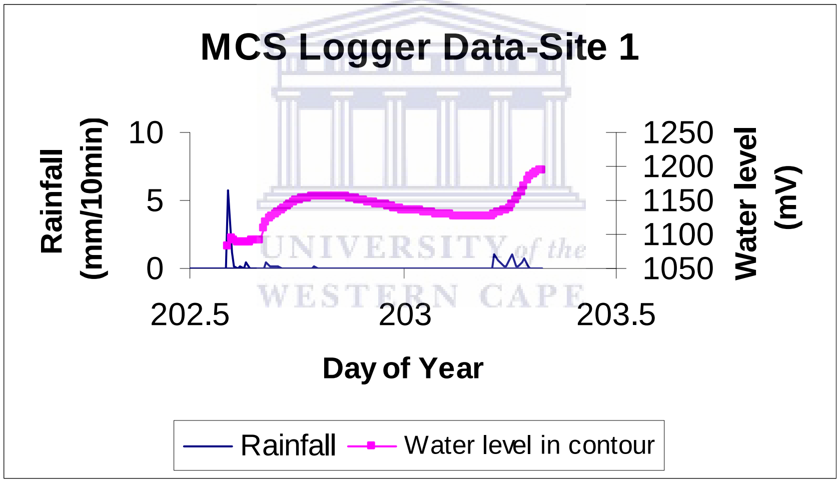
13 June 2006



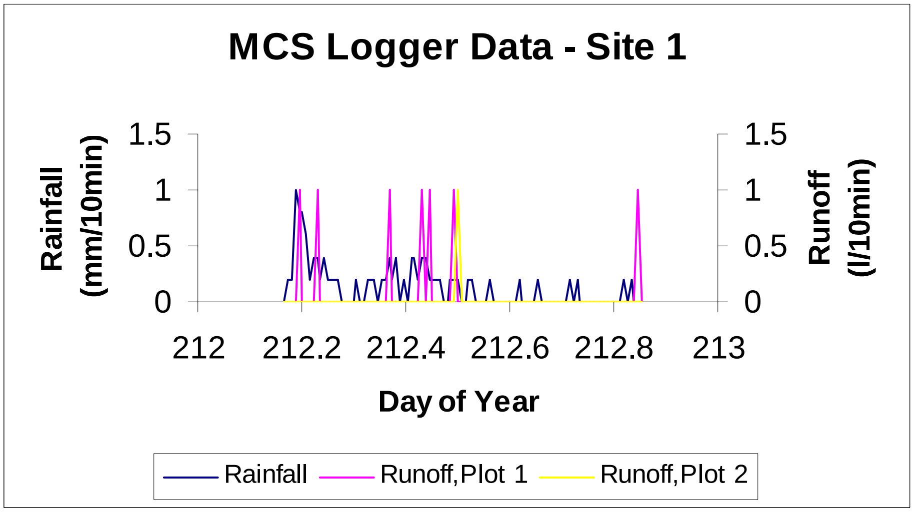


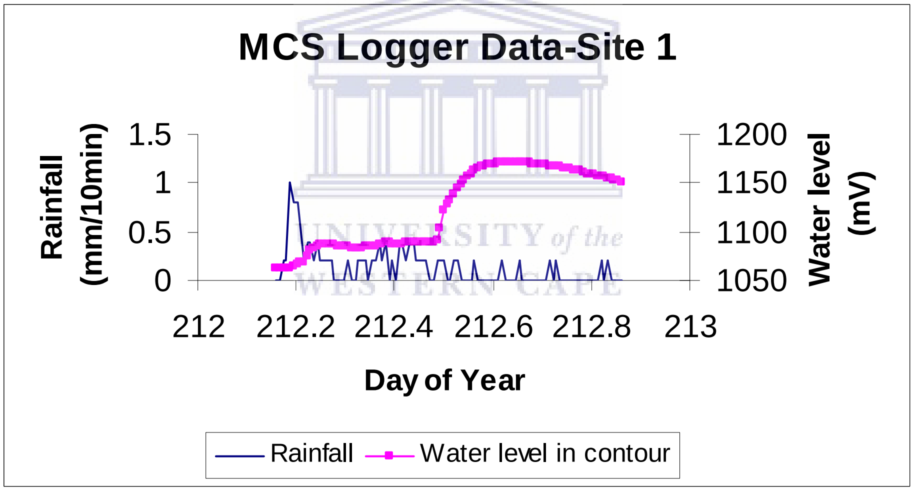
21 & 22 July 2006



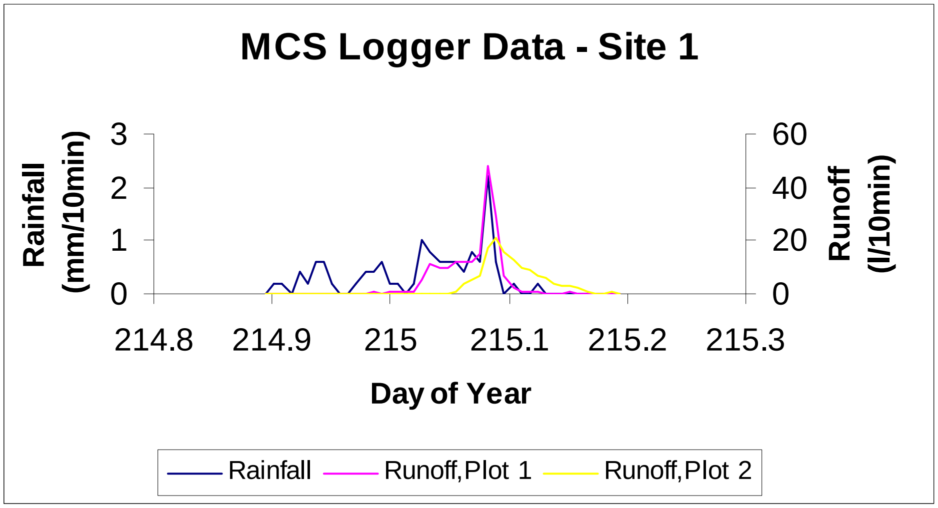


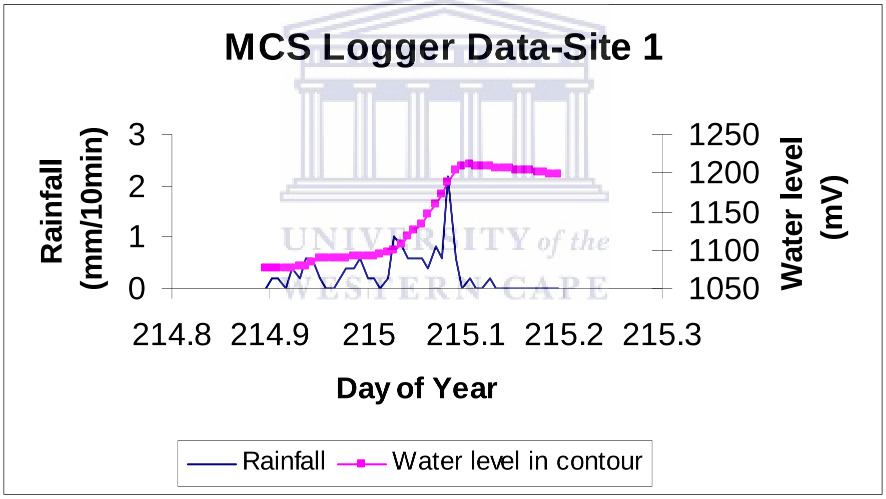
31 July 2006


MCS Logger Data - Site 1
Rainfall (mm/10min)
Runoff (l/10min)
1.5
1
0.5
0
212
212.2
212.4
212.6
212.8
213
Day of Year
Rainfall
Runoff,Plot 1
Runoff,Plot 2

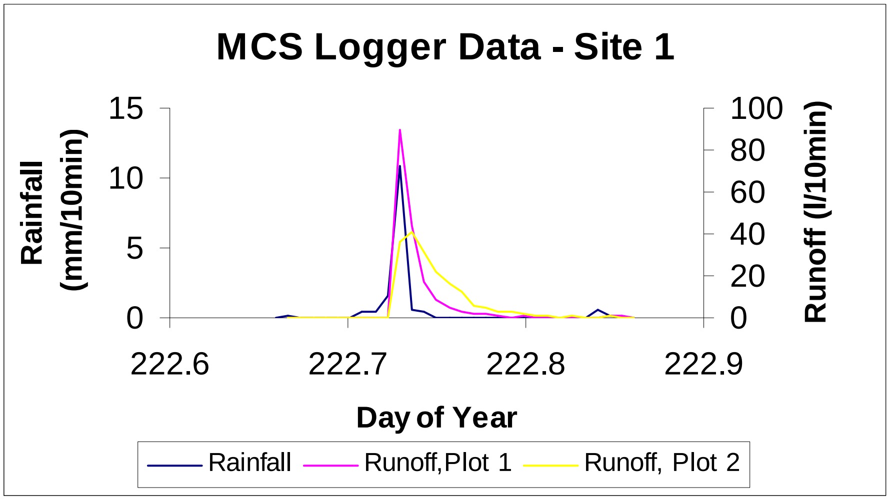

MCS Logger Data-Site 1
Rainfall (mm/10min)
Water level (mV)
1.5
1
0.5
0
1200
1150
1100
1050
212
212.2
212.4
212.6
212.8
213
Day of Year
Rainfall
Water level in contour

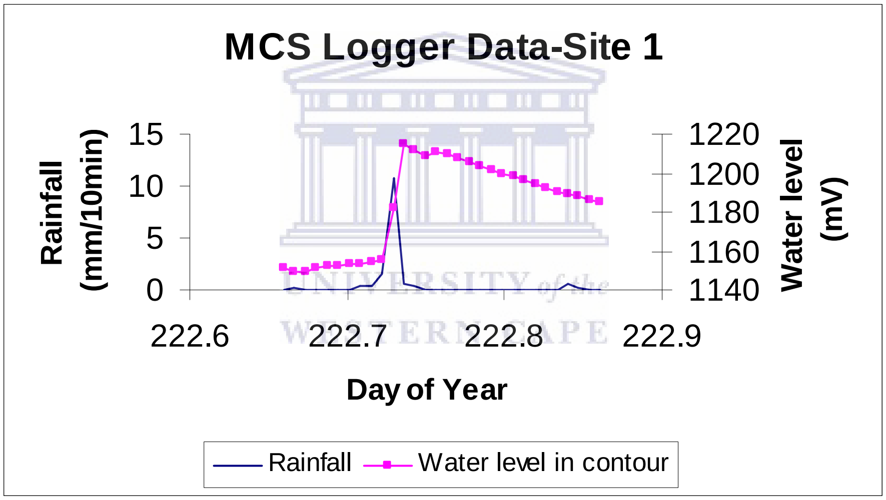
3 & 4 August 2006



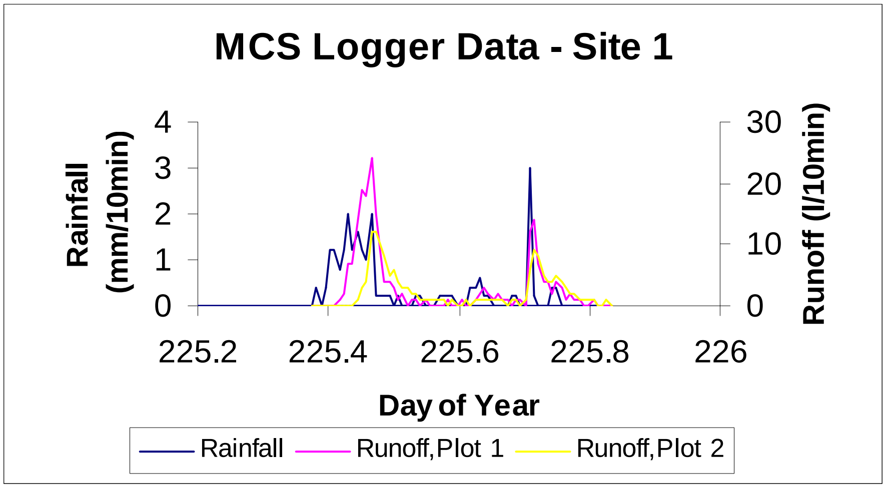


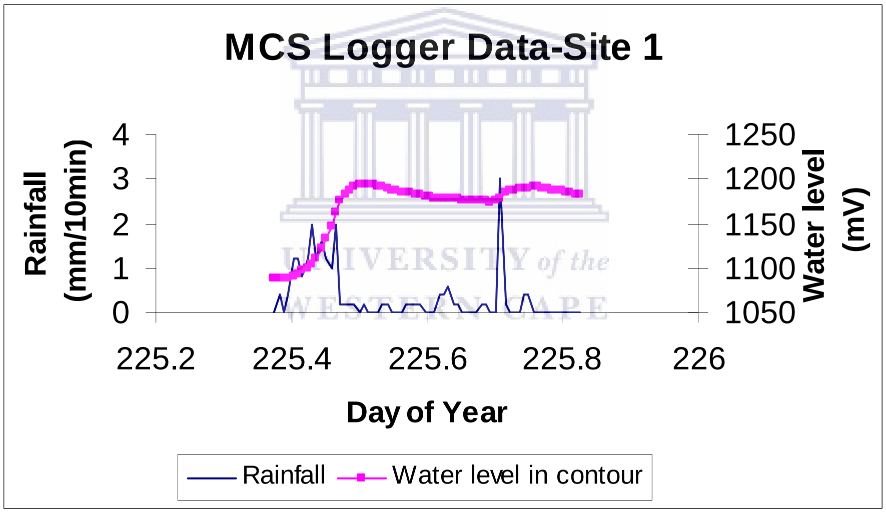
11 August 2006





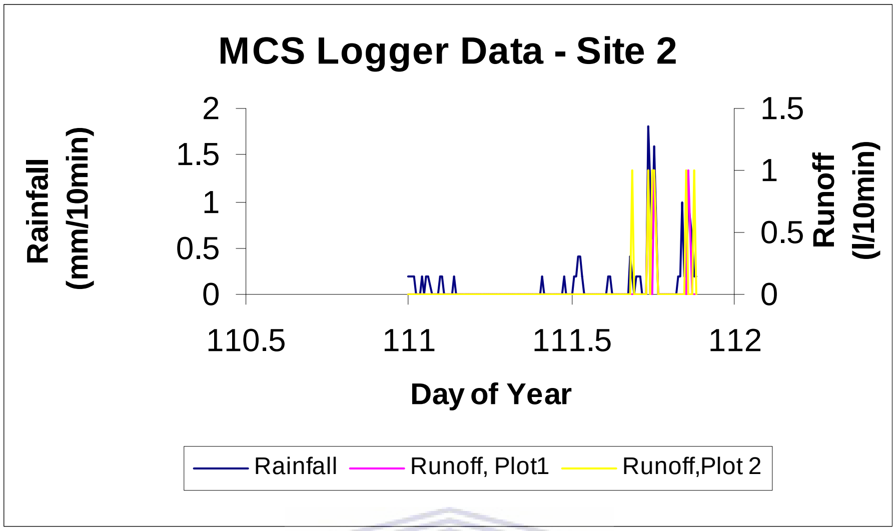
14 August 2006

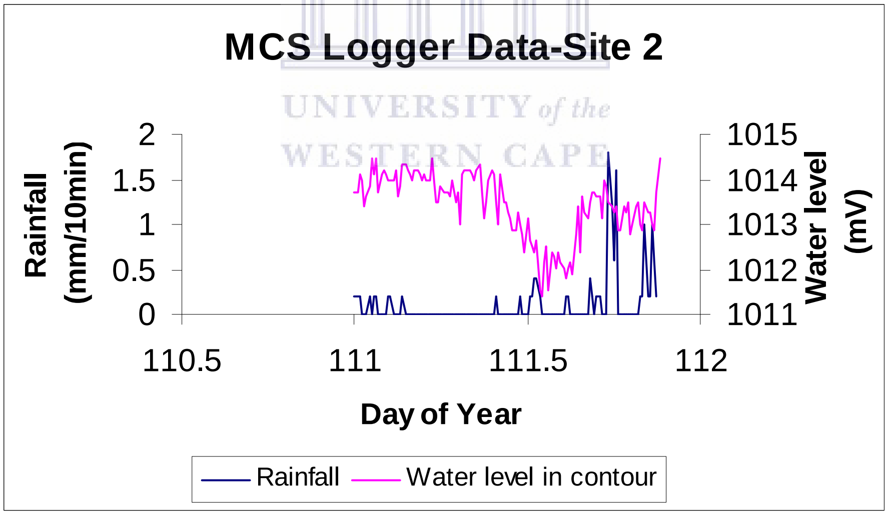




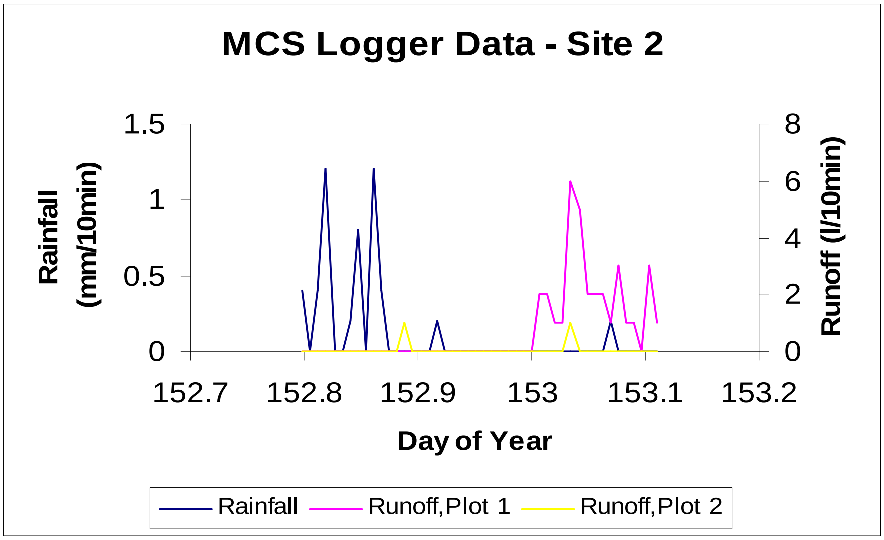
Site 2

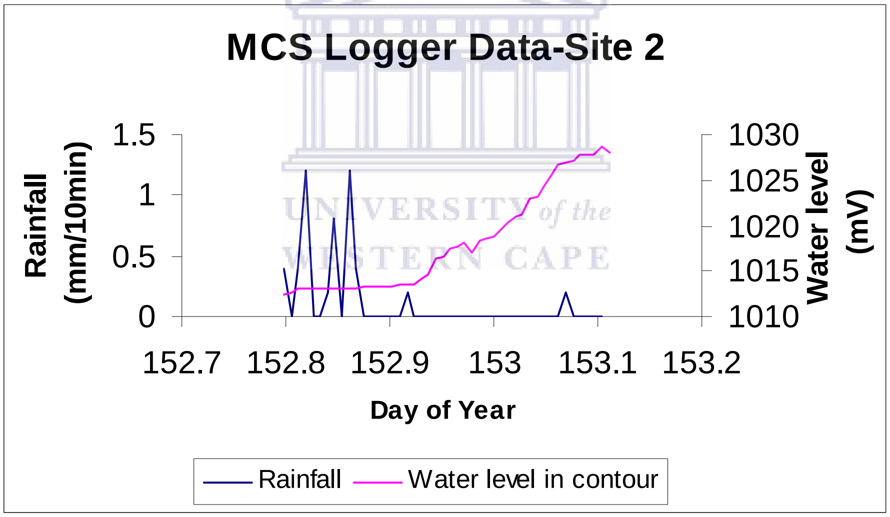
21 April 2006



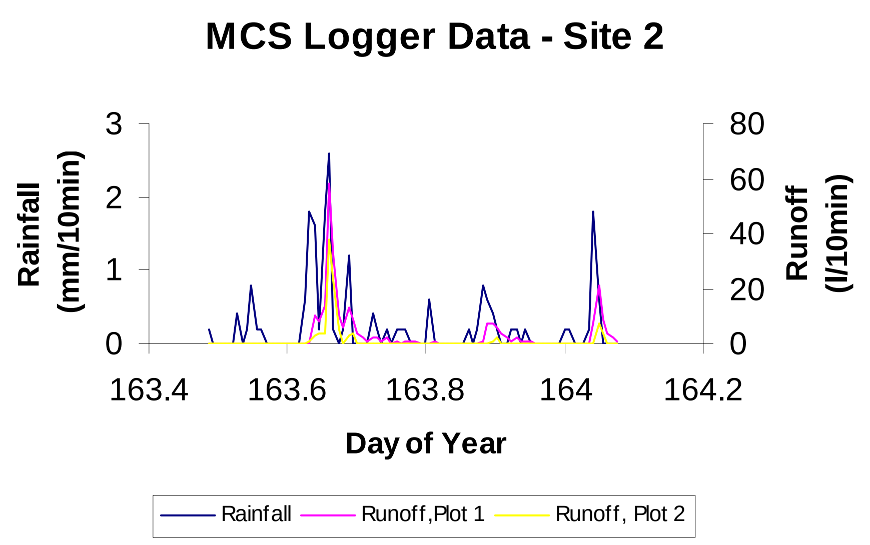


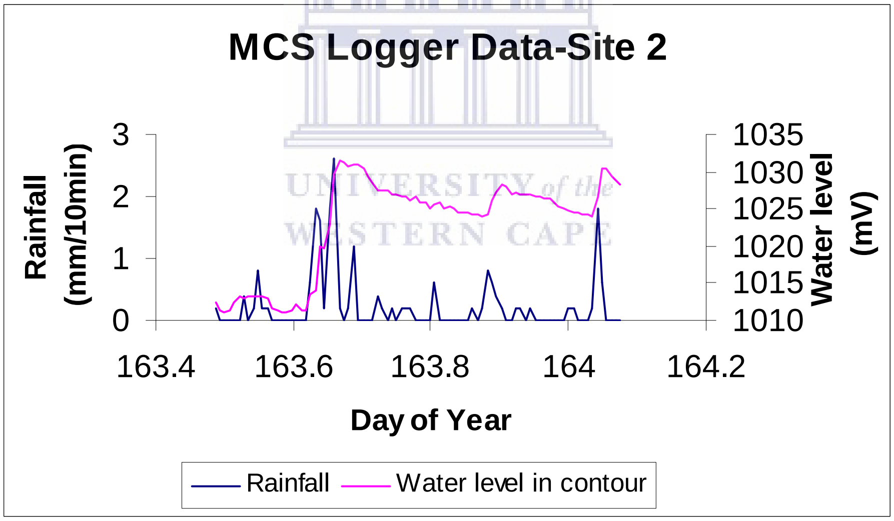
1 June 2006


MCS Logger Data - Site 2
Rainfall (mm/10min)
Runoff (l/10min)
1.5
1
0.5
0
8
6
4
2
0
152.7
152.8
152.9
153
153.1
153.2
Day of Year
Rainfall
Runoff,Plot 1
Runoff,Plot 2

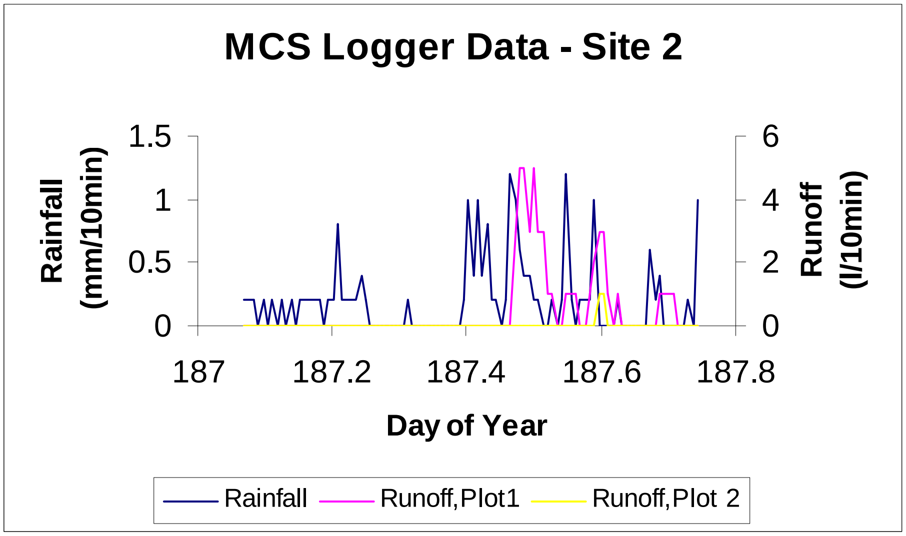

MCS Logger Data-Site 2
Rainfall (mm/10min)
Water level (mV)
1.5
1
0.5
0
1030
1025
1020
1015
1010
152.7
152.8
152.9
153
153.1
153.2
Day of Year
Rainfall
Water level in contour

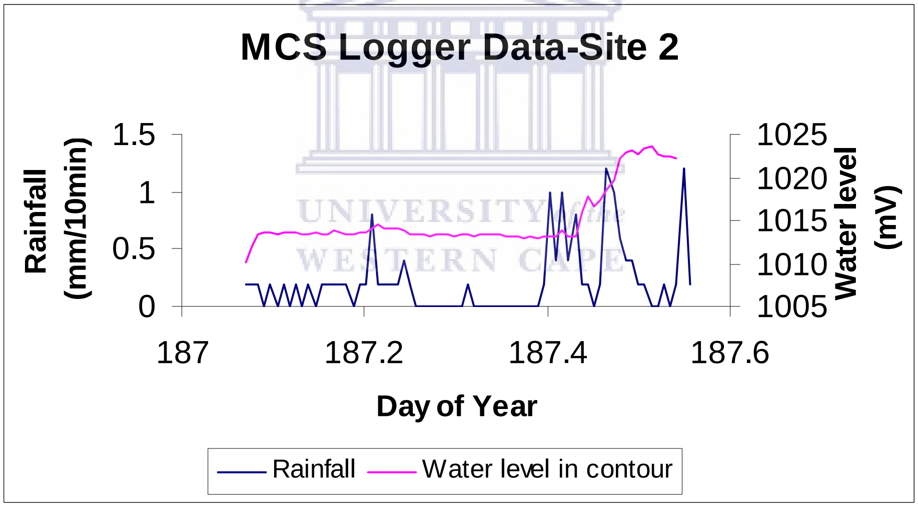
13 June 2006


MCS Logger Data - Site 2
Rainfall (mm/10min)
3
2
1
0
Runoff (l/10min)
80
60
40
20
0
163.4
163.6
163.8
164
164.2
Day of Year
Rainfall
Runoff,Plot 1
Runoff, Plot 2

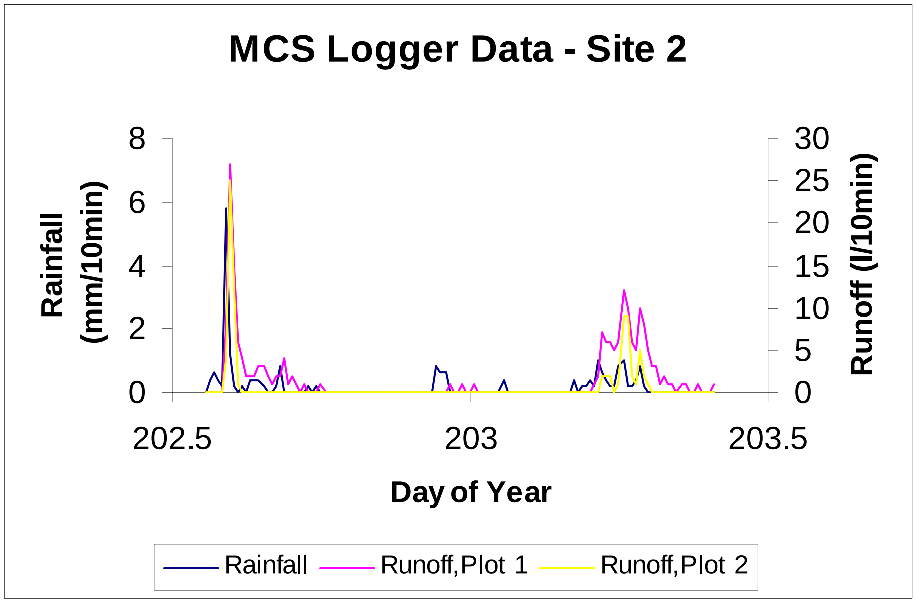

MCS Logger Data-Site 2
Rainfall (mm/10min)
3
2
1
0
Water level (mV)
1035
1030
1025
1020
1015
1010
163.4
163.6
163.8
164
164.2
Day of Year
Rainfall
Water level in contour

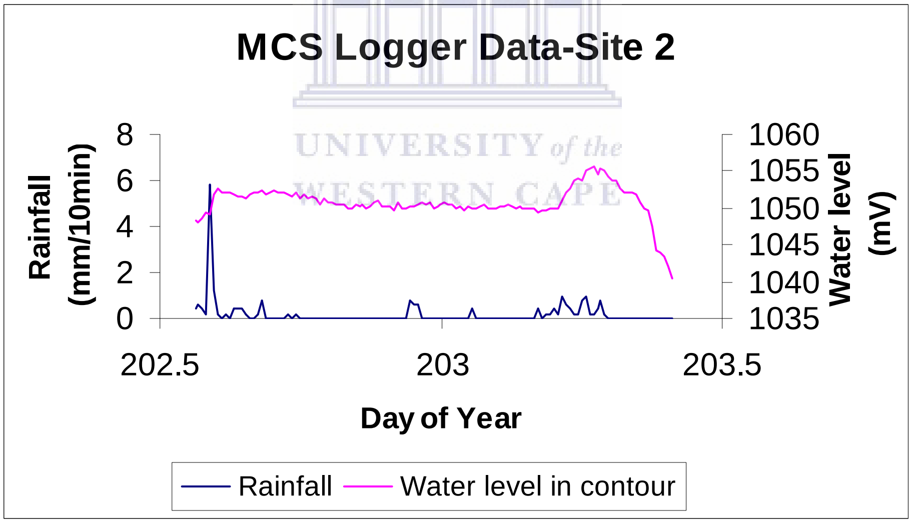
6 July 2006


MCS Logger Data - Site 2
Rainfall (mm/10min)
1.5
1
0.5
0
Runoff (l/10min)
6
4
2
0
187
187.2
187.4
187.6
187.8
Day of Year
Rainfall
Runoff,Plot1
Runoff,Plot 2

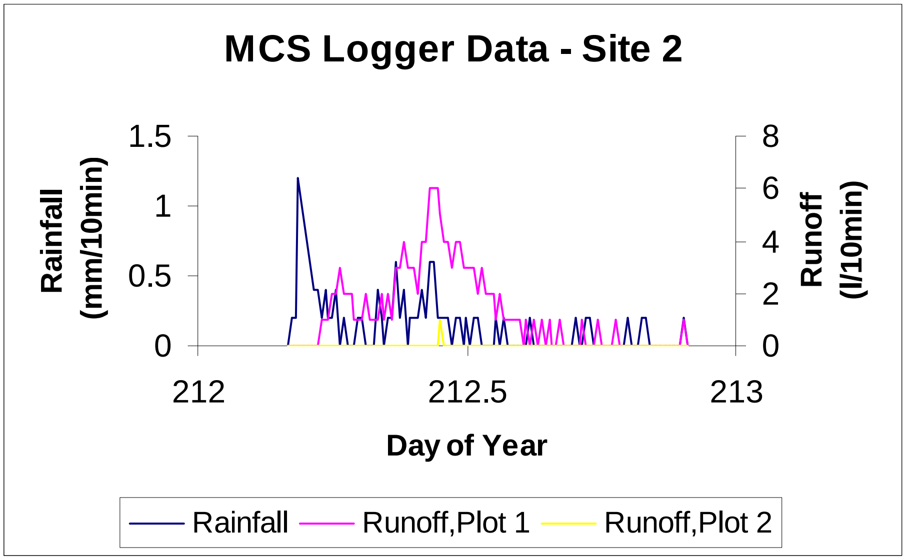

MCS Logger Data-Site 2
Rainfall (mm/10min)
1.5
1
0.5
0
Water level (mV)
1025
1020
1015
1010
1005
187
187.2
187.4
187.6
Day of Year
Rainfall
Water level in contour

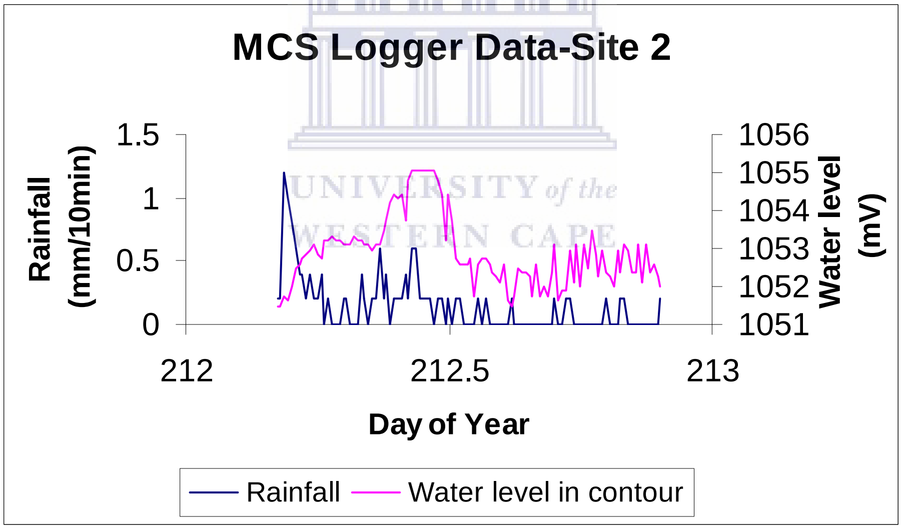
21 & 22 July 2006



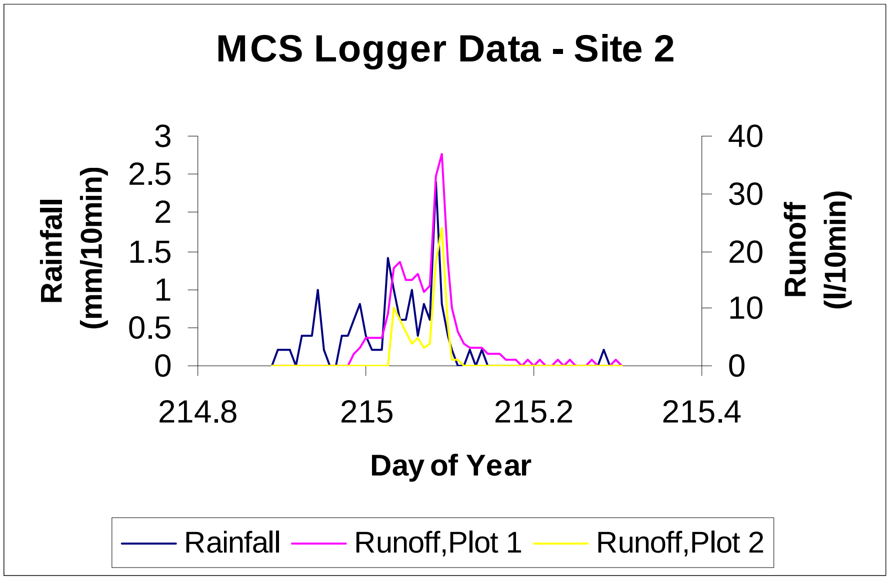


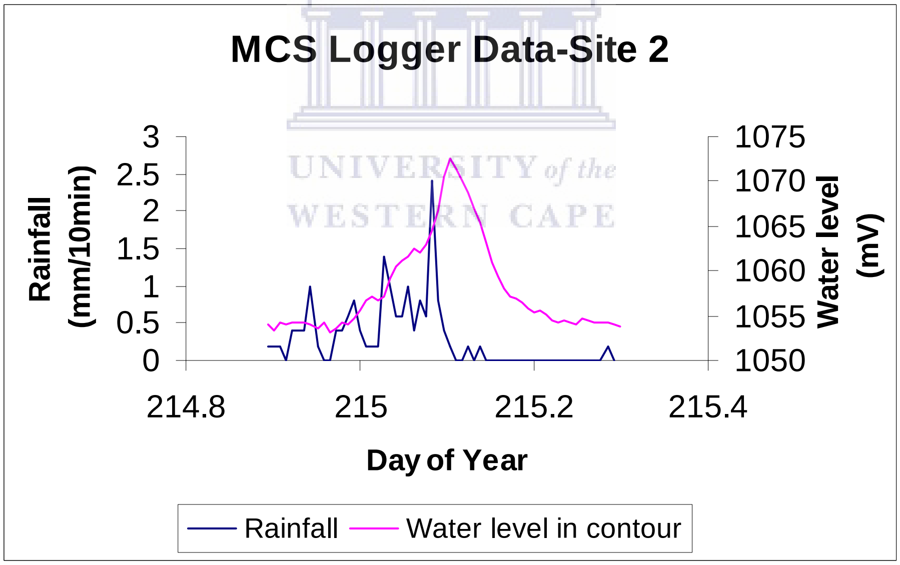
31 July 2006


MCS Logger Data - Site 2
Rainfall (mm/10min)
1.5
1
0.5
0
Runoff (l/10min)
8
6
4
2
0
212
212.5
213
Day of Year
Rainfall
Runoff,Plot 1
Runoff,Plot 2

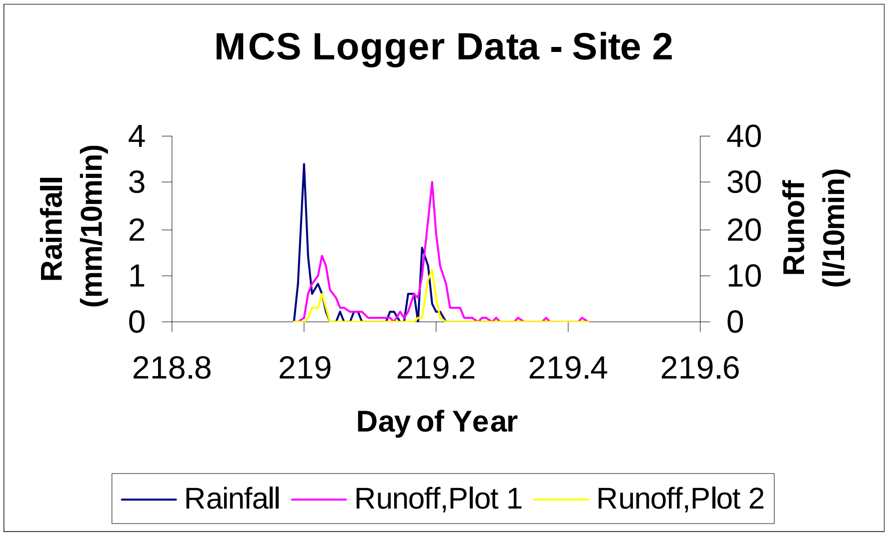

MCS Logger Data-Site 2
Rainfall (mm/10min)
1.5
1
0.5
0
Water level (mV)
1056
1055
1054
1053
1052
1051
212
212.5
213
Day of Year
Rainfall
Water level in contour

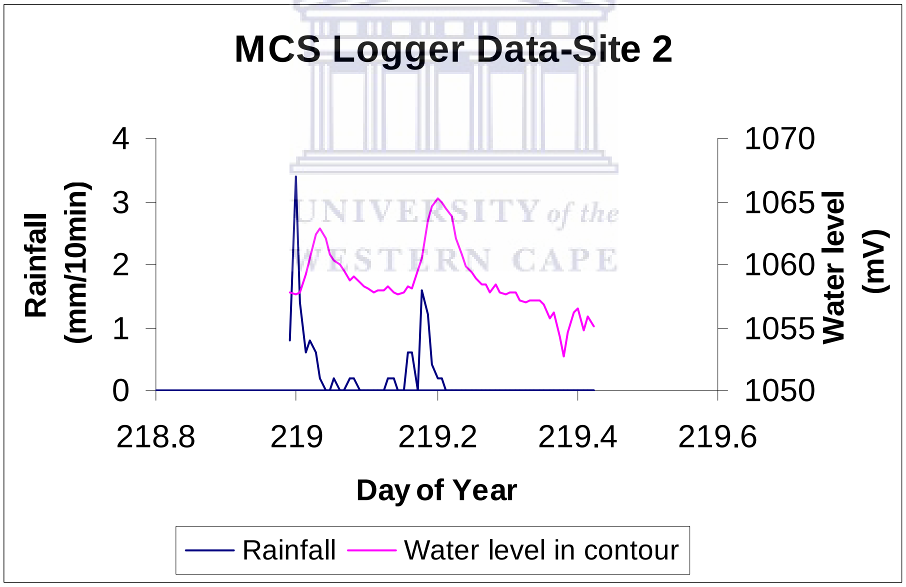
3 August 2006



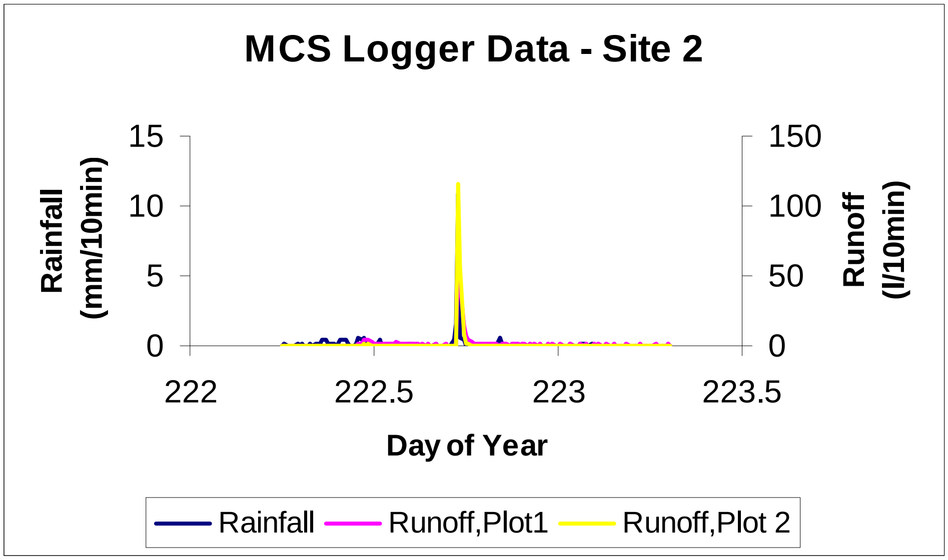


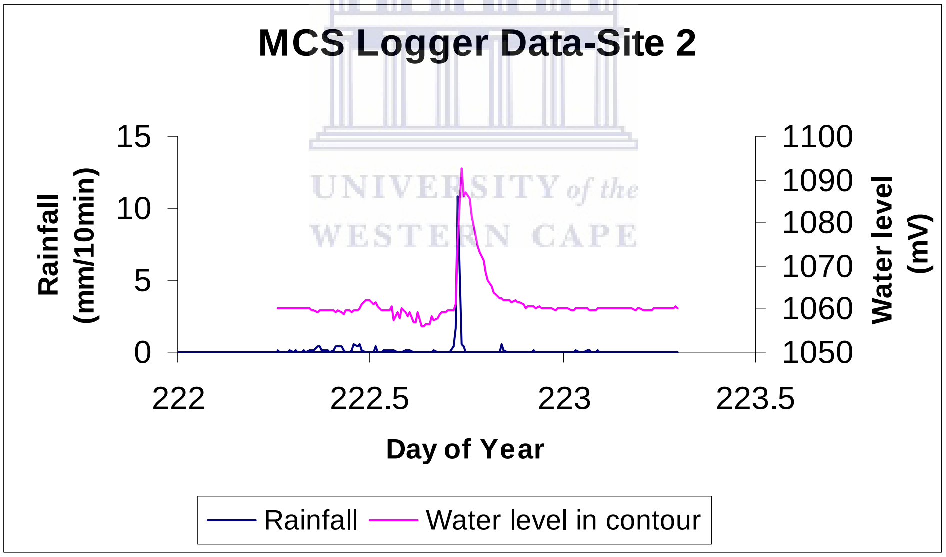
8 August 2006



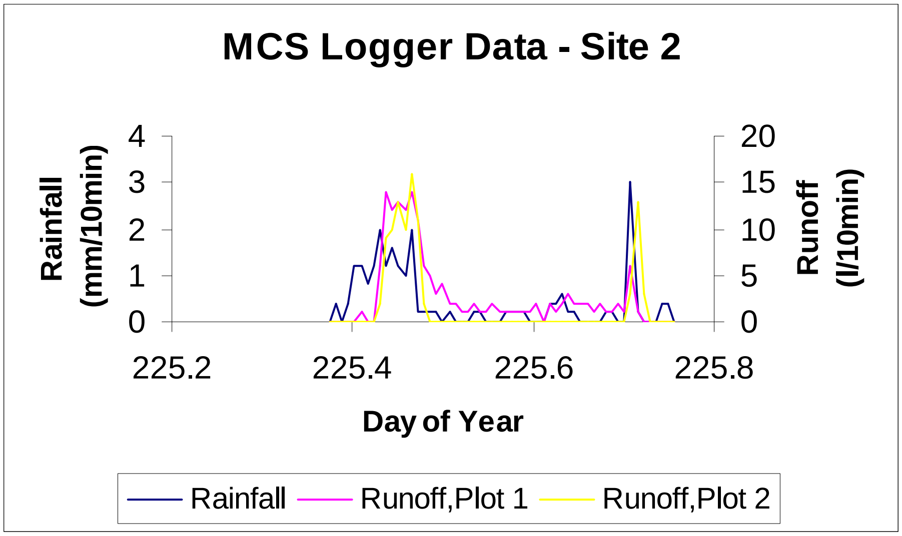


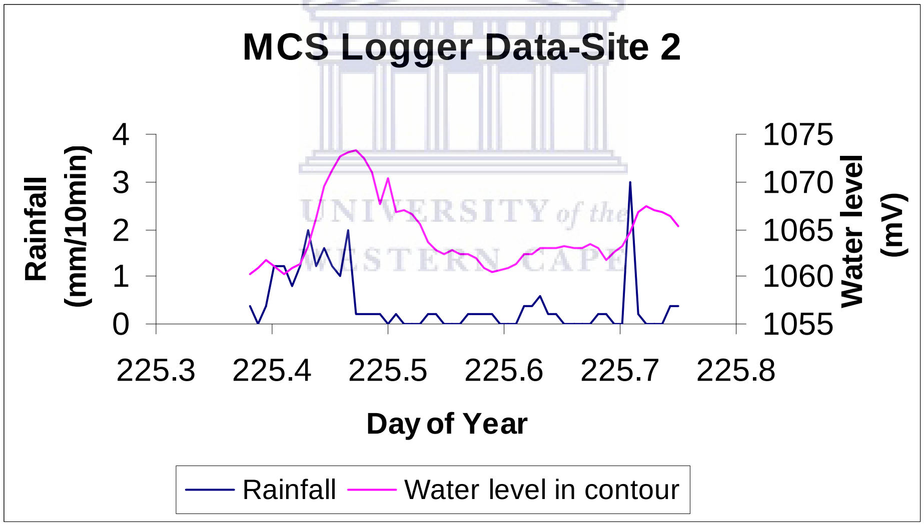
11 & 12 August 2006





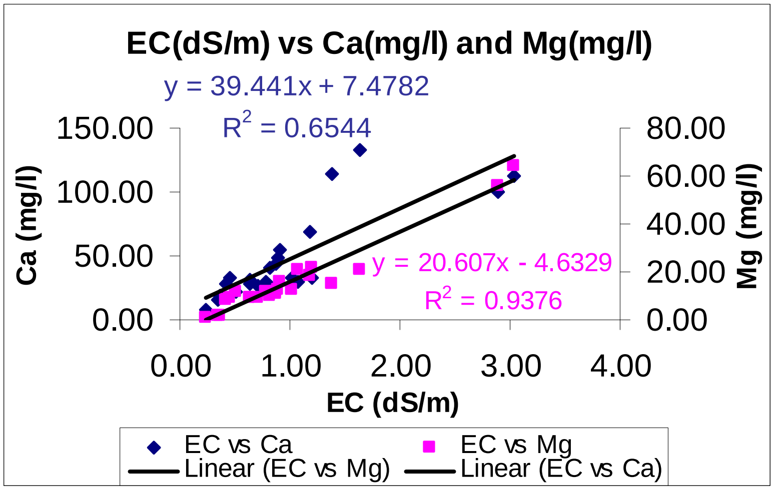
14 August 2006

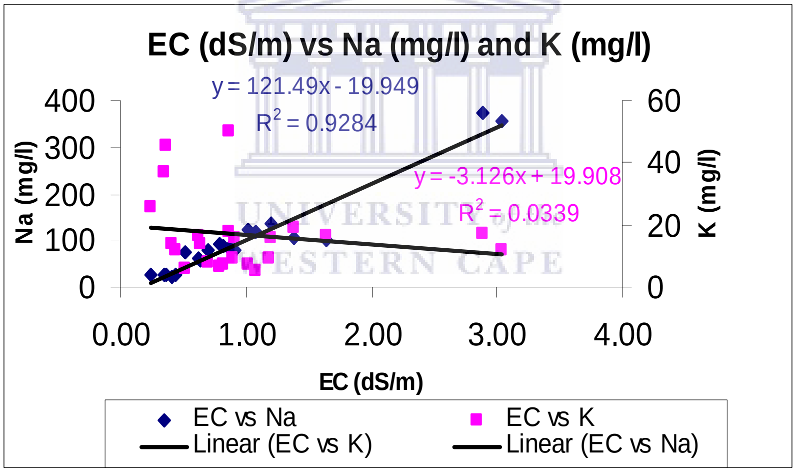


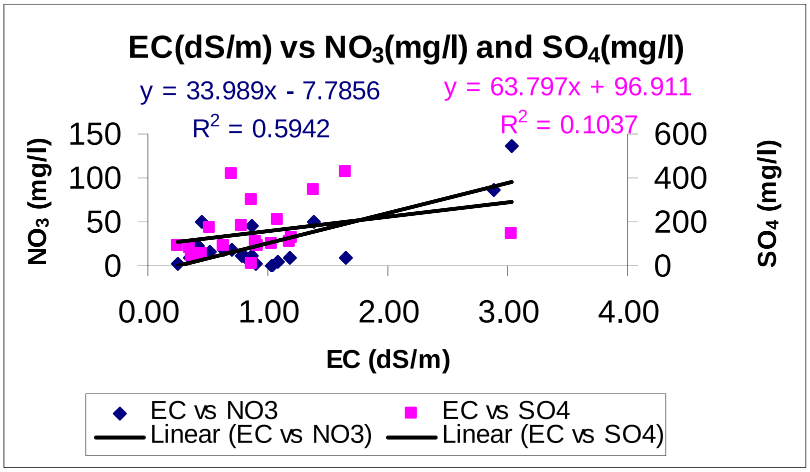


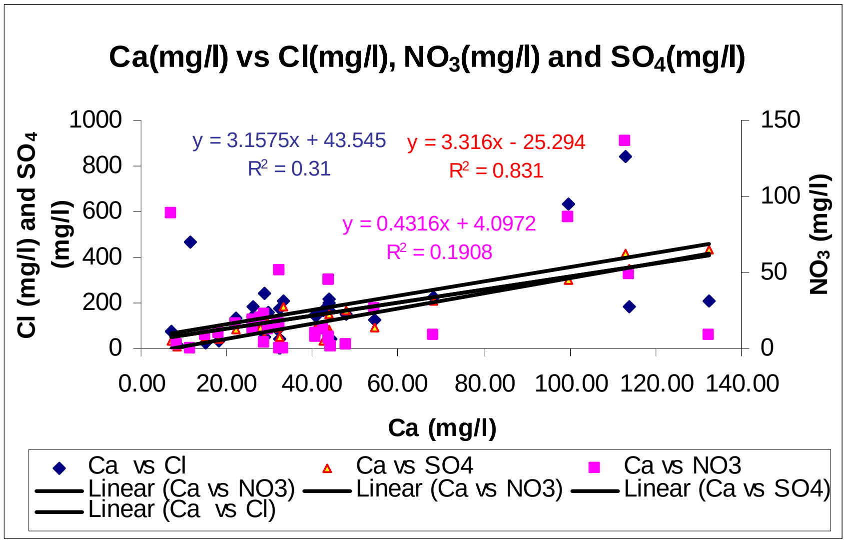
Appendix D. Soil and water chemical speciation.

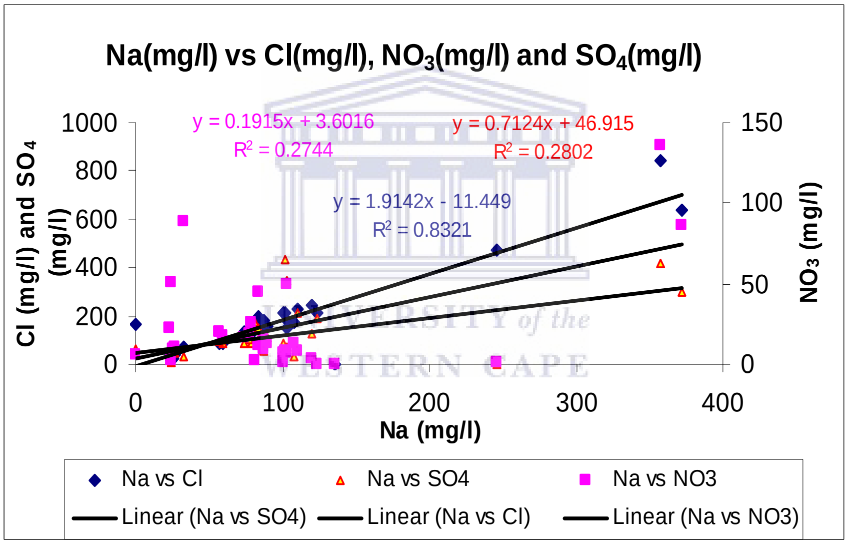
Runoff water sample analysis



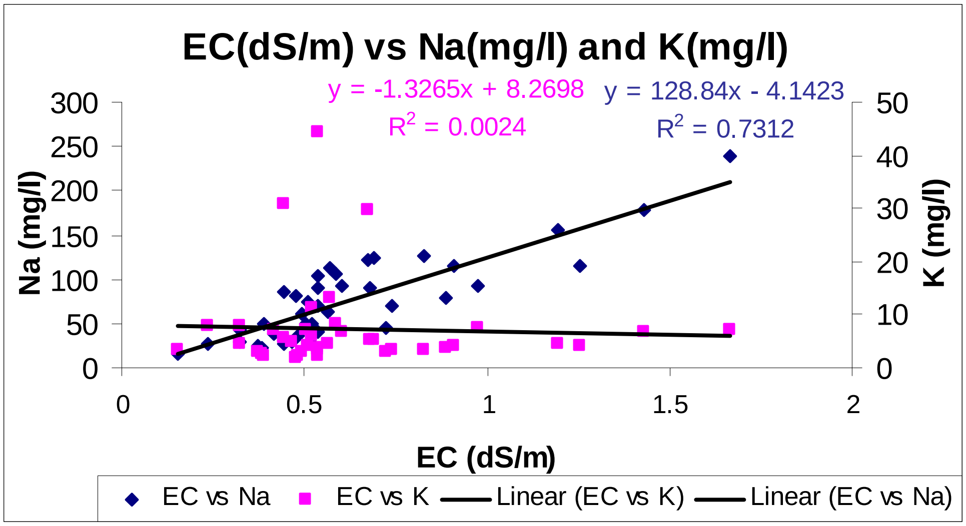


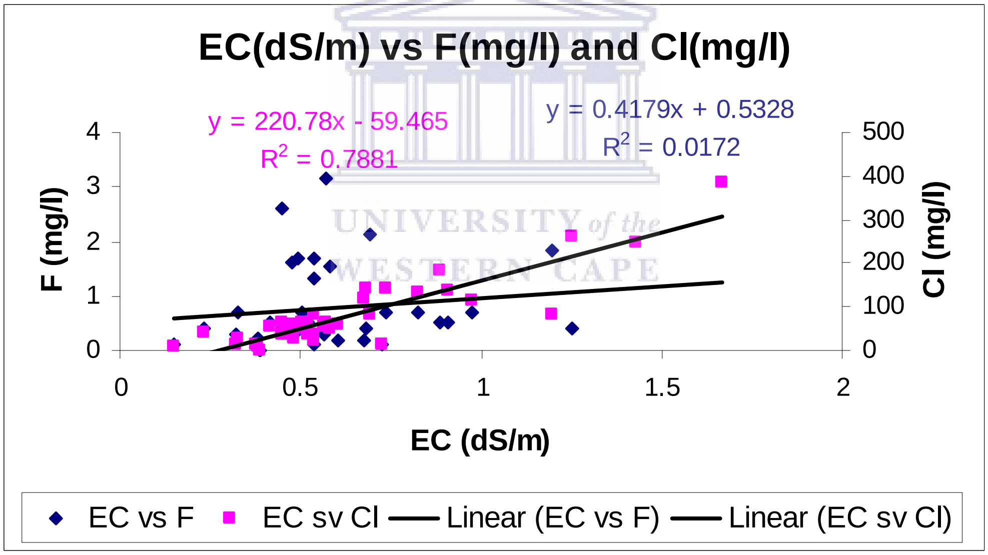



Ca(mg/l) vs Cl(mg/l), NO3(mg/l) and SO4(mg/l)
y = 3.1575x + 43.545
R² = 0.31
y = 3.316x - 25.294
R² = 0.831
y = 0.4316x + 4.0972
R² = 0.1908
Cl (mg/l) and SO4 (mg/l)
NO3 (mg/l)
1000
800
600
400
200
0
150
100
50
0
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
Ca (mg/l)
Ca vs Cl
Ca vs SO4
Ca vs NO3
Linear (Ca vs NO3)
Linear (Ca vs NO3)
Linear (Ca vs SO4)
Linear (Ca vs Cl)

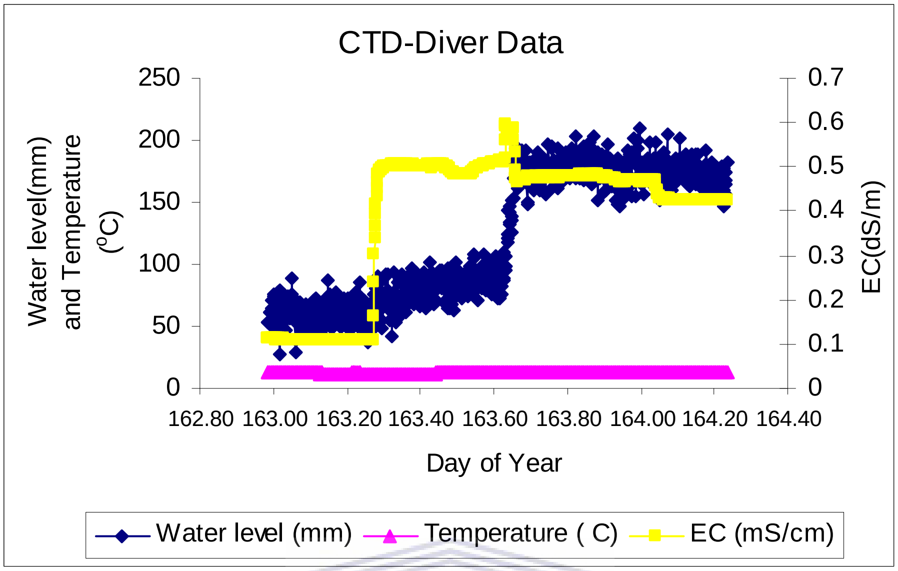

Na(mg/l) vs Cl(mg/l), NO3(mg/l) and SO4(mg/l)
y = 0.1915x + 3.6016
R² = 0.2744
y = 0.7124x + 46.915
R² = 0.2802
y = 1.9142x - 11.449
R² = 0.8321
Cl (mg/l) and SO4 (mg/l)
NO3 (mg/l)
1000
800
600
400
200
0
150
100
50
0
0
100
200
300
400
Na (mg/l)
Na vs Cl
Na vs SO4
Na vs NO3
Linear (Na vs SO4)
Linear (Na vs Cl)
Linear (Na vs NO3)

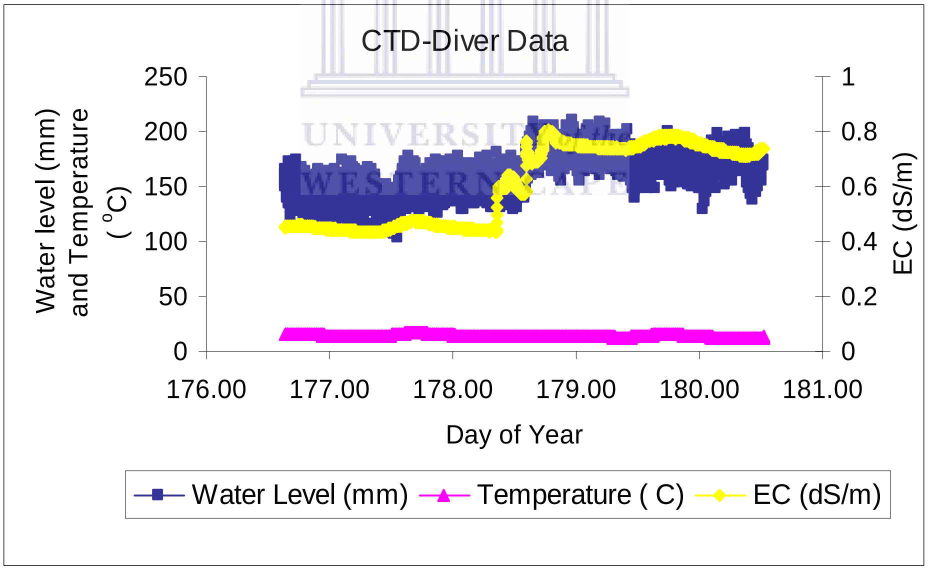
1:5 Soil/water ratio extracts analyses

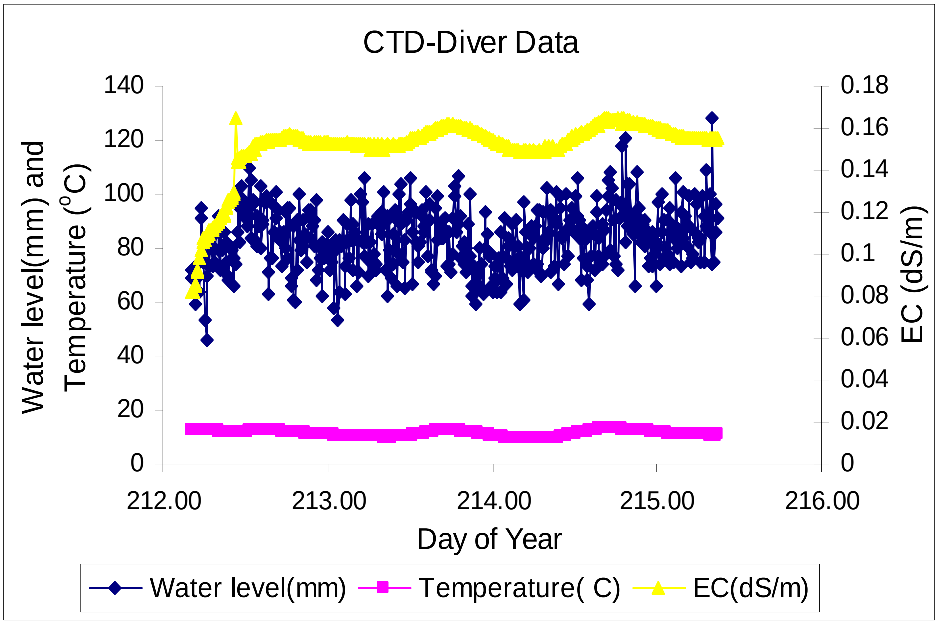


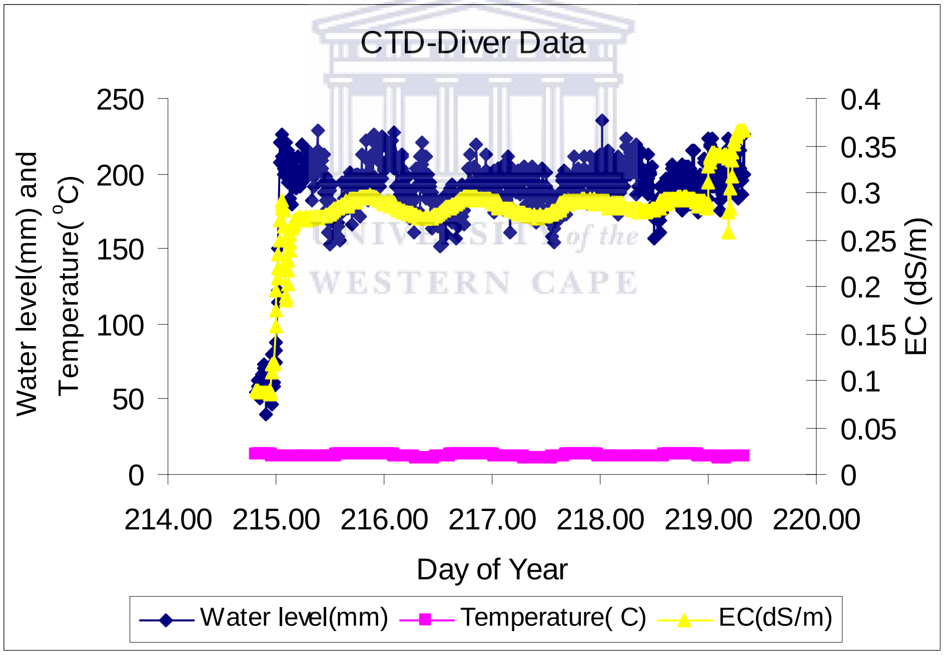


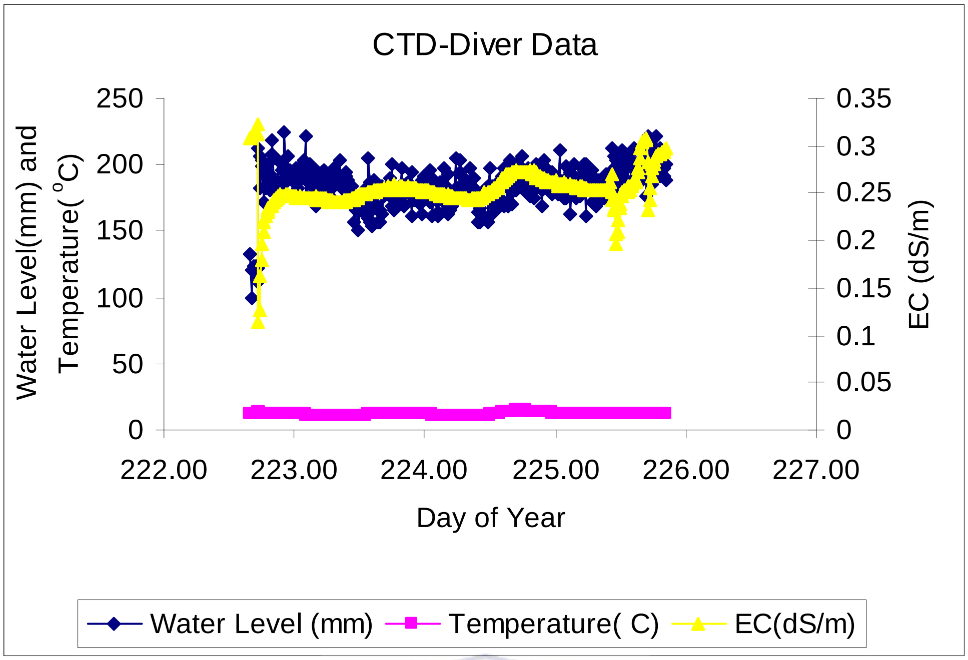
Appendix E. 2006 CTD-Diver Data





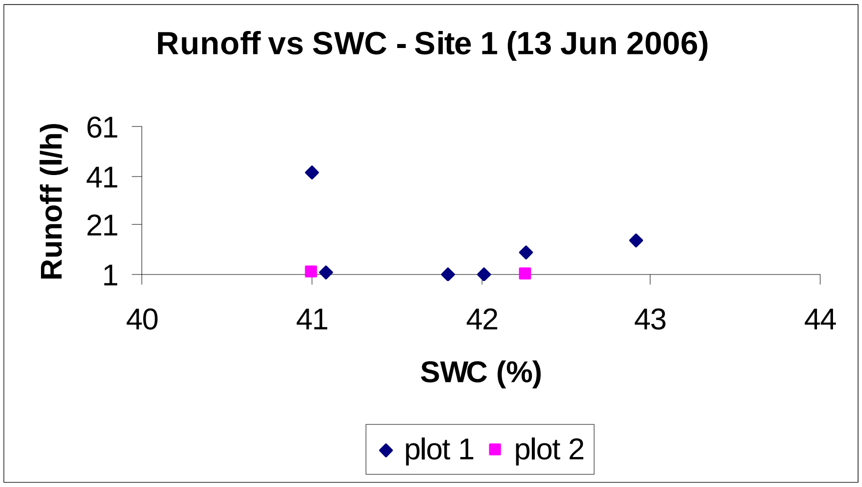

CTD-Diver Data
Water level(mm) and Temperature (^{o}C)
140
120
100
80
60
40
20
0
EC (dS/m)
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
212.00
213.00
214.00
215.00
216.00
Day of Year
Water level(mm)
Temperature(C)
EC(dS/m)

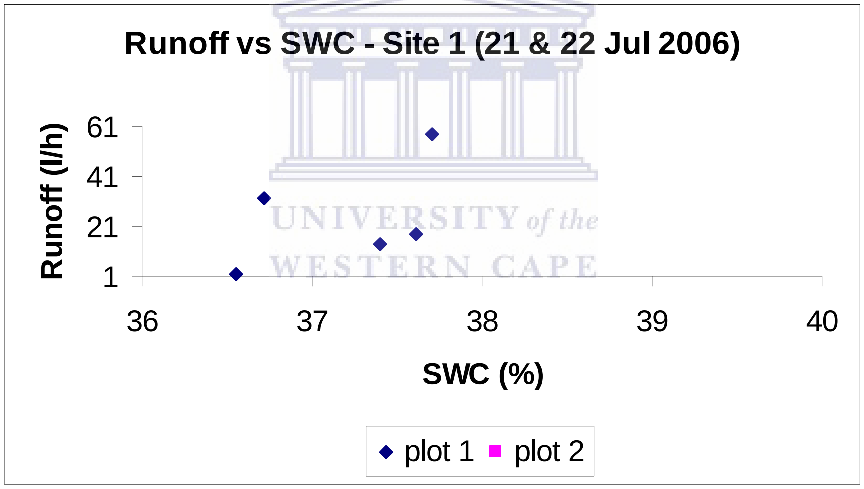

CTD-Diver Data
Water level(mm) and Temperature(^{o}C)
250
200
150
100
50
0
EC (dS/m)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
214.00
215.00
216.00
217.00
218.00
219.00
220.00
Day of Year
Water level(mm)
Temperature(C)
EC(dS/m)

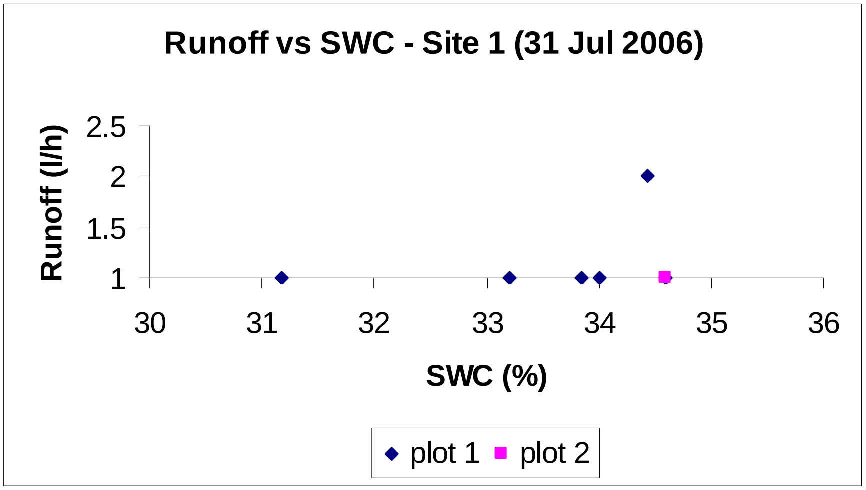


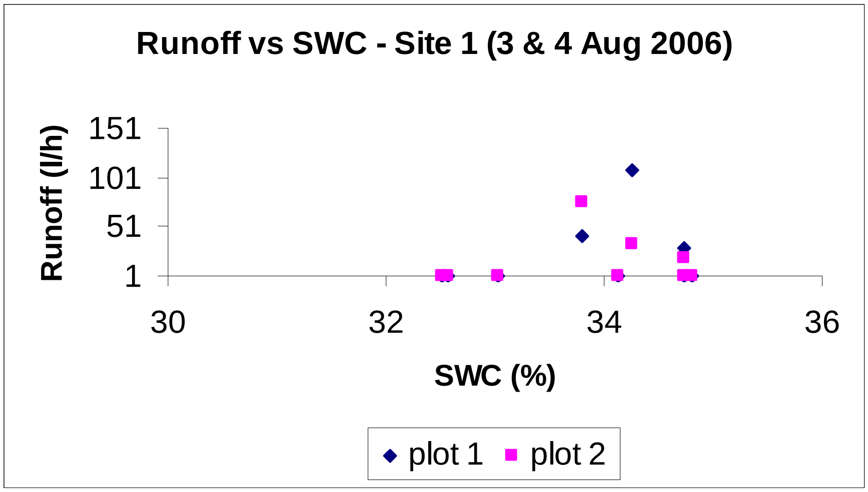
CTD-Diver Data
Water Level(mm) and Temperature(°C)
250
200
150
100
50
0
EC (dS/m)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
222.00
223.00
224.00
225.00
226.00
227.00
Day of Year
Water Level (mm)
Temperature(C)
EC(dS/m)

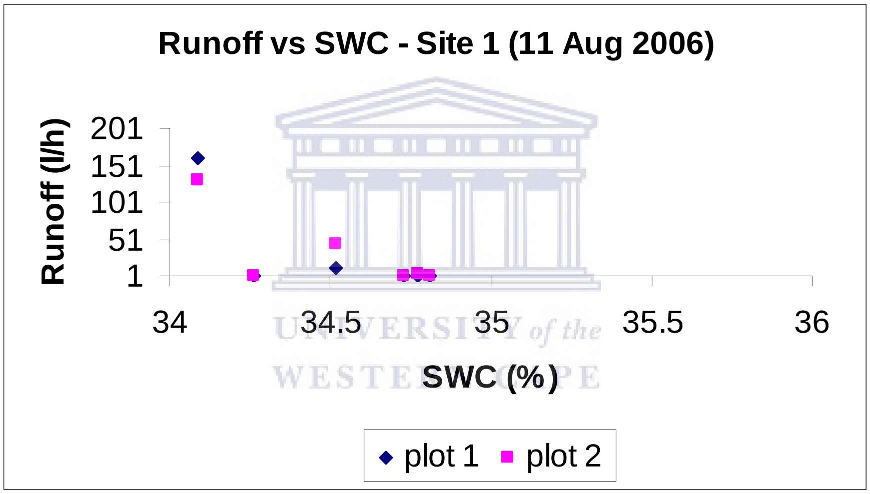
Appendix F. The graphs illustrate the relationship between the Soil Water Content (SWC) and the amount of runoff produced per rainfall event.

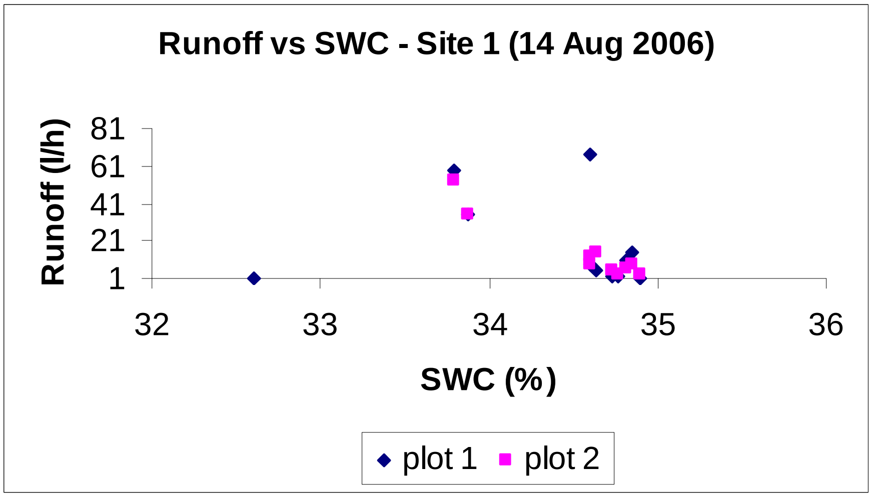


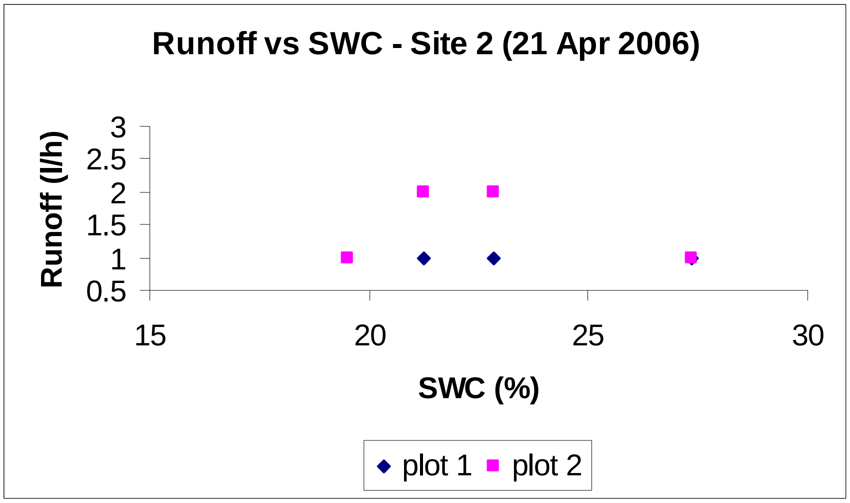


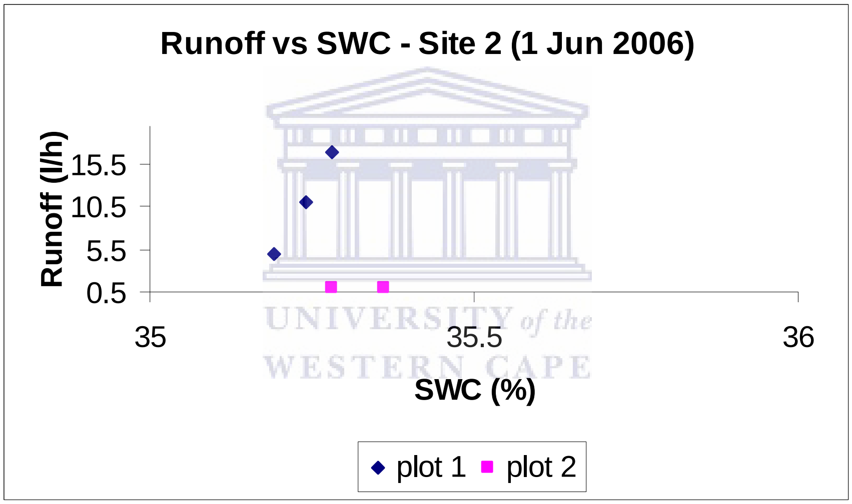


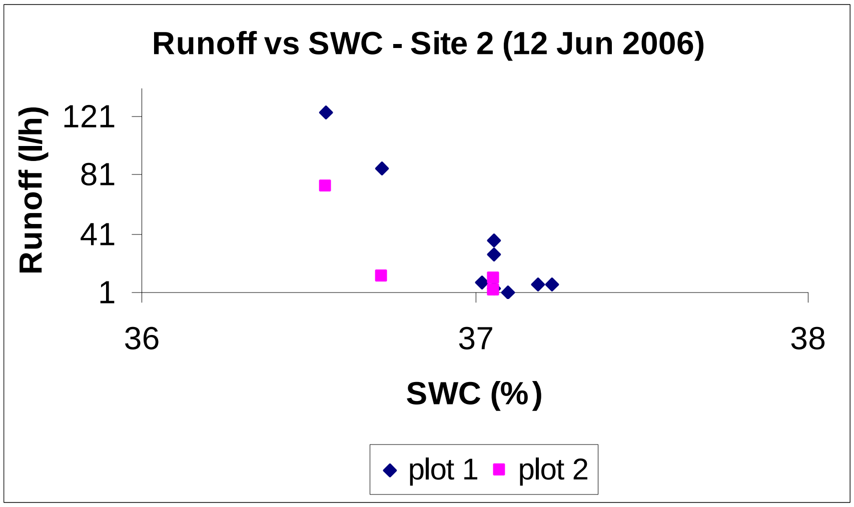

Runoff vs SWC - Site 1 (3 & 4 Aug 2006)
Runoff (l/h)
151
101
51
1
30
32
34
36
SWC (%)
◆ plot 1
■ plot 2

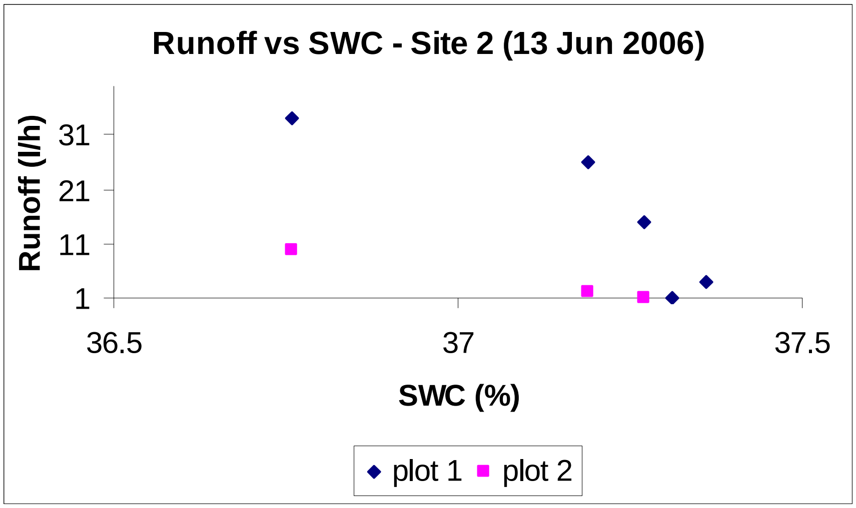

Runoff vs SWC - Site 1 (11 Aug 2006)
Runoff (l/h)
201
151
101
51
1
34
34.5
35
35.5
36
SWC (%)
◆ plot 1
■ plot 2

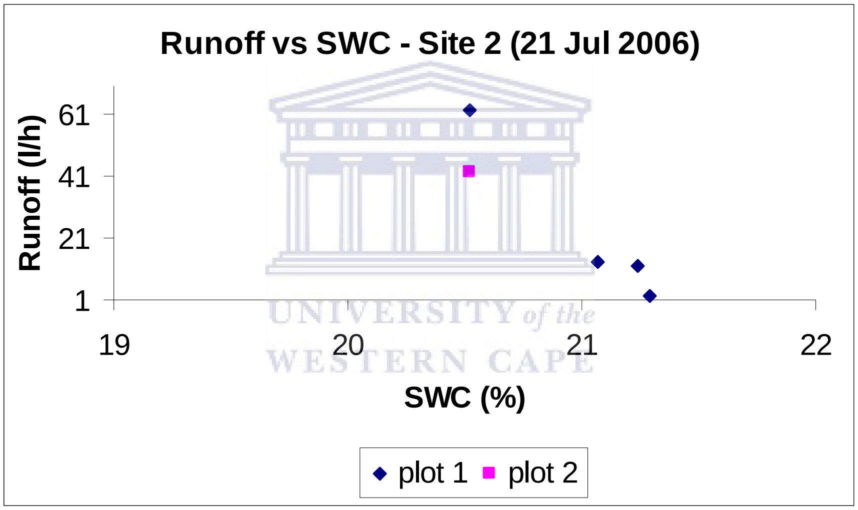

Runoff vs SWC - Site 1 (14 Aug 2006)
Runoff (l/h)
81
61
41
21
1
32
33
34
35
36
SWC (%)
◆ plot 1
■ plot 2

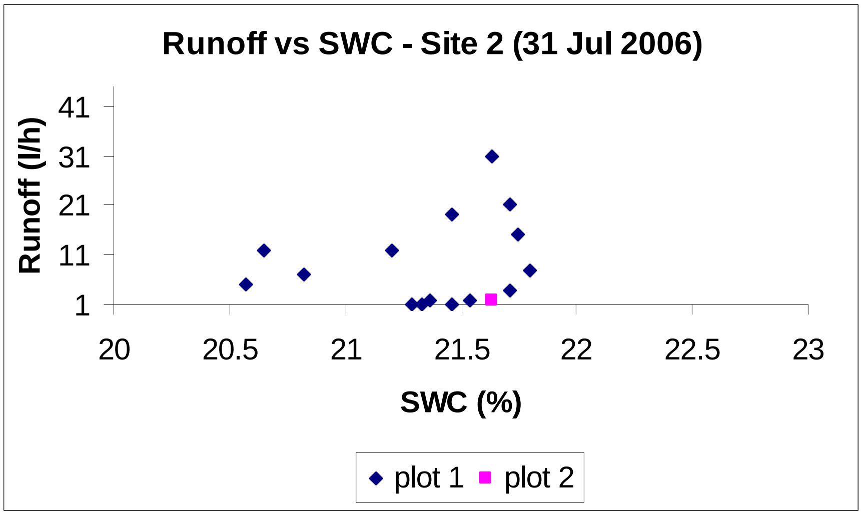

Runoff vs SWC - Site 2 (21 Apr 2006)
Runoff (l/h)
3
2.5
2
1.5
1
0.5
15
20
25
30
SWC (%)
◆ plot 1 ■ plot 2

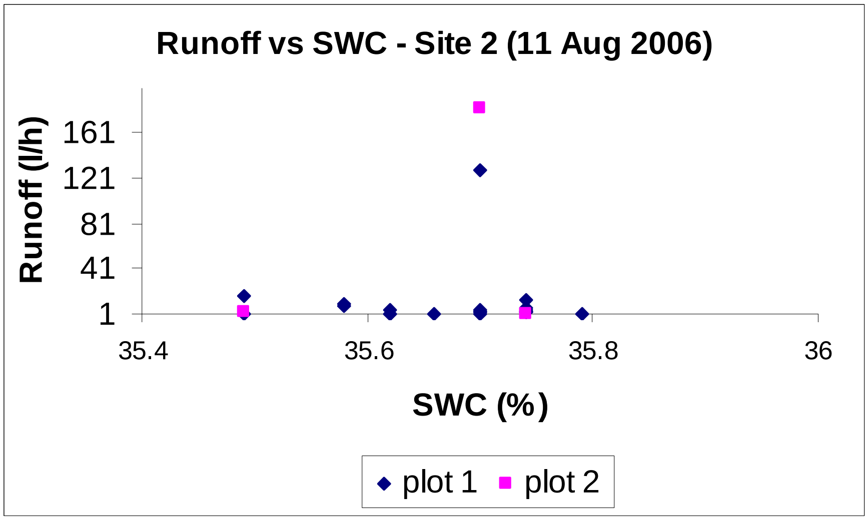

Runoff vs SWC - Site 2 (1 Jun 2006)
Runoff (l/h)
15.5
10.5
5.5
0.5
35
35.5
36
SWC (%)
◆ plot 1 ■ plot 2

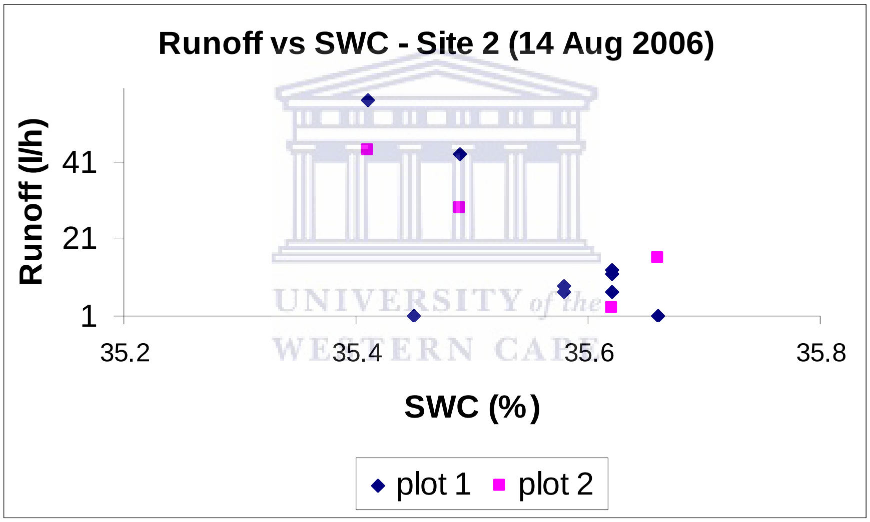

Runoff vs SWC - Site 2 (12 Jun 2006)
Runoff (l/h)
121
81
41
1
36
37
38
SWC (%)
◆ plot 1 ■ plot 2


Runoff vs SWC - Site 2 (13 Jun 2006)
Runoff (l/h)
31
21
11
1
36.5
37
37.5
SWC (%)
◆ plot 1 ■ plot 2


Runoff vs SWC - Site 2 (21 Jul 2006)
Runoff (l/h)
61
41
21
1
19
20
21
22
SWC (%)
◆ plot 1 ■ plot 2


Runoff vs SWC - Site 2 (31 Jul 2006)
Runoff (l/h)
41
31
21
11
1
20
20.5
21
21.5
22
22.5
23
SWC (%)
◆ plot 1 ■ plot 2


Runoff vs SWC - Site 2 (11 Aug 2006)
Runoff (l/h)
161
121
81
41
1
35.4
35.6
35.8
36
SWC (%)
◆ plot 1
■ plot 2


Runoff vs SWC - Site 2 (14 Aug 2006)
Runoff (l/h)
41
21
1
35.2
35.4
35.6
35.8
SWC (%)
◆ plot 1
■ plot 2