SOIL INDICATORS OF HILLSLOPE HYDROLOGY IN THE BEDFORD AND WEATHERLEY CATCHMENTS

By

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Dedicated to **Ronél**
My loving wife and my best friend.

“But my son, be warned: There is no end of opinions ready to be expressed. Studying them can go on forever and become very exhausting!
Here is my final conclusion: Fear God and obey his commands.....”
Ecclesiastes 12:12-13

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DECLARATION

I hereby declare that this dissertation submitted for the Magister Scientiae Agriculturae degree at the University of the Free Sate, is my own work and has not been submitted to any other University.

I also agree that the University of the Free State has the sole right to publication of this dissertation.

Signed:

Jacobus Johannes van Tol

ABSTRACT

There is an interactive relationship between soil and hydrology. Water plays a primary role in the genesis of most soil properties and soil properties influences and governs hydrological processes. Incorporation of these processes into hydrological models is essential for water resource management. Hydrological processes are dynamic in nature with strong temporal variation, making measurements expensive, inaccurate and time consuming. Predictions of these processes, especially predictions in ungauged basins (PUB) are therefore essential. Since soil properties are both a cause and result of this interactive relationship, identifying and interpreting relevant soil properties, can reveal information on key hydrological processes.

The hypothesis is then that soil properties can serve as signatures of hydrological characteristics. Identifying these and interpreting them and their relative distribution at hillslope scale can lead to better understanding of hillslope hydrological response and facilitate the formulation of conceptual hillslope hydrological models. These models can aid in the prediction of hydrological processes in ungauged basins (PUB).

Hydrologically there are three main soil types namely recharge, interflow and responsive soils. Data from previous studies were utilized to accentuate the differences between these soil types. A criterion for distinguishing between two storage mechanisms (perennial and transient groundwater) in the soils of South Africa is also proposed.

Two catchments in the Eastern Cape of South Africa were selected for this study:

A hillslope in the upper catchment (Uc) of the Weatherley was selected to determine the impact of soil types on hydrological response. A conceptual model was developed based on soil morphological properties and their relative distribution. These morphological properties included soil depths, mottling, and clay contents. These properties indicate that there are definite recharge, interflow and responsive areas in this hillslope.

The conceptual model was then evaluated with the use of climate, tensiometer, neutron water meter, hydrograph and evapotranspiration (ET) data. The conceptual model and soil information were utilised to calculate the relative contribution of streamflow generation mechanisms. Base and peakflow calculations gave a very good estimation of the actual streamflow.

In the greater Bedford catchment, three sub-catchments (B3, B4 and B5) were surveyed for hydropedological purposes. All the soil properties which might influence or be influenced by the hydrology were identified and related to hydrological hillslope response. These properties include: soil type, soil depth, weathering of underlying material, and presence of $CaCO_3$. Conceptual models of representative hillslopes in the selected catchments were developed based on the interpreted soil information. The dominant factors governing the streamflow in catchment B4&5 was shallow soils on bedrock with restricted permeability, which facilitated overland flow. In B3 the deeper soils and permeable bedrock facilitated infiltration, interflow as well as recharge of water tables (regional and perennial).

Two levels of detail of soil information namely; Land Type data: level 1 and Observed data: level 2, were used to test the impact of soil information on hydrological modelling. The results were assessed to evaluate the contribution of soil data and the effectiveness of the conceptual model. The contribution of some streamflow generation mechanisms was also calculated.

A method for classifying soils based to their hydrological behaviour was proposed. Future research should focus on several aspects (soil water regime, ET, drainage curves, hydraulic conductivity, flowpaths and storage mechanisms) which describe the hydrology of soil of South Africa. Such a system can benefit hydrological modelling, especially in PUB’s.

Keywords:
Predictions in ungauged basins, Hydrological behaviour, Hillslopes, Soil properties, Recharge soils, Interflow soils, Responsive soils.

OPSOMMING

Daar is ‘n interaktiewe verhouding tussen grond en hidrologie. Water speel ‘n primêre rol in die genese van meeste grondeienskappe, terwyl dié eienskappe hidrologiese prosesse beïnvloed en beheer. Hierdie prosesse word in hidrologiese modelle geïnkorporeer om sodoende waterbronne effektief te bestuur. Hidrologiese prosesse is egter dinamies van natuur en varieer oor klein afstande; dit maak metings van die prosesse onakkuraat, tydrowend en duur. Dit is dus nodig om die prosesse te probeer voorspel. Hierdie voorspellings is veral noodsaaklik in opvanggebiede wat nie oor hidrologiese data beskik nie. Siende dat grondeienskappe beide die oorsaak en gevolg van die interaktiewe verhouding is, kan die identifikasie en interpretasie van die eienskappe waardevolle informasie oor die prosesse beskikbaar maak.

Die hipotese was dus dat grondeienskappe as ‘n kenteken van die hidrologiese prossese kan dien. Indentifisering en interpretering van die eienskappe en hulle relatiewe verspreiding in ‘n heuwelhang, kan bydrae tot ‘n beter begrip van heuwelhang reaksie t.o.v. hidrologie. Dit kan ook help om konseptuele hidrologiese heuwelhang modelle te ontwerp. Hierdie modelle kan baie waardevol wees ten opsigte van die voorspelling van hidrologiese prosesse in opvanggebiede sonder hidrologiese metings.

Daar word onderskei tussen drie tipes gronde gebasseer op hulle hidrologiese gedrag, naamlik: aanvullings-, deur-vloei- en respons gronde. Data van vorige studies is gebruik om die verskille tussen die onderskeie gronde te beklemtoon. Kriteria om tussen twee verskillende stoormeganismes (seisoenale en tydelike grondwater) in Suid-Afrikaanse gronde te onderskei, word ook voorgestel.

Twee opvanggebiede in die Oos-Kaap provinsie in Suid-Afrika was geselekteer vir hierdie studie:

‘n Heuwelhang in die boonste opvanggebied van die Weatherley opvanggebied is geselekteer om die impak van grondtipes op die hidrologie te ondersoek. ‘n Konseptuele model wat gebasseer is op morfologiese grondeienskappe en hul relatiewe verspreiding is ontwerp. Die eienskappe wat gebruik is sluit in diepte, vlekke, en klei-inhoud. Hierdie model toon dat daar ‘n aanvullings-, deurvloei- en respons area in die heuwelhang teenwoordig is.

Die konseptuele model is vervolgens getoets met die hulp van klimaat, tensiometer, neutron water meter, stroomvloei sowel as evapotranspirasie (ET) data. Die konseptuele model en ander grond inligting is ook gebruik om die bydrae van verskillende stroomvloei ontwikkelings meganismes te bepaal.

In die groter Bedford opvanggebied is drie sub-opvanggebiede (B3, B4 en B5) opgemeet vir hidrologiese doeleindes. Al die grondeienskappe wat verband hou met hidrologiese prosesse is geïdentifiseer en gekoppel aan die hidrologiese gedrag wat hulle kan veroorsaak in die heuwelhang. Die grondeienskappe sluit o.a grond tipe, diepte, verwering van onderliggende materiaal en teenwoordigheid van $CaCO_3$ *in. Konseptuele modelle van verteenwoordigende heuwelhange in die geselekteerde opvanggebiede is ontwerp gebasseer op die geïnterpreteerde grond inligting. Die dominante faktore wat stroomvloei in opvangebiede B4&5 beheer is vlak gronde met relatief ondeurlaatbare moedermateriaal, wat oorland vloei bevoordeel. Daarteenoor bevoordeel die dieper gronde in B3 infiltrasie, deur-vloei in die grond asook aanvulling van water tafels (regionaal en seisoenaal)*

Twee vlakke van grond inligting (Land Tipe data: vlak 1 en geobserveerde data: vlak 2) is gebruik om die impak van grond inligting op hidrologiese modellering te toets. Die resultate is gebruik om die bydrae van grond inligting en die effektiwiteit van die konseptuele model te takseer. Die bydrae van sommige stroomvloei ontwikkelings meganismes is ook gedoen.

‘n Metode om gronde te klassifiseer op grond van hulle hidrologiese gedrag word voorgestel. Toekomstige navorsing moet fokus op verskeie aspekte (grond water inhoud, ET, dreineer kurwes, hidroliese geleiding, vloeipaaie en stoor meganismes) wat die hidrologie van Suid Afrikaanse gronde beskryf. So ‘n klassifikasie sisteem kan ‘n groot bydrae lewer tot hidrologiese modelering, veral in opvanggebiede wat nie oor hidrologiese data beskik nie.

Sleutel woorde:
Heuwelhang hidrologie, Voorspellings in opvanggebiede sonder hidrologiese data, Grondeienskappe, Aanvullings gronde, Deurvloei gronde, Respons gronde.

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(1)	Refers to processes discussed in conceptual model of the Bedford catchments
ACRU	Agrohydrological Modelling System – a computer model
$AD_{s>0.7}$	Annual duration of degree of water saturation above 0.7 of porosity
Ag	Augrabies soil form
AN	Arrow number
AN - 1a, etc	Refers to arrow numbers used in conceptual model of the upper catchment of Weatherley
B3	Sub catchment B3 in greater Bedford catchment
B4&5	Sub catchments B4 and B5 in the greater Bedford catchment (considered and discussed as one unit due to similar soils, topography and vegetation)
Bd	Bloemdal soil form
Cf	Cartref soil form
Cl	Clay
COFRU	Coefficient of runoff
CoSa	Coarse sand
CoSi	Coarse Silt
Cv	Clovelly soil form
D_b	Bulk density
$D_{s>0.7}$	Mean duration of s>0.7 events ($days.event^{-1}$)
Du	Dundee soil form
DUL	Drained upper limit of plant available water
ET	Evapotranspiration
ET_0	Potential evaporation
F	Porosity (as a fraction)
f sat	Field saturation
FiSa	Fine sand
FiSi	Fine silt

$F_{s>0.7}$	Frequency of events where s>0.7 (events.year^{-1})
Gh	G horizon
Gi	Groundwater inflow
Go	Groundwater outflow
Gs	E horizon
Gs	Glenrosa soil form
h_d	Air entry value
HOST	Hydrology of soil types (Hydrological soil classification system of the soils of the UK)
Hp	Hard plinthic horizon
Hu	Hutton soil form
K	Effective drainage rate
Ka	Katspruit soil form
Kd	Kroonstad soil form
Kh	Unsaturated hydraulic conductivity (mm.h^{-1})
K_s	Saturated hydraulic conductivity
Li	Lithocutanic B horizon
LL	Lower limit of plant available water
Lo	Longlands soil form
m.d.w	Maximum drainable water
MAE	Mean annual A-pan Evaporation
MeSa	Medium sand
Ms	Mispah soil form
Nc	Neocarconate horizon
Ne	Neocutanic B horizon
Oa	Oakleaf soil form
On	Unspecified material with signs of wetness
ot	Orthic A horizon
P	Precipitation
P221, etc.	Refers to profiles in the Weatherley catchment as well as to neutron access tubes in that specific profile
PGW	Perennial groundwater
Pn	Pinedene soil form
P_o	Porosity

POR	Porosity (%)
PUB	Predictions in ungauged basins
QFRESP	Quick flow response
R	Rock
re	Red apedal B horizon
s	Degree of water saturation
SaCl	Sand clay
SaClLm	Sand clay loam
SaLm	Sand loam
Se	Effective degree of saturation
Se	Sepane soil form
so	Saprolite
SOF	Saturation overland flow
sp	Soft plinthic B horizon
Ss	Sterkspruit soil form
SSSF	Subsurface storm flow
ST_{soil}	Storage capacity of the soil
Sw	Swartland soil form
TGW	Transient groundwater
TMU	Terrain morphological unit (1 – 5)
Tu	Tukulu soil form
Uc	Upper catchment of the Weatherley catchment
Uc8, etc.	Refers to tensiometer nests in the upper catchment of the Weatherley catchment
Va	Valsrivier soil form
V_f	Total pore volume ($mm^3.mm^{-3}$)
V_T	Total bulk volume of material (including void and solid components)
V_v	Volume of void space
VVAR	Correction factor for vertical variations in POR
V_w	Water content ($mm^3.mm^{-3}$)
W1	Crump weir where stream hydrographs were obtained
ye	Yellow-brown apedal B horizon
Θ	Water content ($mm.mm^{-1}$)

Θ_r	Residual water content ($m^3.m^{-3}$)
Θ_s	Water content ($m^3.m^{-3}$ at saturation)
λ	Pore size distribution parameter
ρ_d	Bulk density ($Mg.\ m^{-3}$)
ρ_s	Particle density ($Mg.\ m^{-3}$) assumed to be 2.56 $Mg.\ m^{-3}$
Φ	Porosity (as fraction between 0 and 1)

CHAPTER 1

INTRODUCTION

1.1 Background and motivation

The National Water Act (1998) requires a clear understanding of key hydrological processes for effective water resource management. This understanding involves the identification, definition and quantification of the pathways and residence times of components of flow making up stream discharge; it is essential that these aspects be efficiently captured in hydrological models for accurate water resources prediction, estimating the hydrologic sensitivity of the land for cultivation, contamination and development, and for quantifying low flow mechanisms (Lorentz *et al.*, 2007a). Knowledge of the role of flowpaths is becoming increasingly important in arid and semi-arid areas for the sustainability of agricultural practices. The quality of water is also influenced by the residence time since most of the chemical and biochemical reactions in the soil are time related (Karvonen *et al.*, 1999; Bennie & Hensley, 2001; Asano, Uchida & Ohte, 2002; Kjellin *et al*., 2006 and Ticehurst *et al*., 2007).

Soils integrate the influences of parent material, topography, vegetation/land use, and climate and can therefore act as a first order control on the partitioning of hydrological flow paths, residence time distributions and water storage (Park, McSweeney & Lowery, 2001 and Soulsby *et al.* 2006). Soils play a major role in catchment hydrology by facilitating infiltration, and thereby largely controlling stormflow generation, by acting as a water store which avail soil water for evapotranspiration and by redistributing water, both within and without the soil profile, and by drainage below the root zone and eventually into the groundwater zone which feeds baseflow (Schulze, 1995 and Sivapalan, 2003).

The influence of soil on hydrological processes is due to the ability of soil to transmit, store and react with water (Park, McSweeney & Lowery, 2001). The hydrological model ACRU has an advanced soil routine (Schultze, 1995). The way in which the soils of a catchment influence various contributions to streamflow is expressed by ACRU via two composite parameters QFRESP and COFRU. This was well demonstrated by the results of Royappen *et al.,* (2002) for eight different small catchments distributed over a wide area in South Africa. The parameter

QFRESP calculates the fraction of the stormflow generated that will exist in the catchment on the same day as the stormflow-producing rainfall event. COFRU, the coefficient of baseflow response, is the fraction of water from the intermediate/groundwater that is released as the baseflow component of streamflow on a particular day. In the catchments studied Royappen *et al*., (2002) found good correlations between QFRESP and the average soil depth, and between COFRU and the average profile plant available water in the soils.

The relationship between soil and hydrology is interactive. Water is a primary agent in soil genesis, resulting in the formation of soil properties containing unique signatures of the way they formed. The formation of these properties, exhibit a common form of organization and symmetry which is also known as a hillslope. The soil properties associated with topography combines to form pedosequences or catenas. In these topo-pedosequences the macropore network of prefered flowpaths in the soil and in the underlying material, govern the hydrological processes. The hillslope forms the backbone of process hydrological studies and is the basic building block for catchment models (Mosley, 1982 and Sivapalan, 2003).

The incorporation of residence time estimates into hydrological models lead to better predictions of hydrological processes (Asano *et al*., 2002; McGuire *et al*., 2005). Ideally these hydrological models could best be developed using measurements of the surface and subsurface lateral flow paths, water table fluctuations and the residence flow time of water through the landscape. Such measurements are however expensive and time consuming because these processes are dynamic in nature with strong temporal variation (Park & Van de Giesen, 2004 and Ticehurst *et al*., 2007).

There is however a strong correlation between the relative importance of the various pathways and the residence time. The dominant pathway will determine the residence time of water and the extent of contribution to streamflow (Karvonen *et al*. 1999; Lin *et al*., 2006 and Ticehurst *et al*., 2007). Soil characteristics determine the relative importance of the various pathways (Mosley, 1982), and therefore residence time distributions. Hydrologists agree that the spatial variety of soil properties significantly influence hydrological processes but they lack the skill to gather and interpret soil information (Lilly, Boorman & Hollis, 1998 and Chirico, Medina & Romano, 2006).

‘Observation is the foundation of all learning’, yet almost all hydrological processes are difficult to observe. Prediction of the hydrological behaviour in ungauged basins calls for a new holistic theory of how water reacts with the entire earth system. Ungauged basins are catchments with insufficient hydrological observations to facilitate the computation of hydrological variables accurate enough for practical water resource management (Sivapalan *et al.,* 2003).

Theory development will advance if we can develop simple models (which may be caricatures of the basin system but, nevertheless, contain within them the basic properties of the actual basins), provided, importantly, that they can be falsified with large-scale patterns extracted from the observed data (Sivapalan, 2003).

"…*the emphasis of pedology is now shifting from classification and inventory to understanding and quantifying spatially and variable processes upon which the water cycle and ecosystems depends"* (Lin *et al.*, 2006). Pedologists therefore have the opportunity to contribute valuable information to the science of hydrology. Regardless of this chance to close the knowledge gap between the two sciences little research has been conducted in the combined science of hydropedology in South Africa.

1.2 Hypothesis and Objectives

1.2.1 Hypothesis

Soil properties can serve as signatures of hillslope hydrological responses. Identifying these and interpreting them and their relative distribution at hillslope scale, can lead to better understanding of hillslope hydrological responses and facilitate the formulation of conceptual hillslope hydrological models. These models should aid in the prediction of hydrological processes in catchments, and especially, predictions in ungauged basins.

1.2.2 Objectives

1. Concept development
    a. To distinguish between South African soil types based on their soil water regime and predicted hydrological behaviour.
    b. To improve the definition of storage mechanisms important in hydropedological studies.

2. Upper portion of the Weatherley catchment:
    a. To interpret existing soil information of a selected hillslope
    b. To develop a conceptual model of the hydrological behaviour of the selected hillslope based on interpreted soil information.
    c. To evaluate the model in relation to hydrological measurements.
    d. To examine streamflow generation areas and estimate their relative importance.

3. Sub catchments B3 and B4&5 in the Bedford region:
    a. To identify modal hillslopes, their pedosequences and interpret relevant soil properties and relate them to hydrological responses.
    b. To develop conceptual models of the hydrological behaviour of the modal hillslopes based on the interpreted soil information.
    c. To evaluate the effectiveness/contribution of the conceptual model to the Pitman hydrological model.
    d. Two propose a preliminary method for determining outflow from a ungauged catchment based on soil information.

The procedures used are discussed in the various chapters.

CHAPTER 2

LITERATURE REVIEW

2.1 Hydrological processes

2.1.1 Flow Paths

Three major flow pathways exist in a typical hillslope: overland flow, subsurface lateral flow and bedrock flow (Karvonen *et al*. 1999 and Ticehurst *et al.,* 2007). Subsurface lateral flow can be divided into: subsurface macropore flow, subsurface lateral flow at A-B horizon interface, return flow at the footslope and toeslope and flow at the soil-bedrock interface (Lin *et al.,* 2006). These flowpaths are not mutually exclusive, and water tends to move between them. Some paths are only connected when the hillslope is wet.

The relative importance of the various pathways is determined by soil characteristics, the macropore network and the parent material at the base of the soil (Mosley, 1982). Hydrologic conditioning is influenced by soil depth, pore size and organic matter distribution, tortuosity and the surface and subsurface topography (Sidle *et al*., 2001).

The role of topography varies with the moisture content of the soil. In drier periods the main controlling factor of movement is soil characteristics. In wetter periods, the topography becomes increasingly important (McGlynn, McDonnel & Brammer., 2002; Stieglitz *et al*., 2003; Park & van de Giesen, 2004 and Lin *et al*., 2006).

For better understanding of the influences of topography and soil characteristics on the different flowpaths, a conceptual hillslope in south eastern Australia serve as example (Figure 2.1), (Ticehurst *et al*., 2007). The hillslope is divided in four geomorphic zones.

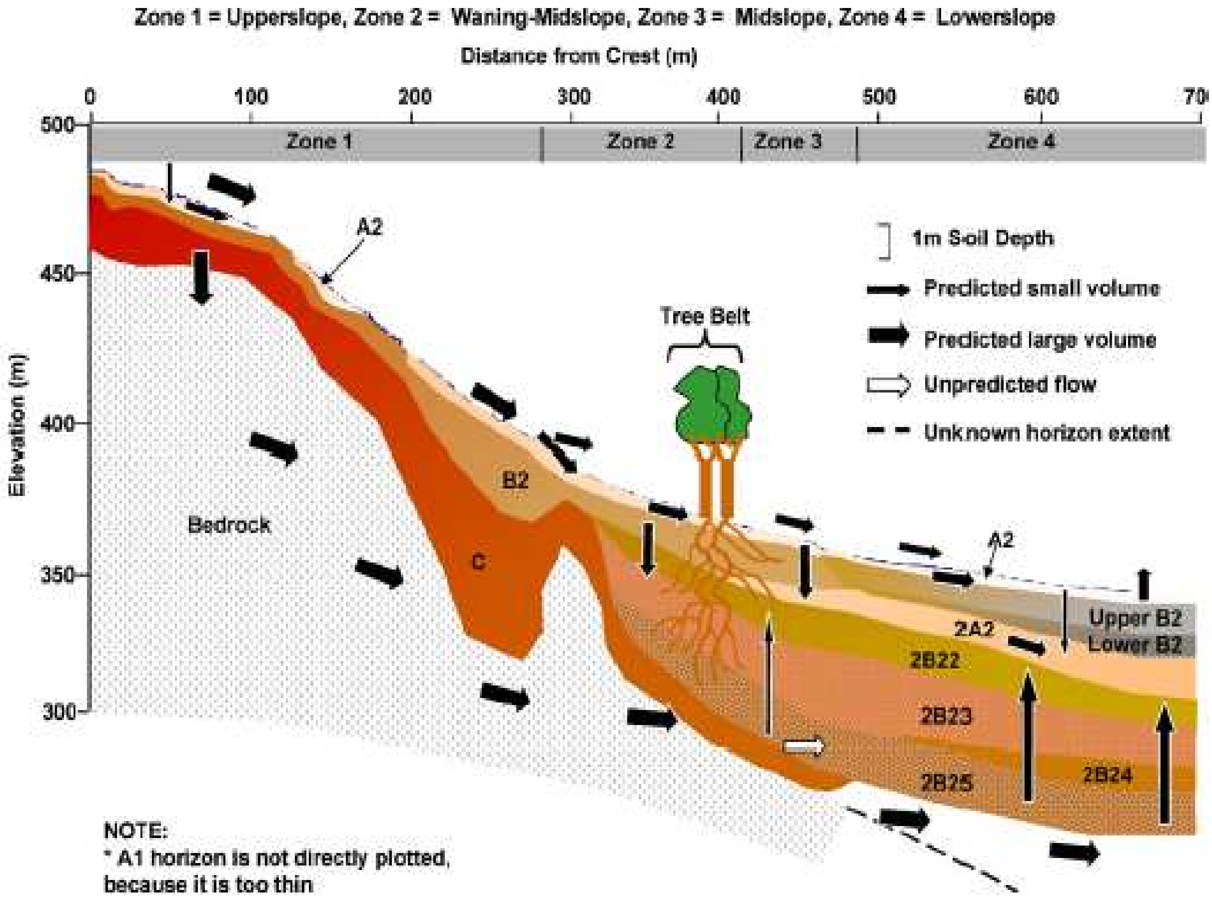

Figure 2.1 Flowpaths on a hillslope in south eastern Australia (Ticehurst *et al*., 2007).

2.1.1.1 Overland flow

Overland flow occurs either as infiltration excess or as saturation excess. The steep slope of the upperslope generates a large volume of overland flow with significant erosive energy. In some areas the A1 and A2 horizons were eroded completely, leaving the B2 horizon exposed (Figure 2.1). Thinner A horizons usually indicate that the overland flow is dominant, in thicker soils we can expect more infiltration due to the greater volume of water needed to saturate the soil. The assumption can be made that thicker soils support more vegetation and this causes a decrease in the overland flow proportion (Ticehurst *el al*., 2007).

At the break of slope (between upper and waning slope), the change in the gradient cause slower movement of the water and therefore a decrease in the runoff (Figure 2.1). The soils in this region are generally thicker, due to deposition of alluvial material and organic matter, which enhance infiltration. Soils in this area are usually lighter in colour due to increased redox concretions.

On the lowerslope the runoff rate tend to slow because of the smaller gradient. These soils are however the wettest in the hillslope and the saturated conditions reduce infiltration rate. In the study of Ticehurst *et al.,* (2007), *s*aturation excess is conducive to overland flow.

Some of the water moves as overland flow down the slope but encounters an area where the soil moisture deficit has not yet been satisfied, the water then infiltrates. This is called the run-on pathway and is often ignored in rainfall and runoff studies. The water available for infiltration then includes the precipitation as well as water supplied from the upperslope (Nahar *et al*,. 2004).

The amount of overland flow is also greatly affected by the texture of the soil specifically the percentage clay and sand. Sand generally is more permeable and has a greater hydraulic conductivity than clay and therefore infiltration excess induced overland flow seldom occur in sandy soils. In a study of Karnoven *et al*. (1999) the conductivity of sandy loam soils are 15 times higher than clayey soils.

Return flow as overland flow at the foot and the toeslope is related to a great amount of precipitation. The water moves lateral underneath the surface from the upperslopes and surface in the lower areas (Lin *et al*., 2006) (Figure 2.2).

2.1.1.2 Subsurface lateral flow

The four major subsurface flowpaths in a hillslope is conceptually illustrated in Figure 2.2. The moisture content of three profiles in different areas (Waning mid-slope, midslope and lowerslope) in the hillslope is also given.

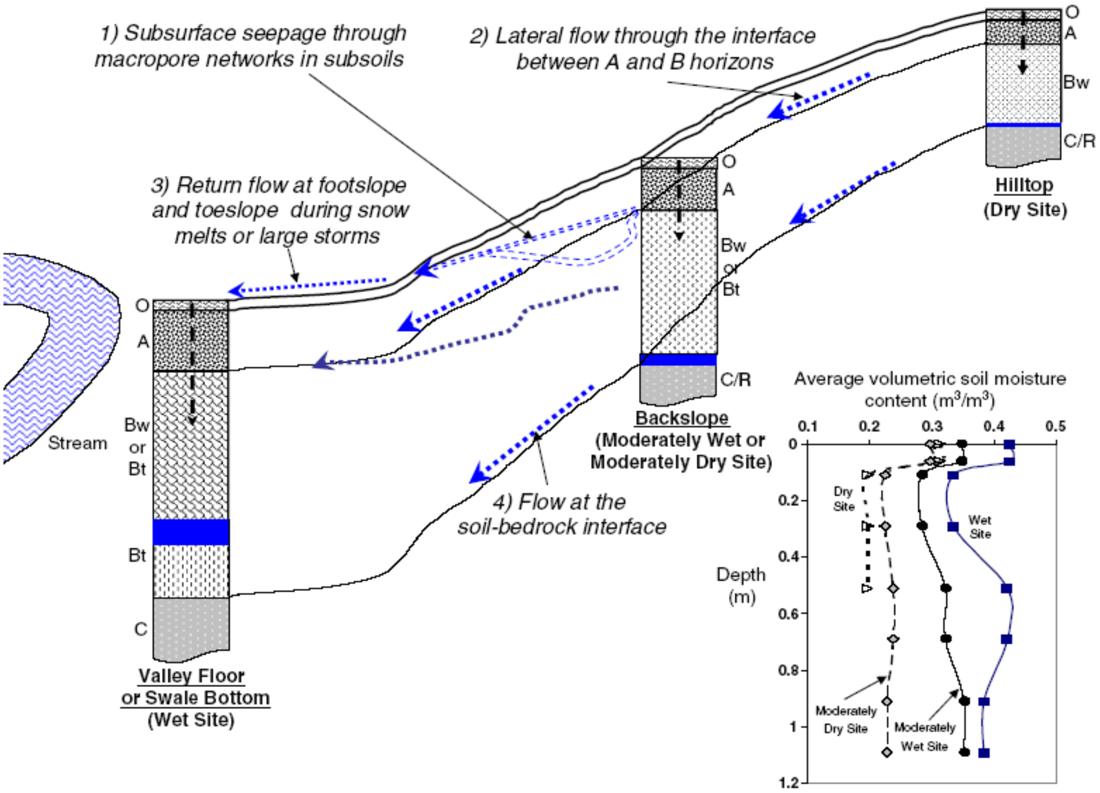

Figure 2.2 Four flow pathways of a conceptual hillslope and the soil moisture content, of three profiles, in different areas of the hillslope (Lin *et al*., 2006).

The movement of water through macropores conducts a considerable amount of water during large storms in forested catchments. Water moves through tree root channels, pores created by organisms (earthworms), as well as cracks. Cracks are usually present in soils with a high 2:1 clay content (like Vertic soils), especially in drier periods (Lin *et al*., 2006). There are three factors determining the contribution of subsurface macropore flow of water namely; size of the macropores, the accessibility and continuity of the pores. The continuity of these pores seem to increase with an increase in soil moisture (Figure 2.3) (Nieber *et al.*, 2000).

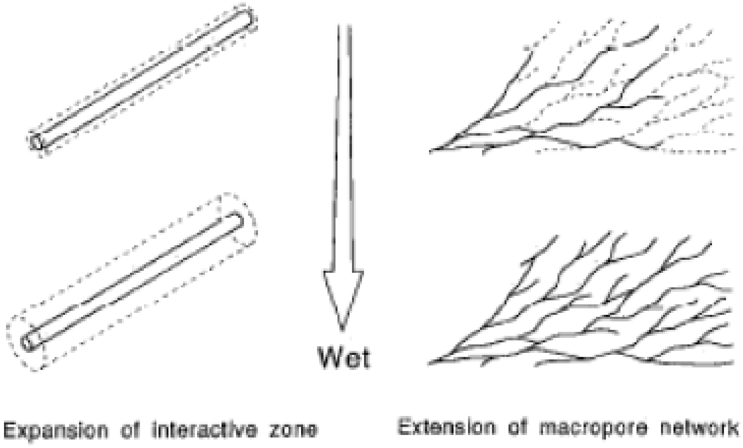

Figure 2.3 Expansion of macropore network with increased wetness (Nieber *et al.*, 2000).

Soil pipes are usually flow pathways parallel with the slope and are formed by soil fauna (moles & mice) as well as dead root channels (Figure 2.4). They contribute a significant amount of subsurface water to streamflow and are usually quick to respond to rainfall. Pipe flow has a smaller influence in hillslopes with high drainable porosity because water table response is lower due to the high storage potential of the profile (Uchida, Weiler & McDonnel, 2006)

Figure 2.4 Soil pipe outlet (macropore flow) (Photo by Le Roux, 2006).

Another subsurface pathway is the one between the A and B horizons. Lateral flow occurs due to differences in the structures, densities and hydraulic conductivities of the horizons. The smallest measured hydraulic conductivity measured by Ticehurst *et al*. (2007), was 43 mm.h^{-1} for the A2 horizon and 1 mm.h^{-1} for the B horizon. Vertical flow would then be hindered and water would tend to move laterally in the more permeable A2 horizon. The flowpath is important in conditions of saturation of the B horizon and therefore becomes more significant in the waning mid-slopes. An increase in the clay and silt content in the A2 horizon of the lower slopes is evident of such a lateral pathway. In the study of Lin *et al*. (2006), the lowest moisture content was recorded at the interface between the A and B horizons due to the great amount of lateral flow. The low gradient of the lower slope would limit this lateral flow and cause water logging as well as overland flow due to excess saturation (return flow).

There is a pathway at the bottom of the profile at the interface between the soil and the underlying parent material. The continuous flow after a storm even with little moisture in the top of the profile suggested that the water moved vertically in the upperslopes and then laterally at or near the soil-bedrock interface (Lin *et al.,* 2006). The permeability, the depth as well as the differentiation between horizons would affect the amount of water moving through this flowpath. Since the clay content of the B horizon in lower slopes usually shows an increase due to luviation, this pathway would originate in the upper slopes. The existence of this pathway is implied by signs of wetness in the saprolite of Swartland soils at Gladstone, Eastern Free State (Hensley *et al.,* 2007 and Ticehurst *et al*., 2007).

2.1.1.3 Bedrock flow

Ticehurst *et al*. (2007) found in their study that the soils from the summit area, which were sandy and shallow, provided and important water intake area for water supply to the bedrock flowpath. The general movement of water in this region is vertical except near the shoulder. Soils in this region are usually well drained especially with smaller summits. Due to the age of the soils and the small amount of deposition, little differentiation between horizons is present and water moves through the B2 horizon into the C horizon. The water that doesn't move on top of the bedrock moves through cracks in the granite bedrock or on solid bedrock within the saprolite (Figure 2.1). On the midslope the depth of this flowpath is about six metres. The bedrock flow accumulates in the waning midslope causing a periodical water table. In the lowerslope the accumulating water table cause saturation of the B horizon (Wilding, Smeck & Hall, 1983; Fanning & Fanning, 1989 and Ticehurst *et al*., 2007). Bedrock flowpath is extremely important for recharge of the lowerslope.

2.1.2 Residence time

Residence time imply the rate at which and object remains in a system or part of a system. In the water cycle, residence time can be defined as the time a water molecule will spend in that reservoir. For catchment hydrology it would be the time the molecule will reside in the catchment and for hillslope hydrology the time it takes for the water molecule to reach the stream. A distinction is made by some researchers between residence time and transit time. Where residence time applies the time spent within the reservoir i.e. subsurface flow, and transit time is the time it takes to exit a flow system. The transit time will therefore include overland and channel flow (McGuire & McDonnell, 2006).

Residence times reveals information on the dominant flowpaths, storage and sources of water and are directly related to the internal processes in the catchment (McGuire & McDonnel, 2006). Since most chemical and biochemical reactions are time related, the residence time of water will significantly influence the quality of the water. In treatment wetlands, the longer the residence time, the more time for sedimentation of particles and chemical reactions to occur and therefore the efficiency of the treatment (Kjelling *et al.,* 2006). The residence time of water in the catchment therefore influences the sensitivity of the catchment or hillslope for cultivation, contamination and development (McGuire *et al.,* 2005).

Residence times are estimated with the use of environmental tracers of the water molecule itself (^{18}O, ^{2}H and ^{3}H). The tracers are applied to the system through rainfall and are isotopically different. That makes them dependable tracers for subsurface flow (Kendall & Caldwell, 1998). Groundwater residence times can be estimated with the use of gas environmental tracers. Numerous studies of residence times have been conducted using tracers, for example: Maloszewski & Zuber (1982); Burns & McDonnell (1998), Soulsby *et al*. (2000); Asano *et al*. (2002); McGlynn *et al*. (2003); McGuire *et al*. (2005), etc.

The residence times in a catchment are influenced by catchment characteristics including the area, flowpath length and flowpath gradient (Figure 2.5) (McGuire *et al.,* 2005).

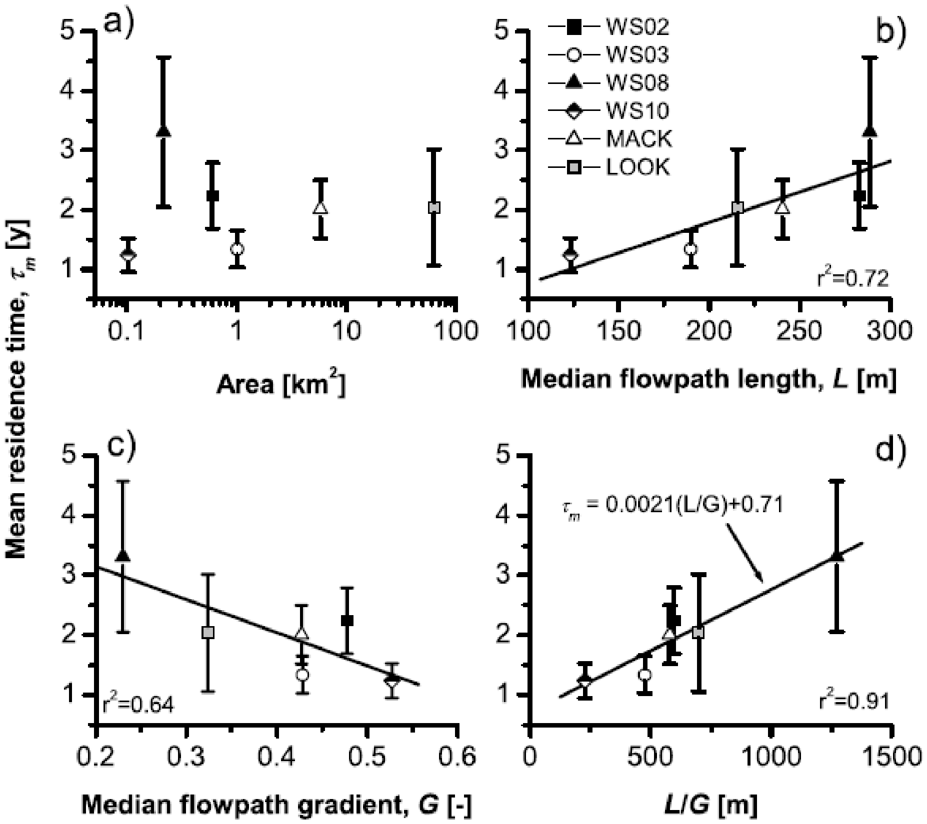

Figure 2.5 Influence of some catchment characteristics on mean residence times (McGuire *et al*., 2005).

Two topographical properties, influencing soil formation and distribution of soils in the pedosequence, have a good correlation with residence time (Figure 2.5). The size of the catchment does not control the mean residence time. The flowpath length has a greater influence on the residence time than the gradient. The best correlation was obtained by the ratio of the median flowpath length to median flowpath gradient.

Soil properties also influence the residence times of catchments. Although the impact of soil properties may be averaged out in larger catchments (Schultze, 1995), the most important parameter controlling hillslope hydrological behaviour is the soil. According to Asano *et al.,* (2002), soil depth has a greater influence on residence time than the length of the upslope contribution area (i.e. flowpath length). Soil porosity, infiltration capacity, infiltration rate, clay content and soil moisture content all have an influence on the residence time.

2.1.3 Water tables and ground water storage

A water table is the upper surface of a water body where the water pressure is equal to atmospheric pressure. It is therefore the dividing line between the saturated and unsaturated zone. The unsaturated zone is known as the vadose zone, while the saturated zone is also termed the phreatic zone (Hiscock, 2005 and Pinder & Celia, 2006).

2.1.3.1 Regional water tables

The regional water tables roughly follow the contour of the overlying land surface. This is usually a deep lying water table where the boreholes are and windmills drink. It is also termed an aquifer since it is a sustainable amount of water within the phreatic zone. An aquitard is a zone within the earth that restricts the flow of water which typically comprise of layers of non-porous rocks or clay with a low hydraulic conductivity. When this aquitard is completely impermeable it is called an aquiclude (McWhorter & Sunada, 1977; Freeze & Cherry, 1979; Hiscock, 2005 and Pinder & Celia, 2006).

When this aquitard is present above a regional aquifer, it is called a confined aquifer (Figure 2.6) i.e. the water table is above the upper level of the aquifer. An unconfined aquifer is also called the water table or a phreatic aquifer since the former is the upper boundary of the aquifer. An unconfined aquifer usually recharges with water directly from the surface while a confined aquifer will recharge via the bedrock flowpath (McWhorter & Sunada, 1977; Freeze & Cherry, 1979; Hiscock, 2005 and Pinder & Celia, 2006).

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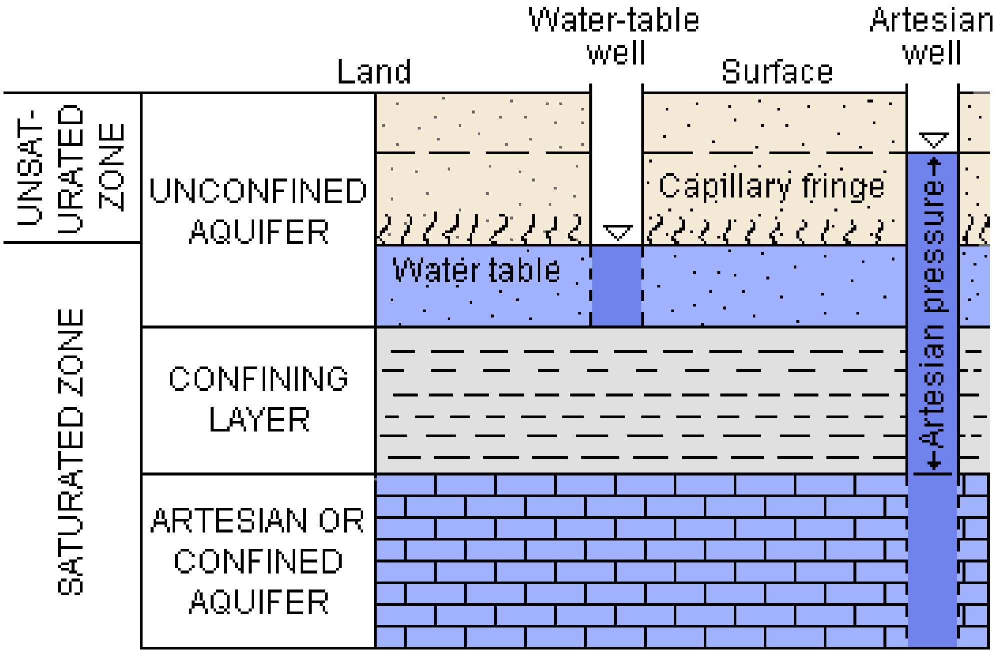


Figure 2.6 Confined and unconfined regional aquifers (Ground water primer, 1997).

A spring forms when this water table reaches the surface. Springs under rivers may contribute to baseflow. Although earlier literature suggests that regional water is the only contributor to baseflow, Lorentz *et al*. (2007) found that the depth of the regional water table in a research catchment was always below the surface and could therefore not be a contributor to baseflow.

2.1.3.2 Perched water tables

A perched water table is a water table or saturated zone which occurs above the regional water table in the unsaturated or vadose zone. This zone is also termed a “sitting” water table, since it “sits” on an aquitard or aquiclude. Two basic types of perched water tables can be recognized namely: perched under the solum (on rock) or perennial groundwater and perched within solum (on clay) or transient groundwater.

Perennial groundwater

This saturated zone can be defined as the saturated area on top of bedrock. Asano *et al*. (2002) used the term perennial ground water (PGW) and this zone is usually associated with G horizons in S. A. soil taxonomy of the Soil Classification Working Group (1991) (Le Roux *et al*., 1999). This water table shows a close correlation with the topography. This phreatic zone was not a single connected unit in the study of Ticehurst *et al*. (2007), (see Figure 2.1), due to the small amount of precipitation. More permanent areas of saturation were however found in the lower slopes on top of the bedrock due to a catchment wide accumulation of water.

In the study of Asano *et al*. (2002), PGW was noticed in sampling points F1 and R1 (Figure 2.7). The presence of this water table can be attributed to the accumulation of an enormous amount of water moving through the bedrock flowpath (Figure 2.1). This water moves upwards in the deeper soil layers in the Rachidani catchment. The negative hydraulic pressure head in these layers is evident of such movement. In the upper horizons a negative pressure head is only present during the driest periods. In Fudoji the hydraulic pressure head was positive for all the layers even at the driest times. This water table was responsible for the spring in both Rachidani and Fudoji catchments.

Transient groundwater

This water table occurs due to a clay layer within the solum with restricted permeability. It is termed Transient groundwater (TGW) by Asano *et al.* (2002) and associated with E horizons of the Soil Classification Working Group (1991) (Le Roux *et al*., 1999). When the hillslope becomes wetter a connection between the perched on clay and perched on rock can be expected (Ticehurst *et al*., 2007).

In the study of Asano *et al*., (2002), TGW was observed in profiles F2, F3, R5 and R6 (Figure 2.7 & 2.8). The time of saturation is normally shorter in these areas. In a study of McGlynn *et al*., (2002) he discovered that during high rainfall intensities the rainfall moved past the upper horizons via vertical cracks. The water then accumulated in the lower half of the profile. Due to lateral flow, this water table was only present for a short period.

We can expect a perched water table at the break of slope (Figure 2.1), where the shape of the slope becomes concave. Less overland flow occurs in this area and infiltration to lower horizons is dominant. A deceleration in the subsurface lateral flowpath, due to a decrease in gradient, may also contribute to the wetness of this region.

2.2 Soil indicators

2.2.1 Soil depth

The influence of soil depth, upslope contributing area as well as vegetative cover on the mean residence time of water was studied by Asano *et al*. (2002) in two catchments in the Tanakami Mountains in Japan with identical climate and geology The Fudoji catchment is forested with an average soil depth of 80 cm and a mean gradient of 37° (Figure 2.7). The Rachidani catchment was deforested 1200 years ago and the average soil depth is 10 cm. The mean slope gradient is 34° (Figure 2.8).

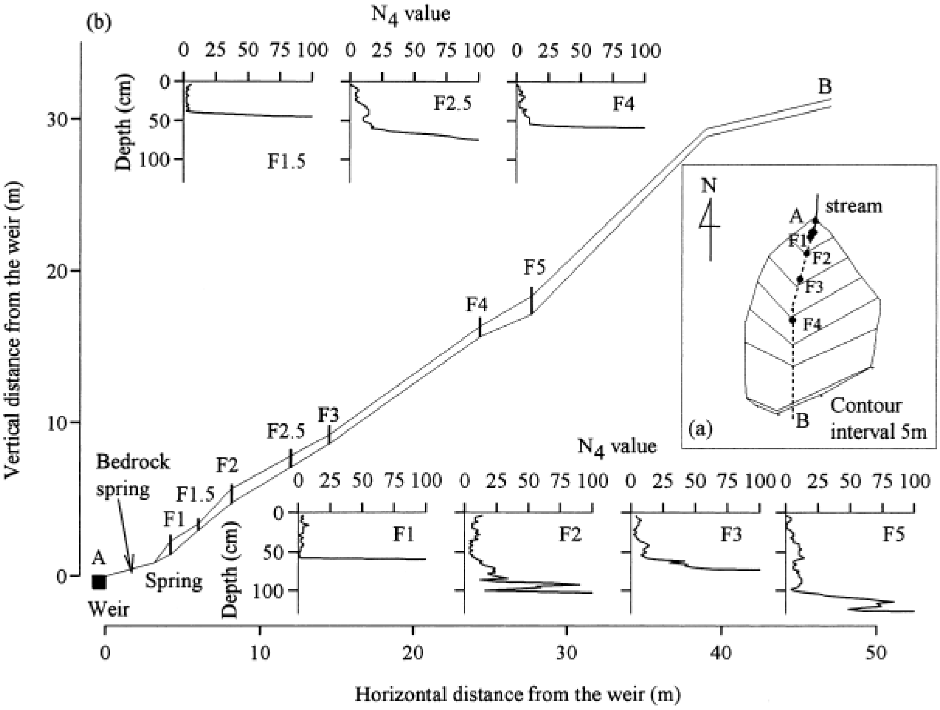


Figure 2.7 Positions of sampling points and depth of profiles for Fudoji catchment (Asano *et al*., 2002).

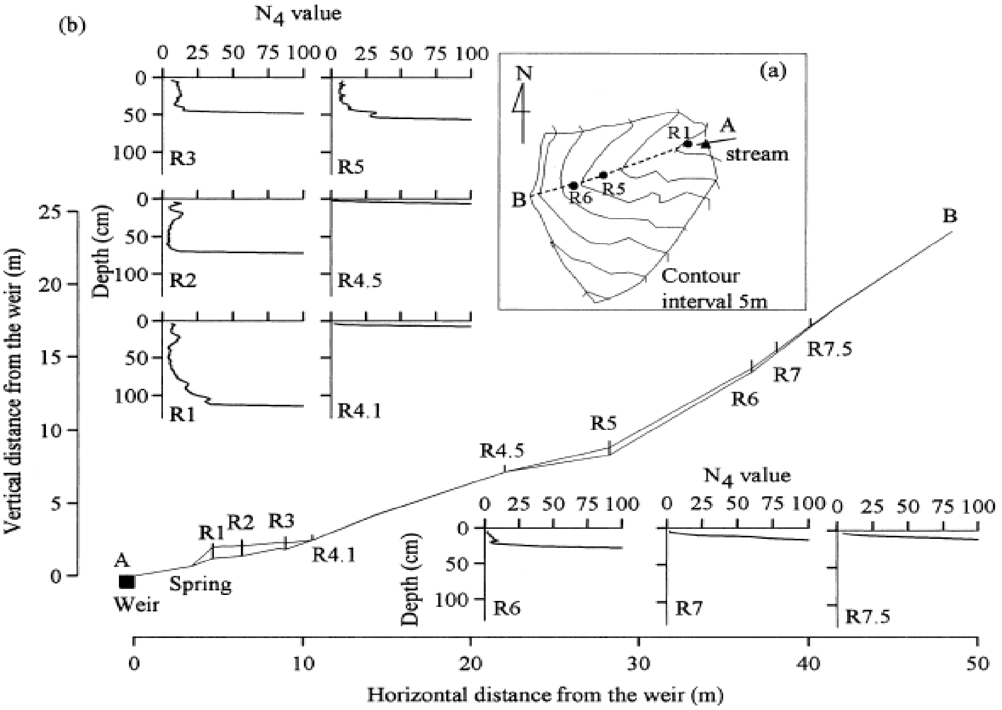


Figure 2.8 Positions of sampling points and depth of profiles for Rachidani catchment (Asano *et al*., 2002).

The N_4 values presented in Figure 2.7 & 2.8 is the number of blows required with cone penetrometer to penetrate 4 cm. It is an indicator of the degree of saprolite weathering.

At F1 and R1 saturated groundwater levels occurred even during baseflow. The groundwater levels remained constant even during the driest periods. Although the water levels at R1 remained constant, there was a decrease in the soil moisture content in the upper slopes during the drier periods. These results indicate that the soil water was constantly recharged even in the driest season. The amount of recharge was greater and more steady in the Fudoji catchment with deeper soils.

Saturated overland flow was generated at the upslope area (R5 & R6) during a storm of 50.1 mm in 100 minutes. In the Fudoji catchment the maximum groundwater levels were higher but the moisture levels didn't raise to the surface due to the thicker soil layer. This indicates that sub surface flow dominate in the Fudoji catchment.

The difference in the preferential flowpaths during rainfall period generated an increase in streamflow of less than one order of magnitude in the Fudoji catchment On the other hand streamflow increased with nearly two orders of magnitude in the Rachidani catchment (Figure 2.9). This illustration of water movement in the two catchments indicates that deeper soils recharge the lower areas more steadily. The volume of streamflow in the Fudoji catchment is not only more constant but also a larger volume in dry periods.

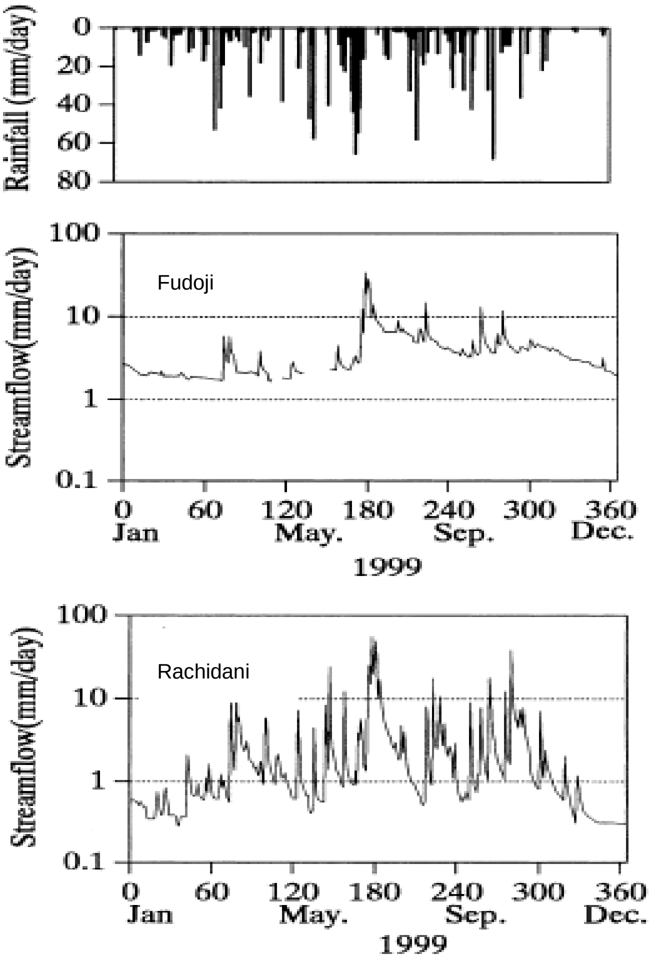
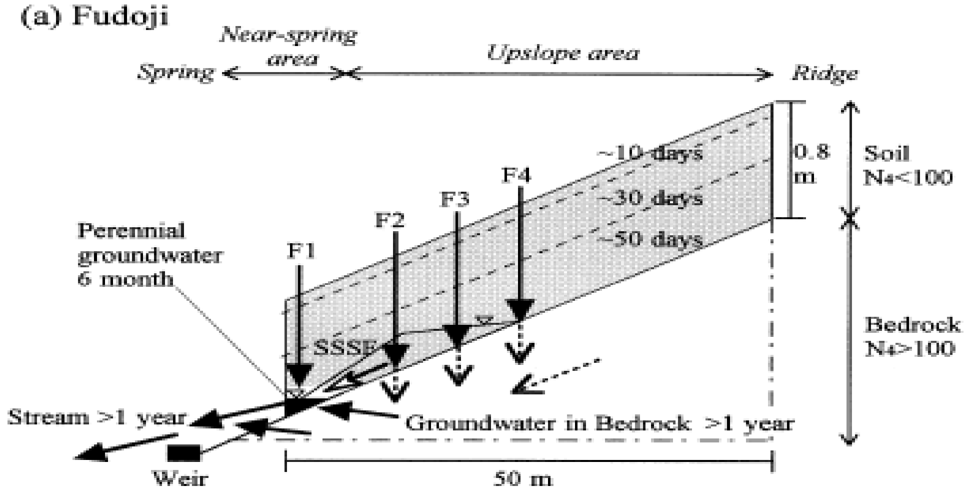


Figure 2.9 Rainfall (same for both catchments) and streamflow for the Fudoji and Rachidani (Asano *et al.*, 2002).

The length of the flowpath has an important effect on the residence time as longer residence times are associated with longer flowpaths (Mcguire *et al.*, 2005). Mcguire *et al.*, (2005) also found that there is an increase in the residence time with a decrease in slope gradient as result of the smaller hydraulic gradient in flatter slopes. The effect of soil depth on the mean residence time is greater than the upslope length (Asano *et al.*, 2002). The mean residence time of the two catchments differs (Figure 2.10).

(a) Fudoji



(b) Rachidani

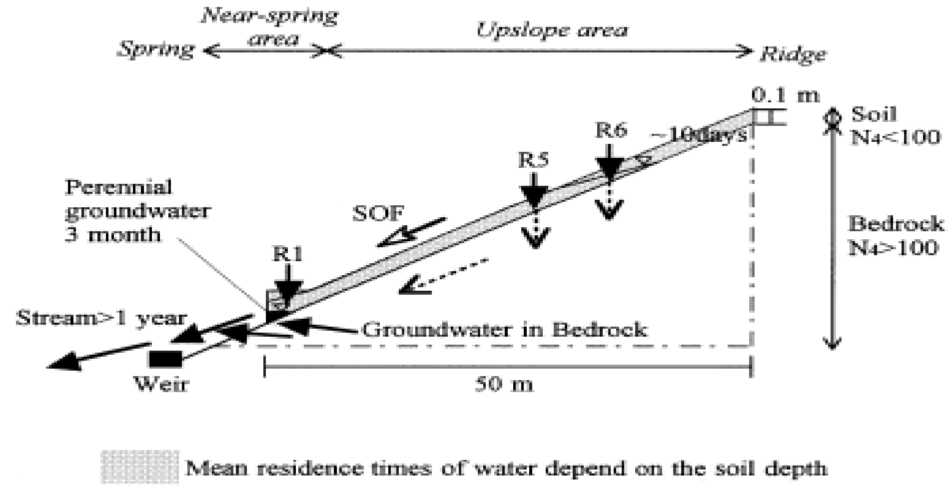


Figure 2.10 A conceptual model illustrating the influence of soil depth on residence time in two catchments in Japan. Saturation Overland Flow (SOF) and Sub Surface Storm Flow (SSSF) are abbreviations used (Asano *et al*., 2002).

In the Rachidani catchment the shallow soil depth causes saturated conditions with relatively little precipitation. Most of the rainfall moves downslope as SOF within a few hours. Some of the water infiltrates and moves through the profile within 10 days. When this water infiltrates into the bedrock it causes a pressure head that pushes the perennial water into the stream.

The thickness of the soil in the Fudoji catchment was the dominant factor for the increase in residence time. It took approximately 50 days for the rainwater to infiltrate to the bottom of the profile. Due to the large storage capacity of the soil, all the water infiltrates in the upper slopes with no SOF. Some of the infiltrated water moves laterally at the soil/bedrock interface. The flow through the bedrock contributed water to streamflow for up to 350 days after the storm event.

2.2.2 Porosity

Porosity is a measure of the total void space in a porous material and is measured, either as a percentage (between 0 and 100%) or as a fraction (between 0 and 1) of the bulk volume. It is defined by the ratio:

$$f = V_v/V_T \quad \text{(2.1)}$$

Where V_V is the volume of the void – space and V_T is the total or the bulk volume of material, including the solid and void components.

In a study by Uchida, McDonnell & Asano (2006), the influence of the drainable porosity on the residence times was investigated. This study was also conducted in Fudoji, Japan but they compared the results with a catchment in New Zealand called Maimai. The slope angle, slope length, soil depth, climate and vegetation of both catchments were very similar. There was however a difference in the drainable porosity. In Fudoji the drainable porosity was between 0.25 and 0.35 and in Maimai between 0.08 and 0.12. Porosity is in general correlated with soil texture. Higher sand fractions usually result in higher drainable porosity. The bedrock in Fudoji was also more permeable than the bedrock in Maimai.

The mean residence time of hillslope discharge were 300% longer in Fudoji than in Maimai while the angle of the baseflow recession curve was smaller. To explain these differences, Uchida *et al.* (2006) made use of a conceptual diagram presenting the storage of hillslope water (Figure 2.11). The storage was divided into three components: baseflow dynamic storage, stormflow storage and residual water storage.
The residual storage is the volume of water stored when flow is at its lowest. Baseflow dynamic storage is the difference between storage at the lowest flow and the shift from stormflow to baseflow. Stormflow dynamic storage is the difference in water content at the transition between stormflow and baseflow and the wettest period of the year.

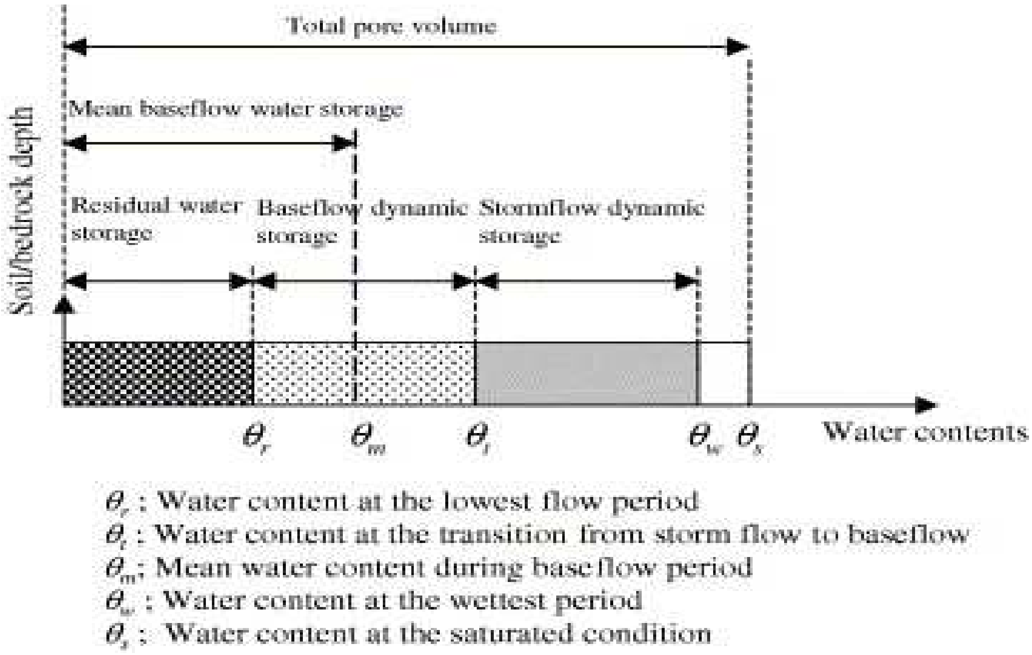


Figure 2.11 Conceptual model of water storage in a hillslope (Uchida *et al.*, 2006).

Two reservoirs namely, the soil and the bedrock, were used to explain the distribution of stored water (Figure 2.12). Although Maimai stored more residual water (due to higher clay content), the amount of stormflow dynamic water stored was greater in Fudoji. Longer and more even flow is expected in Fudoji due to the greater storage capacity (Uchida *et al.,* 2006).

The drainable porosity of the soil did not seem to affect the flow rate for small to medium sized storms (<50 mm). When the water infiltrates the soil it fills the empty pores. The total pore volume (pores not filled with water at the start of the storm) was greater in Fudoji (35%) than in Maimai (10%). It can be expected that saturated excess flow and shallow subsurface lateral flow would first occur in the Maimai catchment. These soil types can also be described as responsive soils associated with an increase in the mean residence time and groundwater recharge (Soulsby *et al.,* 2006). Recharge soils (Fudoji) are better drained with vertical movement of water and mixing with the transient water, increasing the residence time and amount of recharge.

Bedrock pore volume is the first order control for the baseflow hydrograph and mean residence time of baseflow discharge (Uchida *et al.,* 2006).

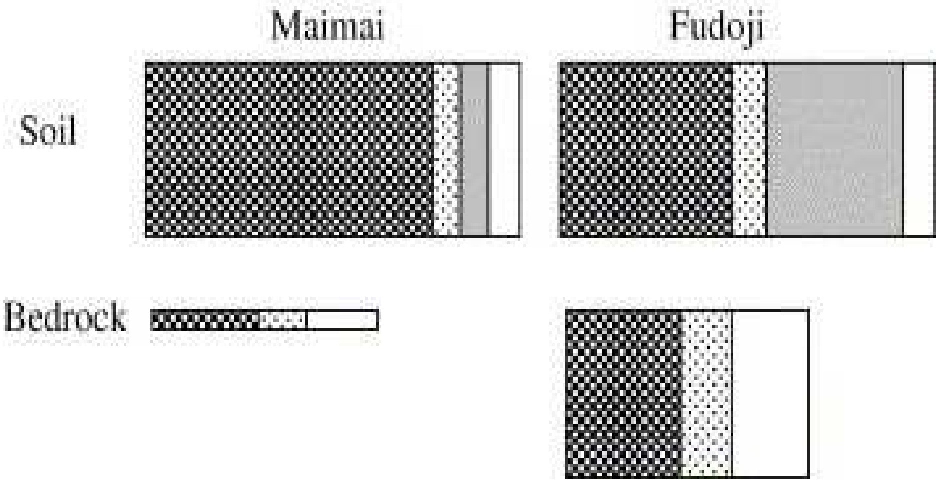


Figure 2.12 Water storage reservoirs illustrating storage dynamics (Uchida *et al.*, 2006).

The mean residence time in Maimai increased in a downslope direction while the residence time in Fudoji increased vertically through the profile. These differences can be ascribed to the restricted permeability of the underlying bedrock of Maimai.

2.2.3 Presence of calcium carbonate ($CaCO_3$)

Calcretes are materials formed by cementation or selective replacement of the soil particles by carbonate. Calcareous layers in soils are controlled by the soil water regime and are typically found in arid to sub-humid regions. Lime precipitates in the soil due to limited leaching which can be brought about by two processes: leaching that can be limited due to low rainfall/high evapotranspiration or restricting subsoil layers and associated saturated conditions (Netterber, 1978 and Driessen & Deckers., 2001).

In sub-humid to arid regions, calcification is one of the main processes in soils with carbonate rich parent materials. Weathering of the parent material results in the formation of soils with calcium as the major cation on the cation exchange complex. $CaCO_3$, the dominant carbonate in these soils, is pedogenically formed as follows:

$$Ca^{2+} + CO_2 + H_2O \rightarrow CaCO_3 + H_2$$

Weathered Ca^{2+} dissolves in water leaches towards lower soil horizons and flows downslope, and filling voids and pores. Plant roots extract water and precipitation in the form of $CaCO_3$ occurs due to the presence of CO_2. The CO_2 are present in the soil as a consequence of diffusion from the atmosphere, but CO_2 generated by oxidation of plant roots enhance this process, especially when the natural vegetation consists of grasses and shrubs. This process is the first stage of the formation of a calcic horizon. (Fanning *et al.,* 1989; Trombotto, 2002 and Shankar & Achyuthan, 2007).

According to Netterberg (1978), the presence of calcretes can serve as indicators of previous (fluctuating) ground water levels as well as of preferred flow paths (faults).

When the parent material contains small amounts of $CaCO_3$ and the amount of $CaCO_3$ in the profile exceeds the amount that could be released by weathering, the presence of $CaCO_3$ in the soil can be ascribed to the second process namely, deposition of $CaCO_3$ rich dust from coastal shelves (Bockheim & Douglass, 2006).

2.2.4 Redox morphology

Redox features in soils involves localities where there are depletion in Fe and Mn concentrations and localities where there are accumulation of Fe and Mn (Soil Survey Staff, 1992). Depletion in Fe and Mn are associated with low chroma values (grey colours) and accumulation of Fe and Mn are associated with high chroma colours (yellow, red and black) in the form of mottles and concretions (Le Roux, 1996).

Micro organisms utilize O_2, NO_3^-, Mn, Fe and SO_4^{2-} as oxidation agents (electron acceptors) in sequence from most likely to least likely to be reduced and organic matter as reduction agent. In saturated conditions, there is no or very little O_2 available to micro organisms and consequently other agents are used for oxidation. In the oxidized state Fe and Mn are insoluble, and in the reduced state, very soluble. Reduced Fe and Mn are removed and redistributed to areas where it is oxidized again (Van Breedeman & Brinkman, 1976). Grey colours occur where Fe and Mn were removed. The silicate, quarts and other soil minerals are grey and therefore the grey colours (Vepraskas & Bouma, 1976). Yellow, red and black colours develop where Fe and Mn accumulate in sequence with an increase in Fe and Mn concentration (Le Roux, 1996).

Redox features are easily observed in plinthic soils (Figure 2.13). Plinthic horizons have an accumulation of iron in the form of oxides and hydroxides and are localized in the form of mottles (with high chroma) and concretions. The simple processes leading to the formation of such a horizon are eluviation (removal of constituents), illuviation (accumulation of eluviated material), oxidation and reduction (Fanning & Fanning, 1989). Fe^{3+} is reduced and together with sesquioxides eluviated from the upper lying horizons and Fe^{2+} oxidized and accumulates in the lower horizon. A fluctuating water level is necessary for this to take place.

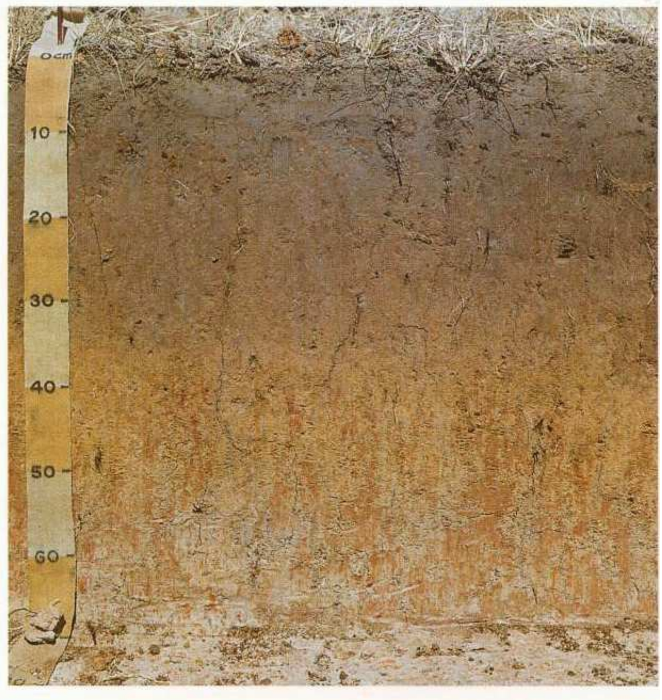


Figure 2.13 Soft plinthic horizon (>35 cm) in a typical Westleigh soil form (Soil Classification Working Group, 1991).

Plinthite normally occurs in highly weathered soils of the regions with rainfall exceeding 500 mm and where a fluctuating water table is active. High temperatures and a high evaporative demand favour plinthite formation since it effects the fluctuation of water levels. The formation of plinthite on different topographical positions corresponds to the climate. In the drier climates plinthite forms in the lower lying areas.

The relationship between wetness and position in the landscape is reflected through the variation in soil colour. In a typical catena the red Fe rich soils are typically found on the higher lying positions of the hillslope (presumable dry), whereas grey gleyed soils can be found in the valleys where it is more wet (Van Huyssteen, 1995).

2.3 Hydrological soil types

Literature distinguishes between three main soil types based on their hydrological response: recharge interflow and responsive soils (Asano *et* al., 2002; Soulsby *et al*., 2006; Vepraskas, Huffman & Kreiser, 2006 and Ticehurst *et al.,* 2007).

Recharge soils is also termed freely drained soils where the dominant flow direction is vertical. Water drains through the soils, out of the reach of ET, into the bedrock. These soils are expected to feed the bedrock flowpath resulting in ‘recharge’ water tables and other soils downslope (if the bedrock flowpath returns to the soil). There is a good correlation between the area covered by these soil types and the mean residence time. These soils are therefore the main contributors to baseflow (Soulsby *et al*., 2006).

Interflow soils are also known as throughflow soils. The dominant flow direction is laterally through the solum (sect. 2.1.1.2). The flow velocities in these soils are determined by soil and topographical characteristics. Interflow soils contribute mainly to the shoulder of the hydrograph (Snyman, 2007).

Rapid response in streamflow after a rain event is expected if the catchment is covered by responsive soils. These soils are either very shallow or very wet (wetland soils). The response in streamflow is the result of the high percentage of overland flow, due to saturation excess water, generated by these soil types (Soulsby *et al.,* 2006 and Ticehurst *et al*., 2007).

These different soil types are closely correlated with their position in the landscape and are influenced by groundwater flow (Figure 2.14).

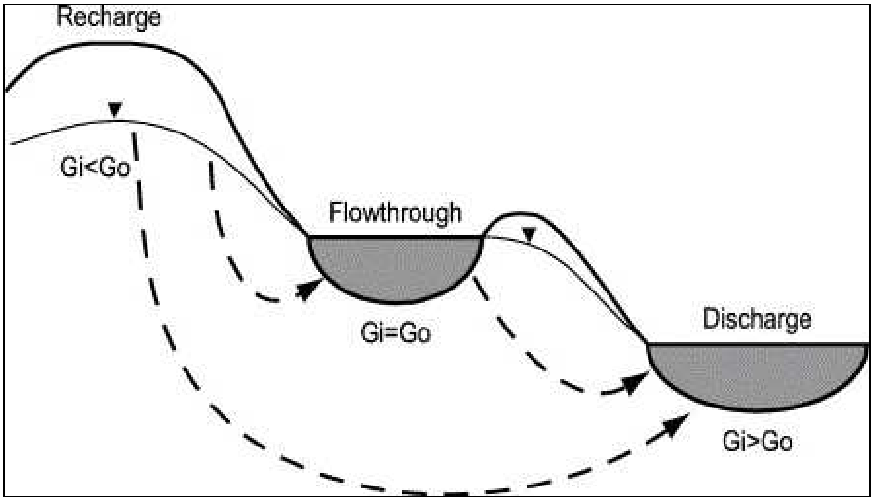


Figure 2.14 Position of different soil types in a typical hillslope and their relationship to groundwater inflow *(Gi)* and outflow *(Go)* (Vepraskas *et al*., 2006).

Soil determines the preferred route/flowpath taken by water after precipitation. This flowpath influence the residence time and the manner in which water is stored in the hillslope. Soil carries signatures unique to the way they are formed. These signatures are both the cause and the result of the interactive relationship between soil and hydrology. To distinguish between different soil types based on their hydrology (recharge, interflow and responsive soils) is one step closer to understanding this interactive and complex relationship.

CHAPTER 3
HYDROLOGY OF SOILS

3.1 Introduction

"Theory development will advance if we can develop simple models (which may be caricatures of the basin system but, nevertheless, contain within them the basic properties of the actual basins), provided, importantly, that they can be falsified with large-scale patterns extracted from the observed data" (Sivapalan, 2003). In order to develop simple conceptual hydropedological models (and to improve our understanding of the role of hydropedology in both the natural environment and agriculture), it is necessary to understand key hydrological processes, the impact of soil on these processes and the influence of these processes on soil formation. Soil is both the cause and the result of an interactive relationship between soil and water. Interpreting soil properties governing and resulting from this relationship can therefore serve as indicators of key hydrological processes.

This relationship between soil and water is however difficult to comprehend at hillslope or catchment scale. For example; Water drains from the soil into the rock and returns to the soil. It may exit the soil again as return flow. Where a water table occurs in the soil it is often uncertain whether the soil is feeding the rock aquifer or vice versa.

This interaction between soil and hydrology can be simplified by studying this interaction at a smaller scale. In this chapter the hillslope is divided into different soil types based on their hydrological behaviour. Although the three soil types discussed in the literature review are used as basis for differentiation (sect. 2.3), a number of new concepts regarding these soil types were developed. This chapter also proposes an improved characterisation of two water storage mechanisms in a hillslope.

3.2 Results and discussion

3.2.1 Hydrology of soil types

Soils can be grouped in three main types based on their hydrological response: recharge soils, interflow soils and responsive soils. Data from the Weatherley catchment (Van Huyssteen *et al*., 2005) was used to distinguish between the soil types.

The degree of water saturation (s) is used to distinguish between the hydrological response of the different soil types. If s is the volume of water relative to the pore volume or porosity (f) (Hillel, 1980), then porosity can be calculated as:

$$f = 1 - \rho_d/\rho_s \quad \text{(3.1)}$$

Where: f = porosity (as fraction)

ρ_d = bulk density (Mg. m^{-3})

ρ_s = particle density (Mg. m^{-3}); (2.56 Mg.m^{-3})

The degree of water saturation can then be calculated as:

$$s = V_w/V_f \quad \text{(3.2)}$$

Where: s = degree of saturation (as fraction)

V_w = water content (mm^3.mm^{-3})

V_f = total pore volume (mm^3.mm^{-3})

Complete saturation ($s = 1$) is seldom reached since air is usually trapped in pores by water (Hillel, 1980).

The term “annual duration of degree of water saturation above 0.7 of porosity” ($AD_{s>0.7}$) is the first approximated threshold value for the onset of reduction (Van Huyssteen *et al.,* 2005). The degree of saturation before the start of reduction will however differ between areas, soil forms horizons since numerous factors influence redox conditions in soils (sect. 2.2.4). $AD_{s>0.7}$ was measured in days per year. The mean value of events where $s>0.7$ was calculated using the duration of such an event over years divided by the frequency of events per year (Van Huyssteen *et al.,* 2005):

$$D_{s>0.7} = AD_{s>0.7}/F_{s>0.7} \quad \text{(5.3)}$$

Where: $D_{s>0.7}$ = mean duration of s>0.7 events (days.event^{-1})

$AD_{s>0.7}$ = duration of s>0.7 (days per year)

$F_{s>0.7}$ = frequency (events.year^{-1})

3.2.1.1 Recharge soils

Several soils in the Weatherley catchment qualify as recharge soils. The best examples are P221 and P240, both Hutton 2100 soil forms (Van Huyssteen *et al.*, 2005). The average annual duration of saturation above 0.7 of porosity ($AD_{s>0.7}$) is not significant (Figure 3.1) as conditions near saturation only occur when drainable water accumulates The data shows that water draining through the soil exits the solum to enter the fractured rock underneath.

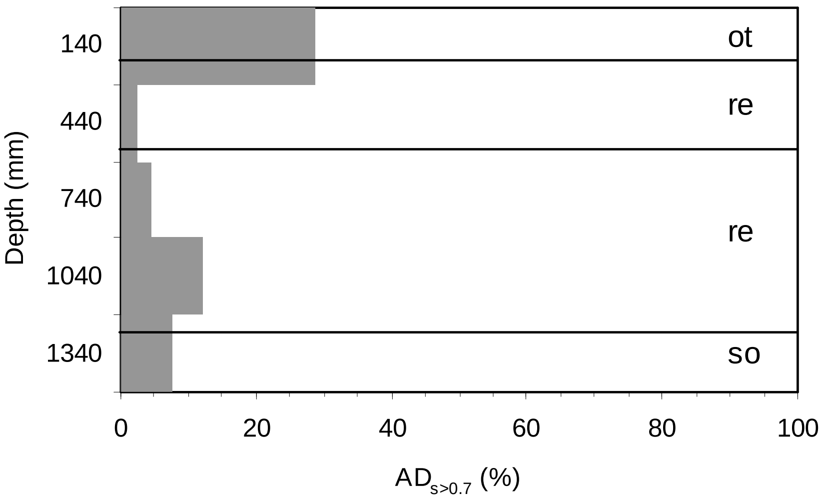


Figure 3.1 Mean $AD_{s>0.7}$ (%) values in a typical recharge soil. P221, Hutton 2100, Weatherley (after Van Huyssteen *et al.*, 2005).

Thus, in recharge soils, the dominant flow direction is vertical. These soils typically occur on the crest positions of a hillslope associated with gentle slopes. Precipitation infiltrates the soil and water flows vertically through the pedon under gravitational forces. The underlying permeable bedrock facilitates infiltration of water. From a hydrological perspective the formation and distribution of recharge soils is therefore dependant on the permeability of the underlying material. Depending on the nature of the underlying material the infiltrated water can either recharge regional water tables, or in the case of aquicludes or aquitards, move laterally. This lateral moving water can then recharge the stream through transient or perennial groundwater. Its contribution to transient groundwater is uncertain. Since these flowpaths through the bedrock are usually the longest, recharge soils are important for generating base flow.

The contribution of recharge soils to catchment hydrology by implication stops when the soil water balance is negative (i.e ET>P). This limits its activity to the wet part of the rain season (Figure 3.2).

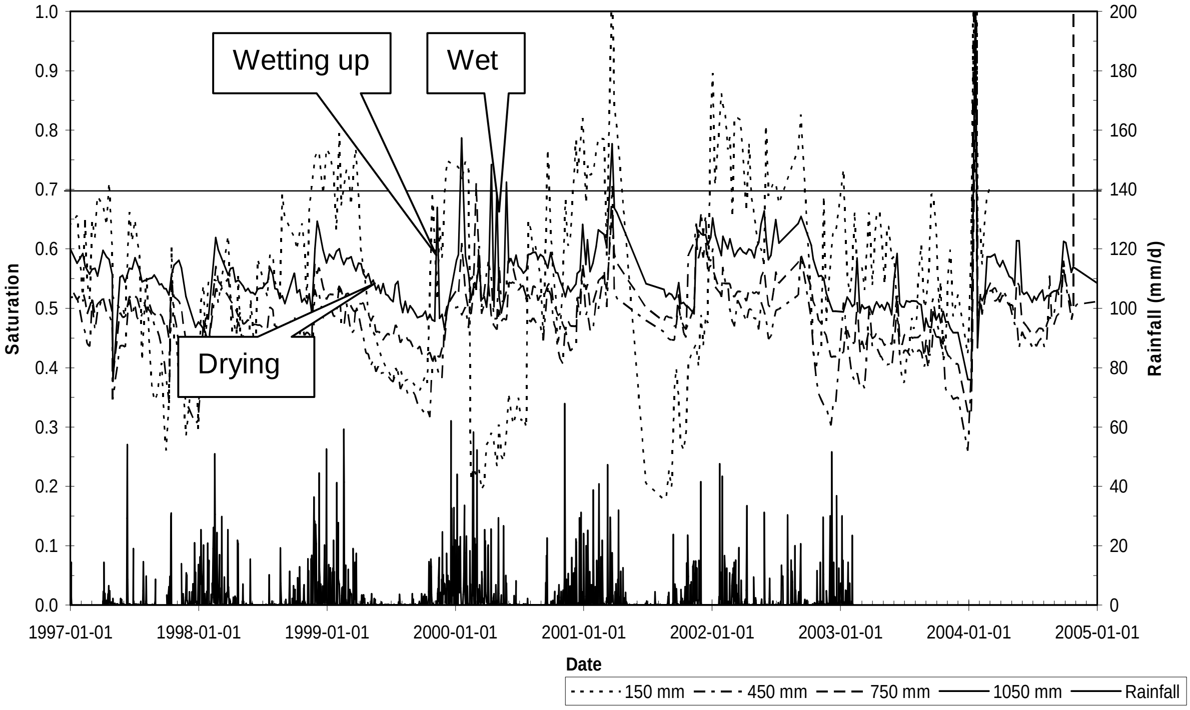


Figure 3.2 Degree of saturation vs. rainfall over 8 years of a recharge soil, P221, in the Weatherley catchment (after Van Huyssteen *et al*., 2005).

Three phases are clearly visible in the graph namely a wetting up cycle with the start of the rain season, a wet phase during the rain season and a drying phase in the waning portion of the rain season. The drying phase is only stopped by the start of the wetting up phase of the following rain season.

The wetting up cycle depends on the precipitation, atmospheric demand (ET) and the size of the reservoir. As the grass vegetation of the Weatherley catchment mainly extracts its water from the upper 900 mm (Zere, 2005) of soil, a relative large volume of soil has to be brought to drained upper limit (DUL) before draining starts. In the majority of years (four out of six) this, cycle is two weeks in duration.

In the wet cycle the water content of the recharge soils depends mainly on the distribution of rainfall events. Profile water exceeding DUL drains beyond reach of the grass roots. This is visible in Weatherley as return flow at the observations P204 and Uc8 as water moving out of the Longlands soils and falling over the cliff.

Some of the soil forms of South Africa which will typically form part of recharge soils are: Hutton, Kranskop, Inanda, Valsrivier, Oakleaf, Griffin, Pinegrove, Namib.

3.2.1.2 Interflow soils

Several soils of the Weatherley catchment qualify as interflow soils for example the soils of observation points P201, P204 and P225. They are all of the Longlands soil form. The ($AD_{s>0.7}$) values in the subsoils is distinctive (Figure 3.3). Conditions of water contents near saturation (drainable water) occur in all horizons but typically increase with depth. The contribution of precipitation draining vertically through the soil after the rain an interflow from higher lying polypedons is unknown. Although increased clay content in the subsoil creates the idea of a restrictive layer, namely aquiclude or aquitard, there may be a saturated zone juxta positional higher lying fractured rock.

Interflow soils are associated with subsurface lateral flowpaths (sect 3.1.1.1). For interflow to occur a layer with lower hydraulic conductivity must be present (clayey B horizon or bedrock with restricted permeability) as well as a slope favouring lateral movement down the slope. Interflow soils are therefore typically found in midslope positions with varying gradients. Water starts moving laterally when infiltrated water encounters a layer with lower hydraulic conductivity (A/B horizon interface; soil – bedrock interface or a saturated layer) or when water, fed from recharge soils, encounters such a layer and may return to the soil.

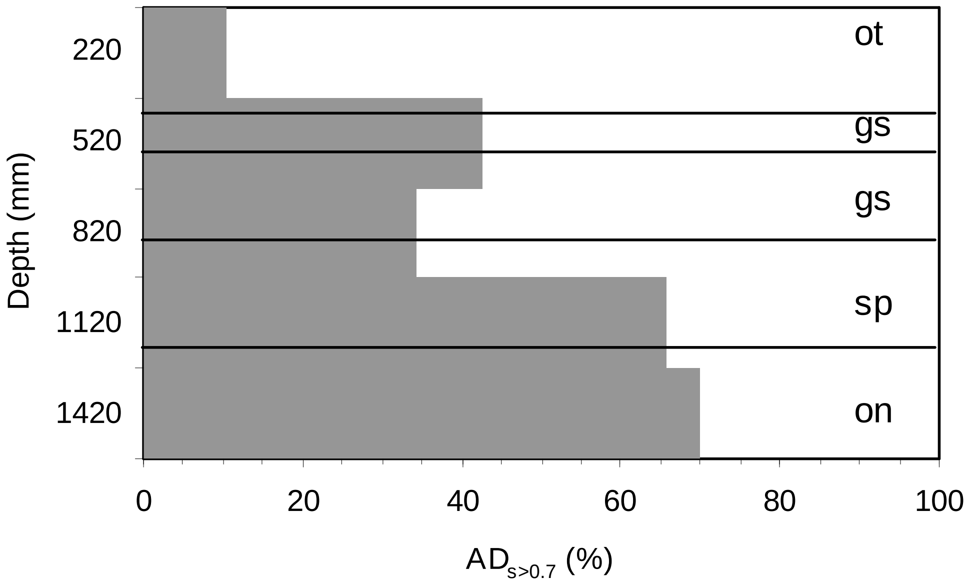


Figure 3.3 Mean $AD_{s>0.7}$ (%) values in a typical interflow soil P225, Longlands 1000, Weatherley (Van Huyssteen *et al.*, 2005).

Interflow soils have a distinctive drainage phase additional to the wetting up, wet and draining phase (Figure 3.4). The duration of ADs>0.7 in the soft plinthic horizon of 8 months (Figure 3.4) is an indication that this soil body is releases water up to the end of August. This implies a 5 month draining phase.

Interflow conditions are favourable for 4 to 8 months in the soft plinthic horizon of Longlands soils of Weatherley. The end August limit of interflow conditions co-indices with the duration of interflow as predicted by the subsoil routine of ACRU (Lorentz *et al.,* 2007b see Figure 6.2).

During the wet phase drainage and ET are sometimes slower than precipitation and interflow resulting in a rise of the transient groundwater into the plinthic, E and A horizons. A fluctuating water table is typical of subsoils with plinthic and E horizons (Soil Classification Working Group, 1991). These fluctuations are event driven and can be related to rainfall events. The catchment must first fill up before transient groundwater can occur.

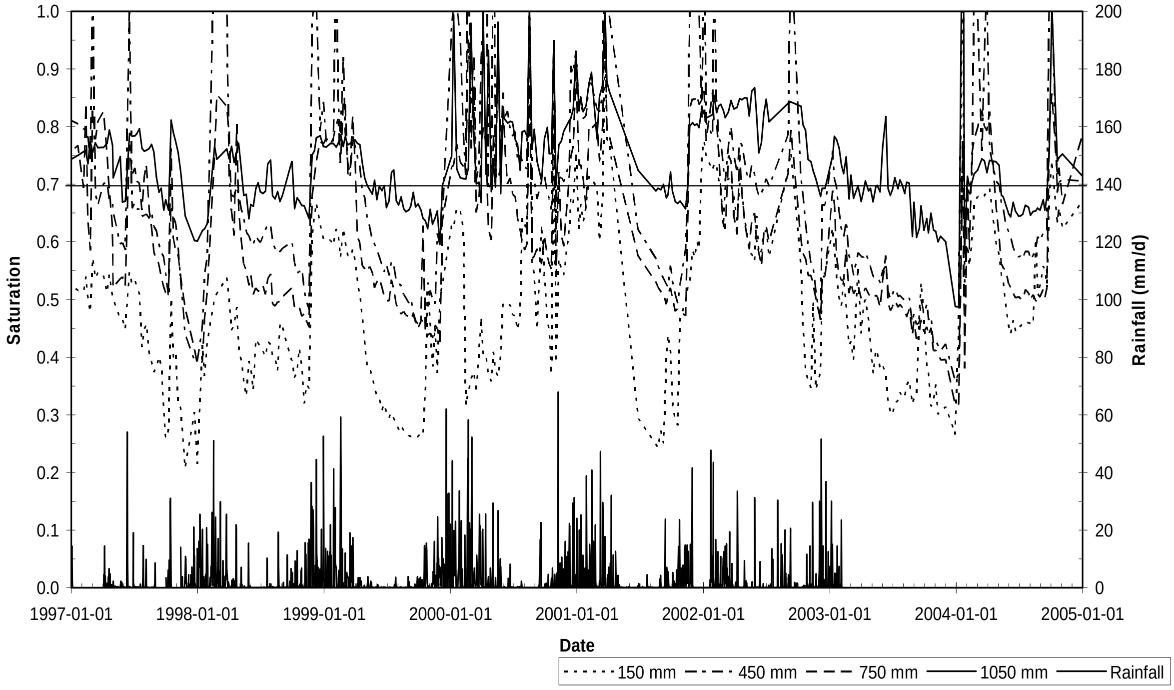


Figure 3.4 Degree of saturation vs. rainfall over 8 years of an interflow soil, P225, in the Weatherley catchment (after Van Huyssteen *et al*., 2005).

Sub soil flowpaths are associated with a residence time shorter than the bedrock flowpaths and longer than overland flow. Interflow soils would therefore contribute mainly to the shoulder of the hydrograph, and to some extent to baseflow.

Some of the soil forms of South Africa typically associated with interflow soil types are: Longlands, Wasbank, Esctcourt, Klapmuts, Cartref, Westleigh, Avalon.

3.2.1.3 Responsive soils

Responsive soils can either be very shallow soils with low infiltration capacity or saturated soils, which prohibit water infiltration. These soils generate overland flow because the precipitation on these soils runs off. The overland flow component contributes to peak flow as the first part of the peak of the hydrograph.

Several soils in the Weatherley catchment qualify as saturation excess responsive soils. These soils normally have perennial groundwater. These soils are at or near saturation for long periods (Figure 3.5), resulting in conditions called saturation excess overland flow in the rain season.

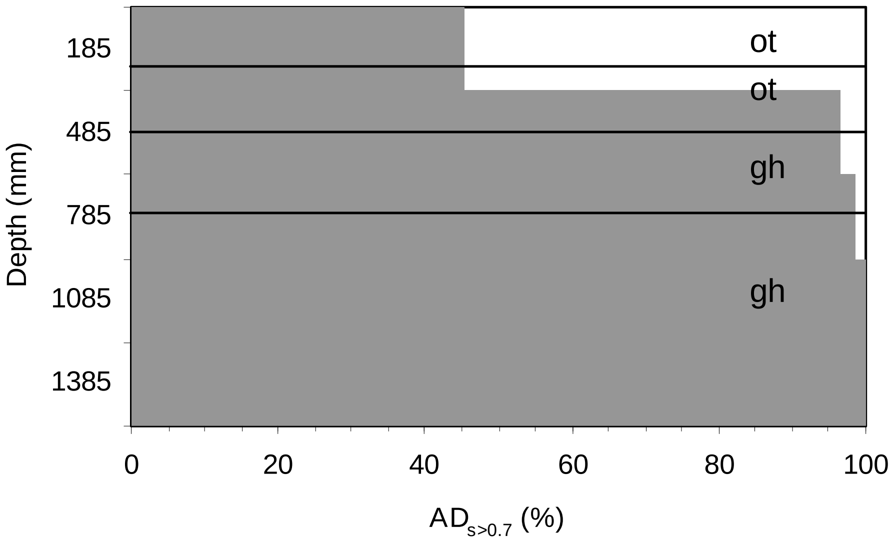


Figure 3.5 Mean $AD_{s>0.7}$ (%) values in a typical responsive soil P235, Katspruit 1000, Weatherley (Van Huyssteen *et al.*, 2005).

Perennial groundwater is present in the G horizon of P235 and keeps the profile saturated for most of the year. The subsoil therefore lacks a wetting and draining phase since it is saturated or close to saturation throughout the year. Only the orthic A horizon loses water to ET during the dry season (Figure 3.6).

In order for these subsoils to remain saturated for such long periods under constant ET demand there needs to be a constant supply of water. It is hypothesized that the recharge soils of the upper slopes supply water to the responsive soils via the bedrock flowpath and to a lesser extent through interflow.

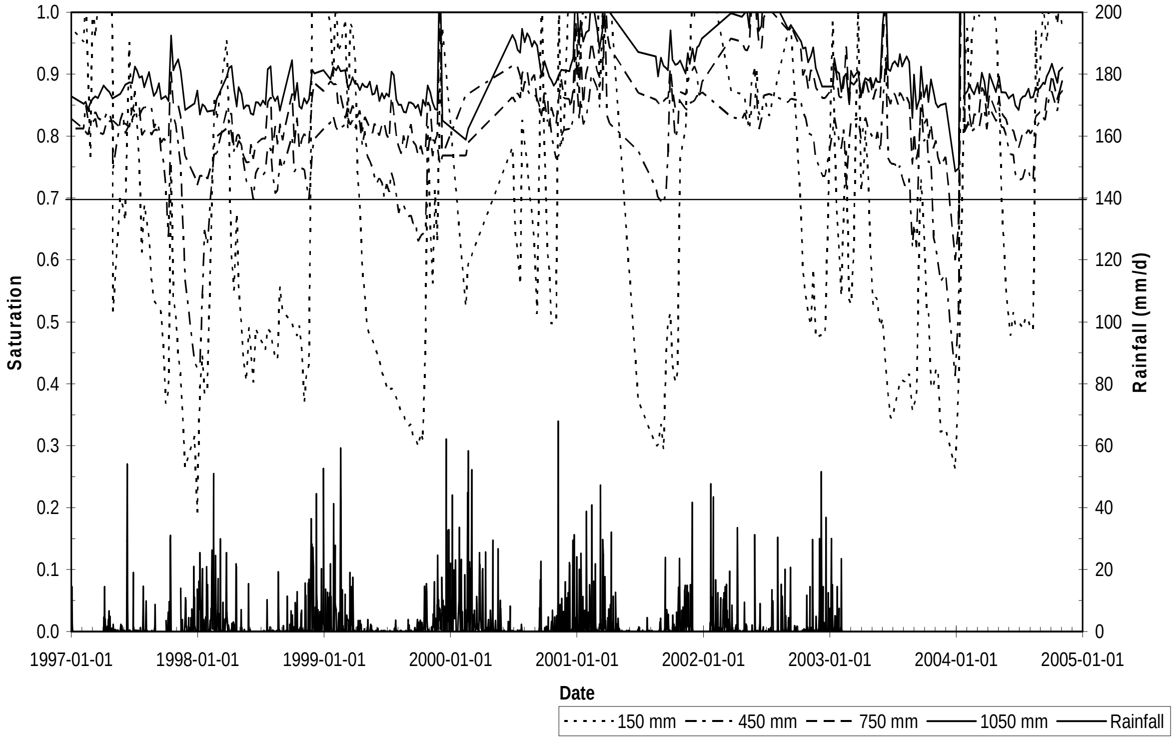


Figure 3.6 Degree of saturation vs. rainfall over 8 years of a responsive soil, P235, in the Weatherley catchment (after Van Huyssteen *et al*., 2005).

Responsive soils classified according to the South African Soil Classification System (Soil Classification Working Group, 1991) can be considered in two categories: 1) Responsive soils as a result of wetness are Katspruit, Rensburg and Willowbrook. While 2) Responsive soils as a result of shallowness are for example Mispah and Milkwood soils.

3.2.1.4 Application of data

The soils of the Weatherley catchment were divided into the different hydrological soil types (Figure 3.7). Hydrologists agree that the division of soils into the different soil types based on their hydrological behaviour can make a valuable contribution to understanding the key hydrological processes in aid of hydrological modelling (Lorentz, personal communication, 2008).

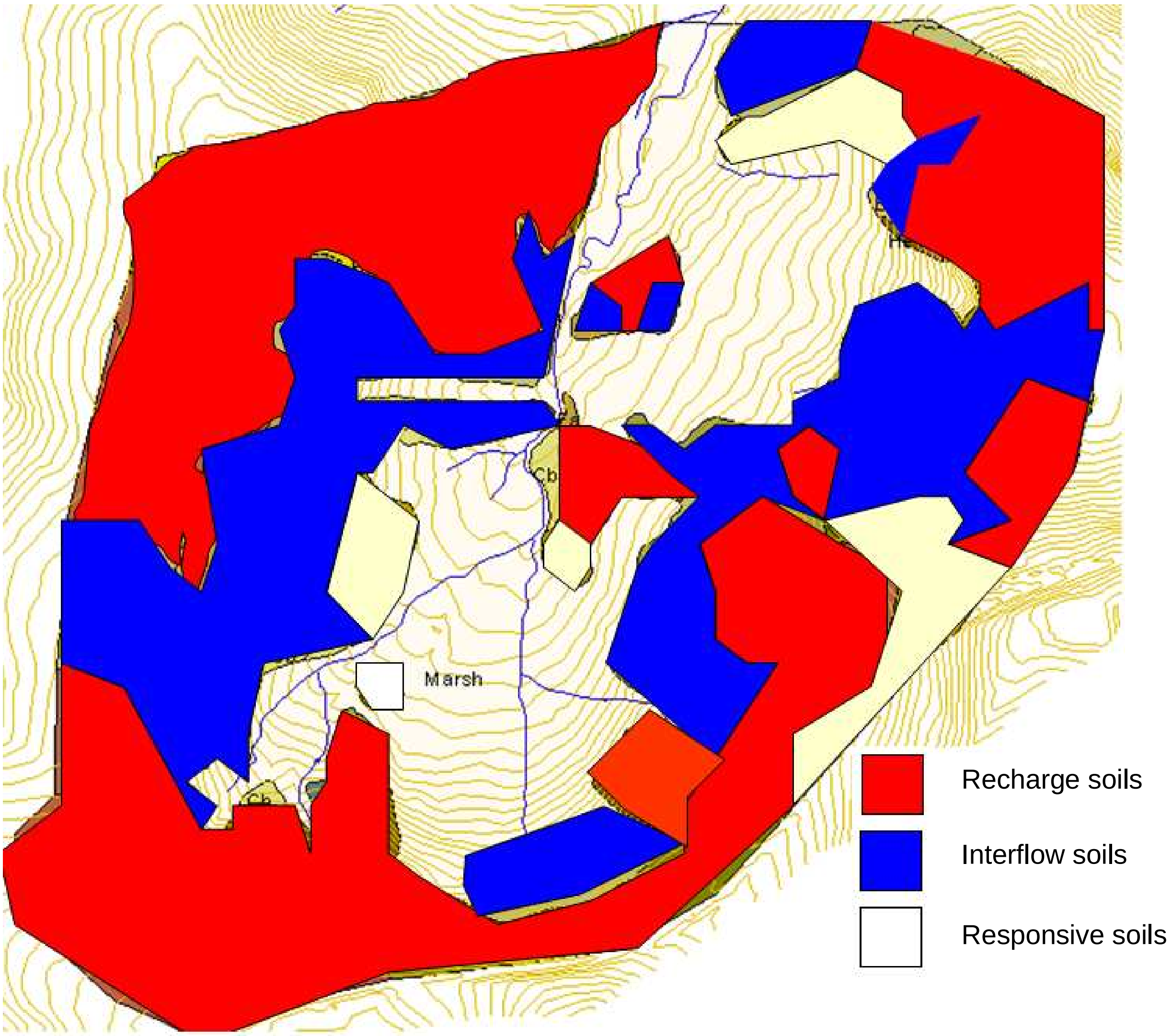


Figure 3.7 Distribution of soil types based on their hydrological response (modified from Roberts *et al*., 1996).

In the Weatherley catchment (Figure 3.7) it is evident that recharge soils predominantly occur on the upperslopes, interflow soils on the midslopes and responsive soils in the valley bottoms. This is also in accordance with the findings of Vepraskas *et al*., 2006 (Figure 2.14).

3.2.2 Water storage

Hillslope water is stored in complicated patterns. Residence time distributions reveal how catchments preserve and release water and solutes, which govern geochemical and biochemical cycling and contamination persistence. Most chemical reactions are time related and longer residence times and subsurface storage of water implies more time for these reactions to occur (McGuire & McDonnel, 2006). Understanding the hydrology of soil types can reveal how groundwater is stored and how this storage mechanisms influence hillslope hydrology.

In a typical hillslope groundwater in the vadose zone can be divided into two types of storage mechanisms: Transient groundwater (TGW) and perennial groundwater (PGW) (sect. 2.1.3.2). Their behaviour is predictable and therefore of value in the description of hillslope behaviour (Table 3.1).

Table 3.1 Differences between transient and perennial groundwater

Transient groundwater	Nature	Perennial groundwater
Occur only in the solum. The position in the solum may change.	**Position**	Occurs under the solum in the rock cracks and may exit into the solum.
It is within reach of evapotranspiration.	**ET**	It is mainly beyond reach of evapotranspiration except for the deep rooting systems of trees and shrubs.
Its water is released to lower lying polypedons (E to E horizon, sp/hp to E horizon, saprolite to E horizon). Large amounts of water are lost to ET. On the transition from the interflow to saturation excess responsive soils the TGW may be perched on PGW.	**Pathway**	Release water to the regional water table and to G horizons and generally wetland soils. Release water to atypical Kroonstad soils with diffuse E/G boundaries.

Transient groundwater	**Nature**	**Perennial groundwater**
It is seasonally event driven. In the arid climates it is absent. In the dry semi-arid areas it occurs only in the peak rain season during the wettest years (about 2 out of 10 years). In the wet semi-arid regions it occurs in the peak rain season and in sub-humid climates it may persist several months after the rain season but not into the next rain season – at least not regularly.	**Periodicity**	It is seasonal to permanent. In the arid climates it is typical around fountains and springs only. In the dry semi-arid climates is may form in the landscape in the rock cracks without affecting the soil in dry years. In most years it makes a contribution to wetlands and keeps G horizons wet for longer than E, sp or other drained horizons.
Occur as a sandy A, B or E horizons in soils of the Katspruit, Cartref, Longlands, Wasbank, Estcourt, Klapmuts, Kroonstad, Westleigh, Bainsvlei, Avalon, Longlands, Dresden and Wasbank forms.	**Soil types**	Occur as the G or uw horizons in soils of Katspruit, Willowbrook, Rensburg, Champagne, Lamotte, Pinedene, Bloemdal, Witfontein, Sepane, Tukulu and Montagu forms.
Flow is by piston action vertical and lateral flow through the sandy layers. Horizons gain water by infiltration as piston and preference flow in cracks (dry soil), biochannels as well as interflow.	**Flow type**	Preference flow is very important both for filling up these reservoirs as for water flow to the regional water table and to lower lying rocks and soils.
Form where vertical permeability is much lower than lateral permeability. The permeability is controlled by increased clay content and higher bulk density. Horizons are sandy with high saturated hydraulic conductivities. Water move by near surface macro pore flow.	**Permeability**	Vertical permeability high in the soil and saprolite. It only reduces in cracks with depth. The water move in cracks deep in the soil

Transient groundwater	**Nature**	**Perennial groundwater**
Quick response to rain events. Primary response.	**Response time**	Respond slower to rain events. Secondary response.
Short residence time (one week to 6 months)	**Residence time**	Have longer residence times (6 months plus).
Little, if any contribution is made to the PGW and no direct contribution to the regional water table are expected. Leakages to PGW through inter - and intrapedal pores visible as sillans.	**Interaction with other water tables**	Feed the regional water table and increased rain events results in “overflow” to exit faster into the low lying soils.
Receive water from recharge and other interflow soils. (Swartland saprolite with signs of wetness to lower lying Estcourt E horizon.)	**Source**	Receive water from recharge soils and to a lesser extend from TGW of interflow soils.
Extreme redox conditions due to organic matter availability and soil surface oxygen supply.	**Redox conditions**	Less variation in redox conditions and less reduced than expected from the long duration of saturation probably due to low organic matter supply.
Respond like a permeable medium on an aquitard. The water level fluctuates and disappears soon after events. Wetness of overlying horizons is in relation and affected by rain events but to a lesser extend.	**Response type**	Respond like a big bucket with steady state conditions and barely changes with rain events and wetter and drier seasons.
Water can perch in the subsoil of red and yellow-brown apedal B horizons of recharge soils without showing signs of wetness. The soils are receiving oxygenated water that moves through the soil and moves down slope on impermeable layers before reduction starts.	**Not to be confused!**	Water probably arrives in soils in a reduced condition and impact on soil morphology as such. It must be kept in mind when compared to lower lying interflow and recharge soils.

CHAPTER 4

THE WEATHERLEY CATCHMENT

4.1 Study area and methodology

4.1.1 Catchment description

The Weatherley research catchment is situated on the footslopes of the Drakensberg mountain range in the north-eastern part of the Eastern Cape, 4 km south-west of Maclear. The catchment covers approximately 160 ha. The catchment is one of many small tributaries of the Mooi River (Figure 4.1).

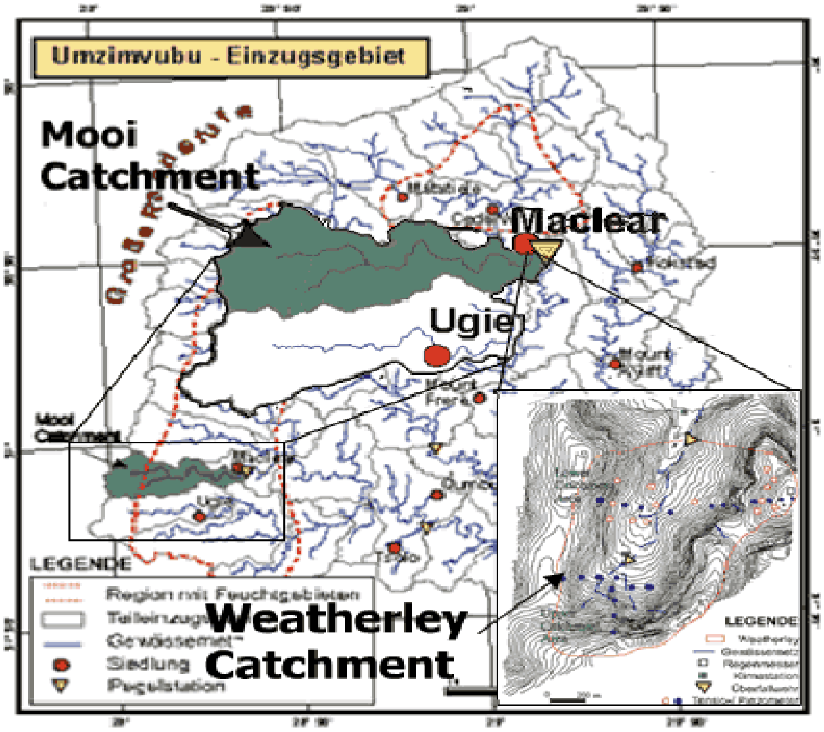


Figure 4.1 Location of the Weatherley catchment.

The highest point in the catchment is in the south western corner at 1352 m above mean sea level. Prominent rock shelves are present at approximately 1320 m above mean sea level. The catchment drains to a north-easterly direction.

The geology consists of sandstone and mudstone of the Elliot Formation above 1300 m above mean sea level (Figure 4.2). Below 1300 m above mean sea level, sandstone and mudstone of the Molteno Formation predominates. Two dolerite dykes with a north-south strike exists in the catchment.

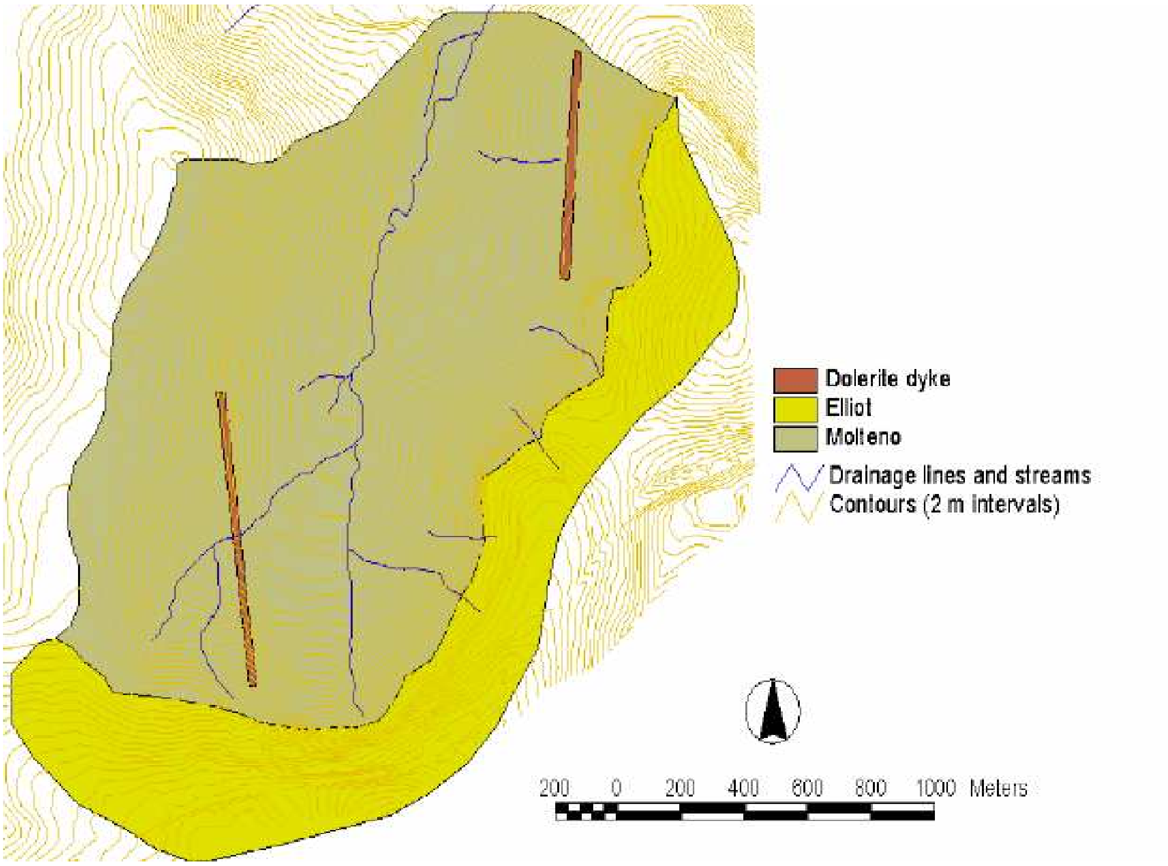


Figure 4.2 Geology of the Weatherley catchment (De Decker, 1981).

The catchment has a relative high rainfall with a Mean Annual Precipitation (MAP) of approximately 1000 mm. year^{-1} (Van Huyssteen *et al*., 2005). The Mean Annual A-pan Evaporation (MAE) is 1488 mm (BEEH, 2003). The winters are cold, with mean minimum temperatures of 4 °C. Frost and snowfall is common, particularly in the higher lying areas. The summers are hot with a mean maximum temperature of 25 °C. (Roberts *et al.,* 1996).

The land cover consists of Highland Sourveld grasslands with a basal cover of 50-75% on the hillslopes. *Eucalyptus nitens, Pinus elliottii* and *Pinus patula* trees were planted on selected areas during 2002 (Figure 4.3). Wetland conditions exist throughout the catchment along the stream with a width of 100 to 400 m. The widest areas of this wetland are associated with seepage lines from contributing hillslopes (Lorentz *et al.,* 2007a).

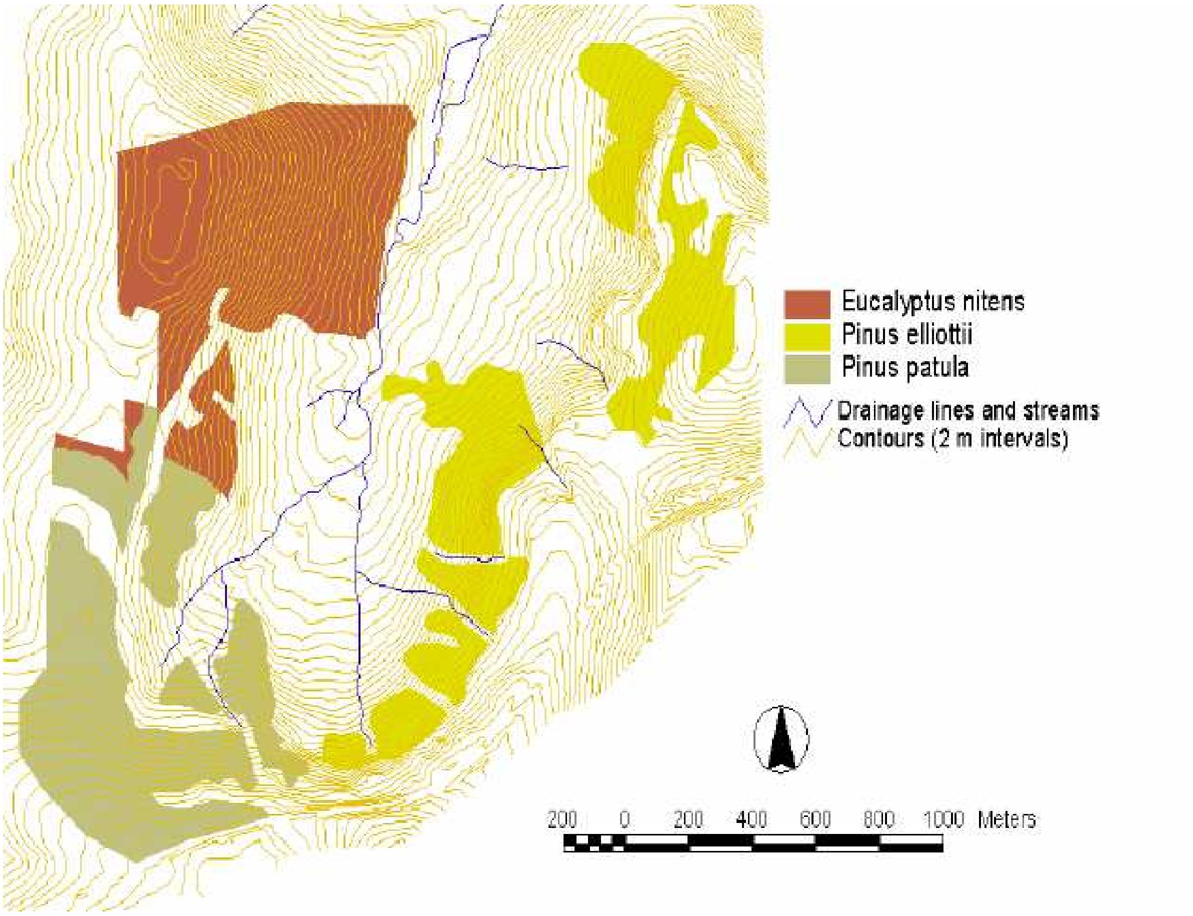


Figure 4.3 Plantations in the Weatherley catchment (BEEH, 2003).

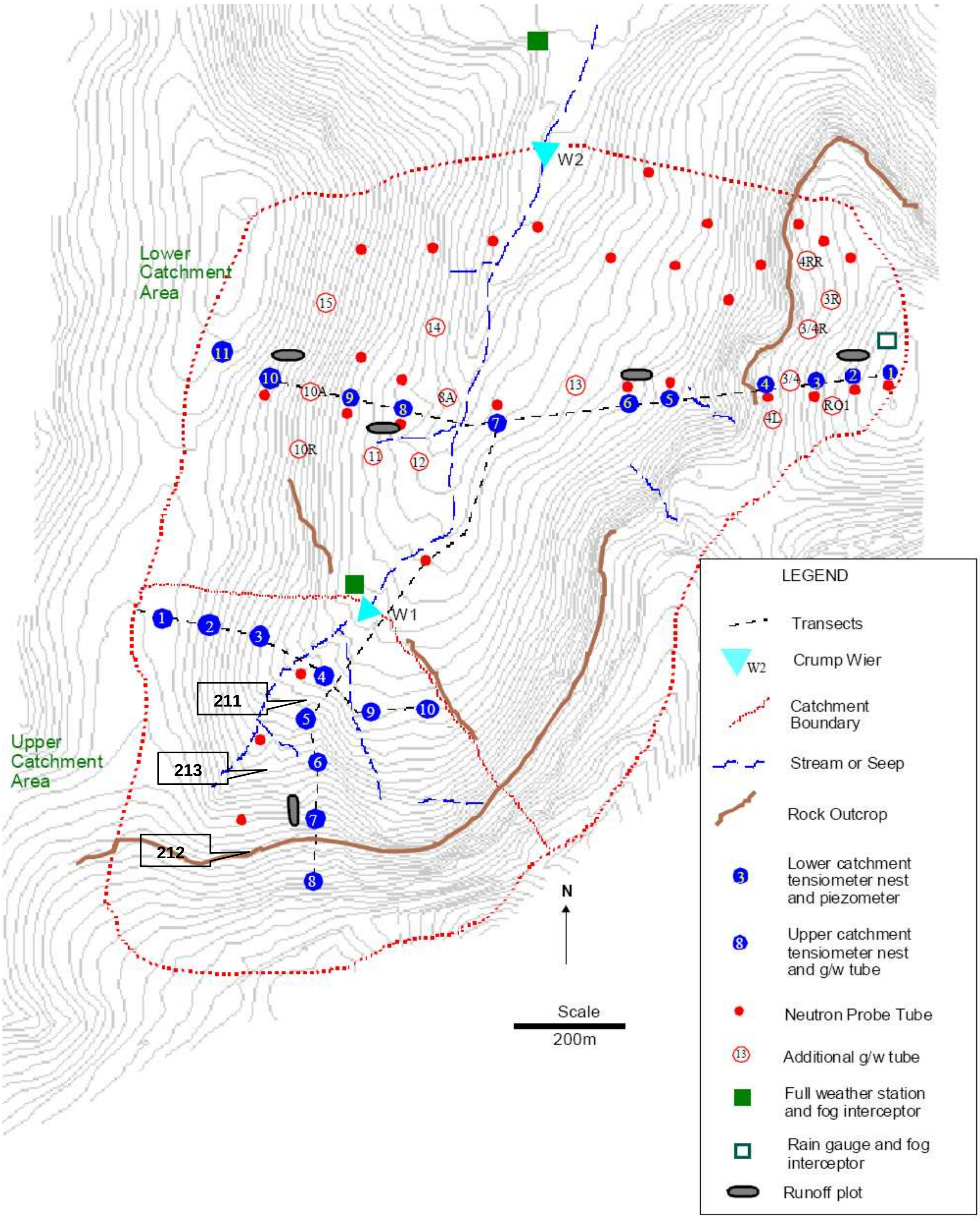


Figure 4.4 The Weatherley catchment and experimental network (Lorentz *et al.,* 2004). The study area was the upper catchment (Uc) demarcated on the diagram. Hydrograph data was collected at crump weir W1.

4.1.2 Soil information

Soil data from the soil survey (Roberts *et al.,* 1996), profile descriptions (Van Huyssteen *et al.,* 2005) as well as auger observations were used for this study. There is a large variety of soils present in the catchment, ranging from very wet (Katspruit soil form) to freely drained (Hutton soil form).

A hillslope in the upper catchment (Uc) was selected for the development of a conceptual hillslope response model (Figure 4.6). The upper catchment was used due to its smaller size (30 ha) and the relative simple soil pattern compared to the whole catchment and stream hydrograph and other hydrological data was also available. Hydrographical data was collected at the crump weir marked W1 in Figure 4.4. Seven profiles, 8 observations, five tensiometer nests (Uc4 – Uc8), as well as three neutron meter access tubes were included in the selected hillslope. The areas, depths (calculated from average depths of 29 profiles) and volumes of specific horizons were used to estimate streamflow generation in the Uc and are presented in Table 4.1. The area covered by different hydrological soil types (Chapter 3) is presented in Table 4.2.

4.1.2.1 Soil map

The pedosequence of the selected hillslope, based on the soil distribution map and observations, include the following soil forms in sequence from the upper slopes to the stream (Figure 4.5):

- Hutton 2100
- Longlands 1000
- Cartref 1121
- Glenrosa 2121
- Oakleaf 2120
- Tukulu 1110 (P212)
- Kroonstad 1000
- Katspruit 1000 (P211 & P213)

This pedosequence of the selected hillslope is improved by adding all available soil information (Figure 4.6).

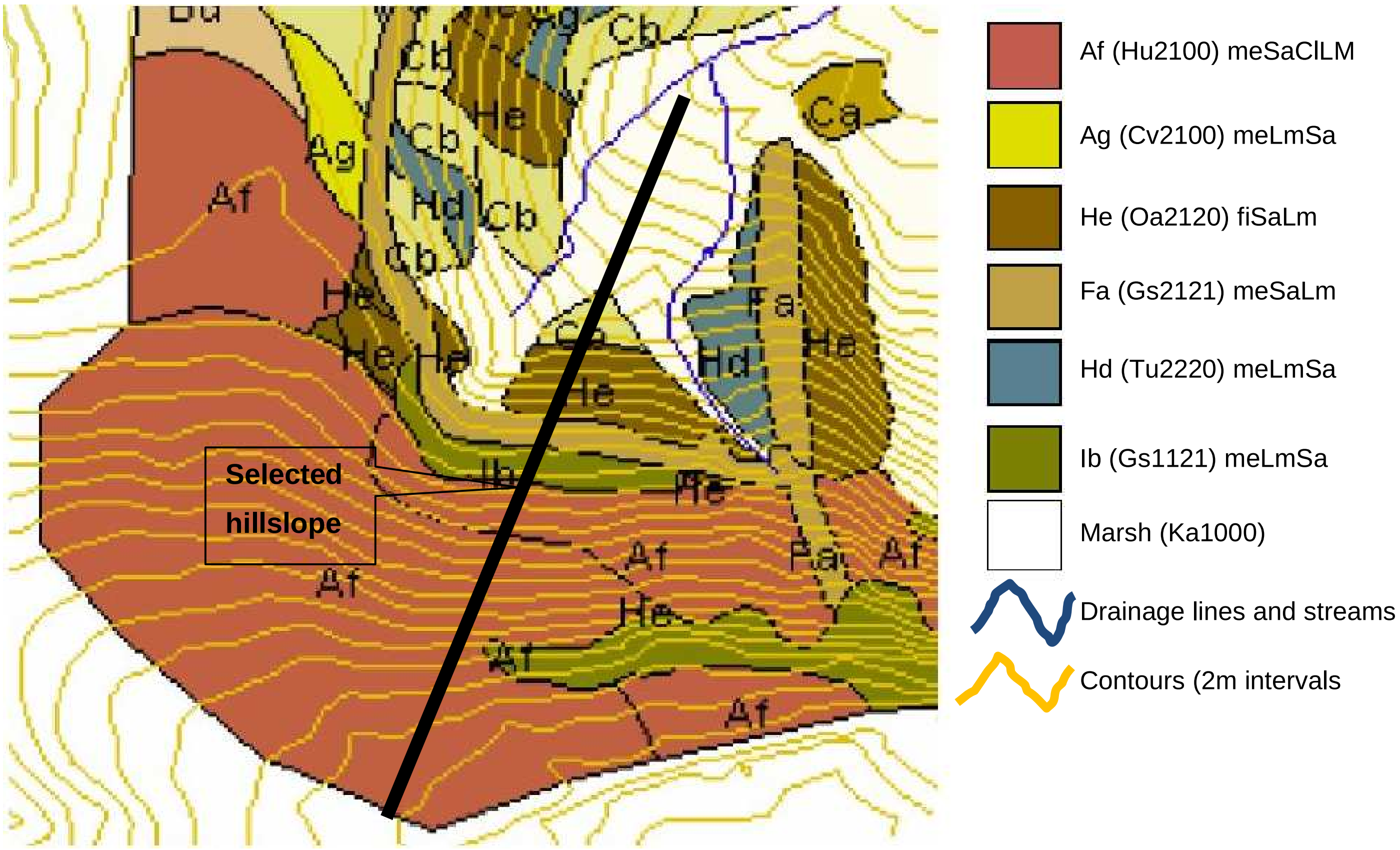


Figure 4.5 Soil distribution map of the Uc of the Weatherley catchment (Modified from Roberts *et al*., 1996). The selected hillslope is indicated by the black line.

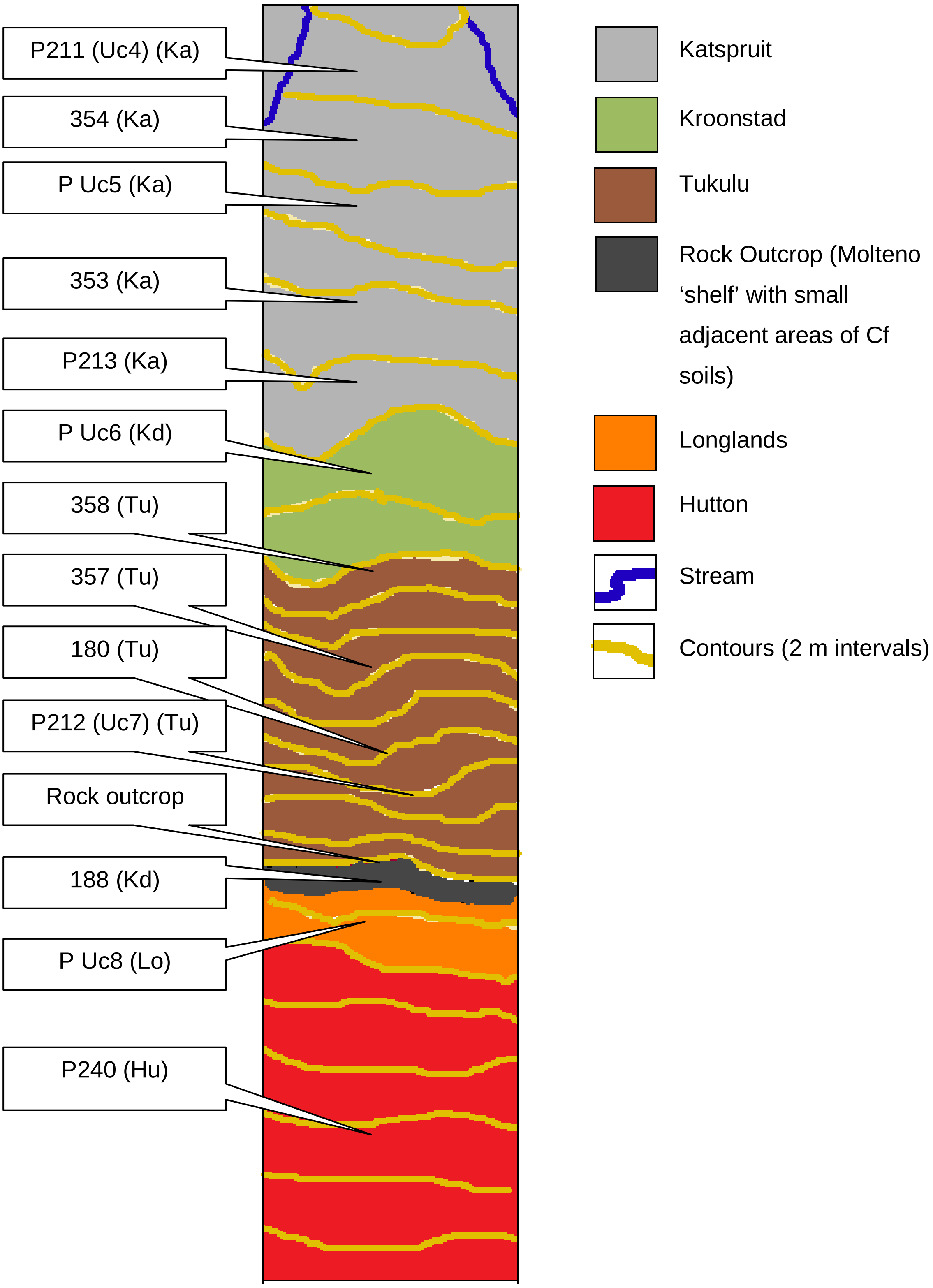


Figure 4.6 Detailed soil distribution of the Uc, with the selected hillslopes (modified from Roberts *et al.*, 1996) together with all additional observations.

Table 4.1 Areas, average depths (calculated from all obseravtions) and volumes of horizons in the Uc

Horizon	Average depth (m)	% of Uc covered	Volume (m^3)
ot	0.35	100	106246
re	0.67	44.8	91117
sp	0.31	2.1	1976
ye	0.43	7.5	9790
on	0.62	14.6	27478
ne	0.71	13.2	28450
gs	0.4	23.1	28049
gh	0.71	24.6	53020

Table 4.2 Area covered by different soil types based on their hydrological response character

Soil type	Area (m^2)
Interflow soils	79860
Recharge soils	149070
Responsive not adjacent to stream	24630
Responsive adjacent to stream*	50000
Total area of Uc	**303560**

*Area which presumably contributes to peak flow.

4.1.2.2 Soil profiles

P211 (Katspruit 1000)

The profile is situated above the dolerite dyke in the Molteno sandstone parent material. It is located on the upper footslope position with a slope of approximately 5%. The orthic A horizon is 150 mm deep, with a G horizon up to 1200 mm deep. The clay content in this profile is relatively high and ranges from 32% in the A horizon to 38% in the G horizon. The profile is situated at tensiometer nest Uc4. A detailed profile description analytical data and a photo are presented in Appendix 3, Tables 1 & 2, and Figure 1 (taken from Van Huyssteen *et al.,* 2005).

P212 (Tukulu 1110)

The orthic A horizon (0 – 300 mm) with a clay content of 10% overlies a yellowish brown neocutanic B1 (300 – 570 mm) with 12% clay on a brown neocutanic B2 horizon (570 – 1300 mm) with 18% clay on unspecified material with signs of wetness (1300 – 1500 mm) with a clay content of 17%. P212 is situated on a slope of 13% on the upper midslope just below the Molteno sandstone shelf which provides the parent material for this soil. This profile is next to tensiometer nest Uc7. A detailed profile description, analytical data and a photo are presented in Appendix 3, Figure 2 and Tables 3 &4 (taken from Van Huyssteen *et al.,* 2005).

P213 (Katspruit 1000)

The profile is situated in the upper midslope with a slope of 6%, on the Molteno sandstone. Both the orthic A horizon (0 – 500 mm) and the G2 horizon (810 – 1500 mm) have a clay content of 27%. The G1 horizon (500 – 810 mm) has a clay content of 30%. A photo, detailed profile description and analytical data are presented in Appendix 3, Figure 3 and Tables 5 & 6 (taken from Van Huyssteen *et al.,* 2005).

P240 (Hutton 2100)

P240 is situated in the upper midslope position with a slope of 10%. This profile consists of an orthic A horizon (0 – 380 mm) on three red apedal B horizons 380 – 800 mm; 800 – 1300 mm and 1300 – 1500 mm respectively. A profile description of P240 is presented in Appendix 3, Table 7 (Le Roux *et al.,* 2005*)*.

P-Uc5 (Katspruit 1000)

This soil is situated in the upper footslope next to tensiometer nest Uc5. The slope is 5%. The clay content increases sharply from A to G horizon. The orthic A horizon (0 – 400 mm) has a clay content of 15% and the G1 (400 – 900 mm) and G2 (1200 mm +) horizons have a clay content of 50%, (Appendix 3, Table 8).

P-Uc6 (Kroonstad 1000)

This soil is situated on the break of the slope between upper slope and footslope. The orthic A horizon (0 – 300 mm) with a clay content of 30% is followed by an E horizon (300 – 500 mm) with clay content of 30%. The G horizon (500 mm +) has a clay content of 60%. P-Uc6 is situated close to tensiometer nest Uc6, (Appendix 3, Table 9).

P-Uc8 (Longlands 1000)

This soil is situated just above the rock outcrop (Molteno shelf) close to tensiometer nest Uc8. The orthic A horizon (0 – 300 mm) has a clay content of 12% and the E horizon (300 – 700 mm) has a clay content of 25%. The shallow soft plinthic B horizon (700 – 900 mm) also has a clay content of 25%, (Appendix 3, Table 10).

4.1.2.3 Soil auger observations

The selected hillslope includes 8 observation points. These observations are presented in Table 4.3 (Roberts *et al.,* 1996). The observation points are not in the same order as their numbering and their position in the hillslope are presented in the conceptual model (Figure 4.7).

Table 4.3 Description of observations in the selected hillslope (Roberts *et al*., 1996)

OBS NUM	SOIL FORM/FAM	HORIZON	DEPTH (mm)	CLAY (%)	MUNSELL COLOUR
180	Tu2210	A1	400	15	10YR3/4
		B1	900	15	5YR5/6
		C1	1500	20	
188	Kd2000	A1	200	20	
		E1	600	16	
		B1	90	30	
353	Ka1000	A1	300	10	10YR4/2
		G1	500	40	10YR5/3
354	Ka1000	A1	350	25	2.5YR4/2
		G1	1500	45	2.5YR6/0

Table 4.3 continued

357	Tu2110	A1	400	8	10YR4/1
		B1	900	10	10YR5/2
		C1	1510	10	10YR5/3
358	Tu2220	A1	550	18	10YR4/3
		B1	1450	25	7.5YR4/4
		C1	1510	30	5YR4/4
359	Ka1000	A1	400	15	10YR3/3
		G1	1000	30	10YR5/3
360	Ka1000	A1	400	15	10YR3/3
		G1	1000	30	10YR5/3

Results and discussion

4.2.1 Conceptual model

Soil morphology (Appendix 3) and distribution patterns the hydrotoposequence (Figure 4.6) were used to develop a conceptual model of the dominant hillslope hydrological response of the upper catchment (Figure 4.7). The selected hillslope includes profiles 211 – 213, observation points 180, 188, 353, 354, 357 – 360 and tensiometer nests Uc4 – Uc8 (Figure 4.4) since there was tensiometer nest in this hydrotoposequence from which to obtain soil water content information, Uc 1 situated on the east facing slope of the catchment (Figure 4.4) was also used for this purpose (Figure 4.6 and Table 4.3).

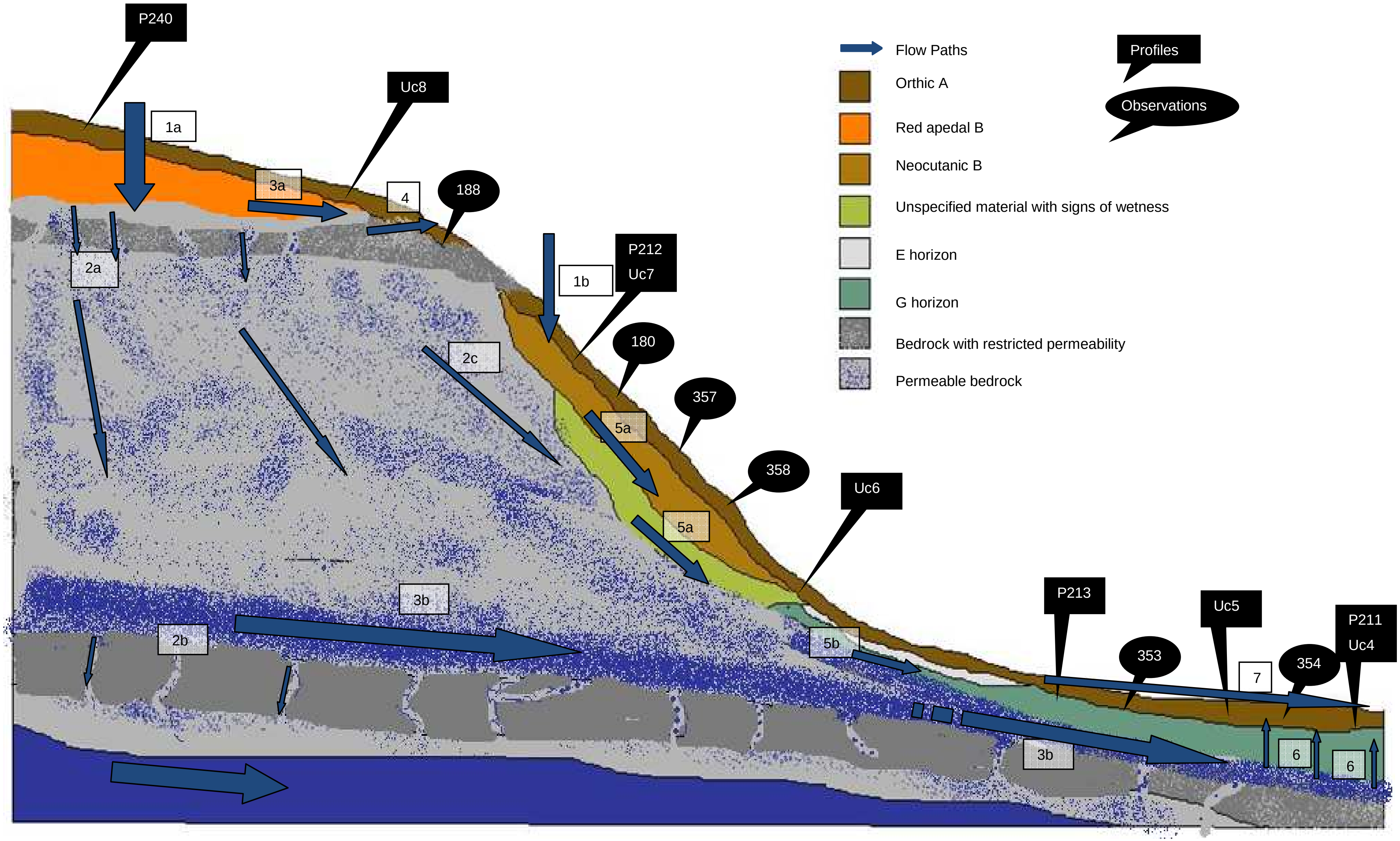


Figure 4.7 Conceptual hydrological behaviour of a hillslope in the Uc of the Weatherley catchment. Additional detail is given in Figures 4.5 and 4.6)

The dominant processes (flowpaths and storage mechanisms) are indicated by numbered arrows in Figure 4.7 (AN, for example AN-1a refers to arrow number 1a in Figure 4.7). A discussion of these processes follows in what can be considered as a hydropedological hypothesis:

1. Infiltration dominates in the upper regions of this hillslope (AN-1a). Gentle slopes as well as dense vegetation growth facilitate the infiltration process and impede overland flow. The organic C content of P240 was higher (1.42%) than the other profiles on this hillslope. The correlation between soil organic C and vegetative growth implies that the densest vegetation can therefore be expected in this region. Organic C also facilitates micro structure formation which is favourable for infiltration. In the Hu 2100 soil of the upperslope, vertical drainage through the profile is dominant. The texture is non-luvic and the clay content therefore is relatively uniform with depth. No or very little lateral flow occurs at the A/B horizon interface. These are true recharge soils. Only a slight variation in clay content with depth is recorded in the red apedal B horizon reflecting the uniform condition of this profile.
2. No signs of wetness were recorded in P240 up to a depth of 1500 mm indicating that water does not perch within the pedon within this depth. Water draining through P240 either infiltrates the subsurface layers (AN-2a) or flows at the soil/bedrock interface (AN-3a). Water which did infiltrate the subsurface layers can then either flow vertically and recharge regional aquifers (AN-2b) or, when it encounters a layer with restricted permeability (aquitard) it would flow laterally (AN-3b) and recharge perennial groundwater downslope.
3. The presence of interflow soils (Lo 1000, Cf 1100, Gs 1121 and Kd 2000 soil forms) located where the rock bedding plain surfaces near Uc8 is an indication that this layer has restricted permeability and there is flow at the soil/bedrock interface (AN-3a). The greater part of the water draining through the Hu soil forms of the upper slope is therefore expected to flow laterally at the soil/bedrock interface. The 2121 and 1112 families of the Gs soil forms (signs of wetness in the lithocutanic B horizon) is an indication of flow at the soil/bedrock interface. The water responsible for the redoximorphic features in the gs, sp and li horizons must come from the recharge soil forms of the upperslope (AN-1a and AN3a).

4. The sequence of Lo, Cf and then ‘wet’ Gs soil forms is an indication that the laterally moving water comes nearer to the surface as it approaches the Molteno shelf rock outcrop. Return flow to the surface is expected as this infiltrated water flowing at the soil/bedrock interface reaches this position (AN-4). The infiltrated water exceeds the storage capacity of the soil and returns to the surface and contributes to the overland flow component. It is expected that the overland flow will quickly end as this water will tend to infiltrate when it reach the Oa and Tu soil forms below the outcrop (AN-1b).
5. Subsurface lateral flow (AN-5a) in the form of flow at the soil/bedrock interface is indicated by the unspecified material with signs of wetness (on) horizon present in the Tu 1110 soil form of the midslope. This soil body is situated on the Molteno Formation. Groundwater responsible for the redoximorphic features is evidently supplied from the recharge soils (Hu 2100) as return flow from the bedrock (AN-2c). This return flowpath is expected to result in a fairly constant feed of water during the wet seasons to this horizon, reflecting its association with perennial groundwater. Infiltration (AN-1b) of precipitation and return flow (AN-4) at the rock outcrop can also contribute to this groundwater. In this case the presence of the groundwater will be linked to rainfall events as with transient groundwater.
6. The gs horizon in the Kd 1000 form (P Uc6) of the lower slopes is an indication of interflow of transient groundwater dominating at the A/B horizon interface (AN-5b). The grey colour of the E horizon is an indication that this horizon is wetter than the yellowish E horizon of observation 188 (Kd2000). This can be due to the larger contributing area resulting in a greater volume of water and a longer duration of saturation in the Kd 1000 soil forms of the lower part of this hillslope.
7. Gleyed Ka 1000 as well as Kd 1000 profiles cover the entire TMU 4 & 5 positions of this hillslope. The gleyed conditions (eg. P211; Ka1000) are indications that these profiles are saturated for long periods. The clay content of the G horizons (ranging from 30 to 40%), coupled with the relatively high CEC of the soil (± 14 $cmol_c.kg^{-1}$ at P211) indicating a high content of swelling clays, has a low hydraulic conductivity that impedes infiltration. Precipitation does not infiltrate these soils as they are already saturated. The water saturating these lower areas must therefore have another origin. It is believed that there is another layer with restricted permeability present in the hillslope (Figure 4.7). This layer transports water which infiltrated through the recharge soils (Hu 2100) of the upperslope

towards the lower lying areas (AN-3b), resulting in the presence of a perennial aquifer.

8. P211 is wetter for longer periods than P213. Rusty root channels are present in P211 while bleached root channels are predominant in P213. The rusty root channels are an indication that these channels are the first to reach an oxidized state. The matrix remains wet. Bleached root channels are an indication that these channels reach a reduced state before the matrix. The increasing wetness closer to the stream is because there's a greater area contributing water to the lower lying profiles (AN-3b).
9. The orthic A horizon of the Ka 1000 soil forms in the lower slope have Fe and Mn mottling, indicating periodic saturation of water. When these soils are saturated, infiltration into the soil is restricted. Any precipitation will therefore flow as overland flow in this area (AN-7). These soils are therefore called responsive soils.
10. Since the soils in the lower footslope and toeslope positions (Figure 4.7) are saturated most of the time, the dominant flow direction within the pedon is upward (AN-6). Evapotranspiration extracts much more water from the soil than can infiltrate.

4.2.2 Evaluation of the conceptual model

Climate, tensiometer, neutron water meter, evapotranspiration and hydrograph data for the upper catchment were used to evaluate the conceptual model. The data was obtained from BEEH (2003, 2007).

4.2.2.1 Tensiometer data

The tensiometers used in this hillslope are at Uc4 – Uc8. Uc1, located at the east facing hillslope of the Uc. These tensiometers were also used to represent Bd and Hu soil forms of the selected hillslope, since there are no tensiometer measurements representing these soil forms in the selected hillslope.

The tensiometers are situated in the following soils:

- Uc1 – Bd 2100/Hu 2100
- Uc4 – Ka 1000
- Uc5 – Ka 1000
- Uc6 – Kd 1000
- Uc7 – Tu 2220
- Uc8 – Lo 1000

To improve the understanding of the hillslope hydrological behaviour, two types of periods were selected for evaluation. One type was when the catchment was dry after the winter and was wetting up during spring rain. The wetting up periods selected, each following a relatively dry period, were:

1) 01/09/2000 – 30/09/2000
2) 01/09/2004 – 10/10/2004

The second type was during autumn after the summer rains, as the catchment was draining, at the beginning of the dry season. The two periods selected to scrutinize the drying out of the upper catchment were:

3) 10/04/2001 – 22/05/2001
4) 05/04/2002 – 29/04/2002

Tensiometer data are presented in Figures 4.8 to 4.20. The data for different locations during different events is discussed separately and related to the conceptual model in sect. 4.2.1 (Figure 4.7) using the arrow numbers (AN) in the same manner as in the discussion of the conceptual model.

Tensiometer readings are expressed as the matric pressure head (m.p.h) in mm. There are many reasons why tensiometers may sometimes give spurious readings. Because of their remote location at Weatherley it was probably very difficult for the responsible scientist stationed at Pietermaritzburg to maintain them in perfect condition. For this reason all apparently spurious results have been excluded.

Uc1 – Bd 1100 or Hu2100 (period 1)

The orthic A horizon (300 mm) responded, becoming wetter, approximately 3 days after commencement of the series of rain events totalling about 57 mm between 13 and 20

September 2000 (Figure 4.8). This horizon came close to but never reached saturation during this period. The rapid decline in the matric pressure head is an indication that water does infiltrate rather quickly to a depth of 300 mm as predicted in the conceptual model (AN-1a).

The tensiometer reading at a depth of 1000 mm in the re horizon shows a slight reaction to the rainfall events, showing that a small amount of water reached this depth (AN-1a). It is therefore unlikely that these events would have contributed to the processes described by AN-3a and AN-2a. This horizon never reached saturation during this period as is expected in a recharge soil.

The unspecified material with signs of wetness horizon (1900 mm) horizon is saturated for most of the period even after the preceding long dry winter. This saturated state confirms that this horizon overlies a layer with restricted permeability (bedding plain) (Figure 4.7) It might also be an indication of interflow at the soil/bedrock interface (AN-3a). There is clearly some error in readings from this depth from 25th September onwards.

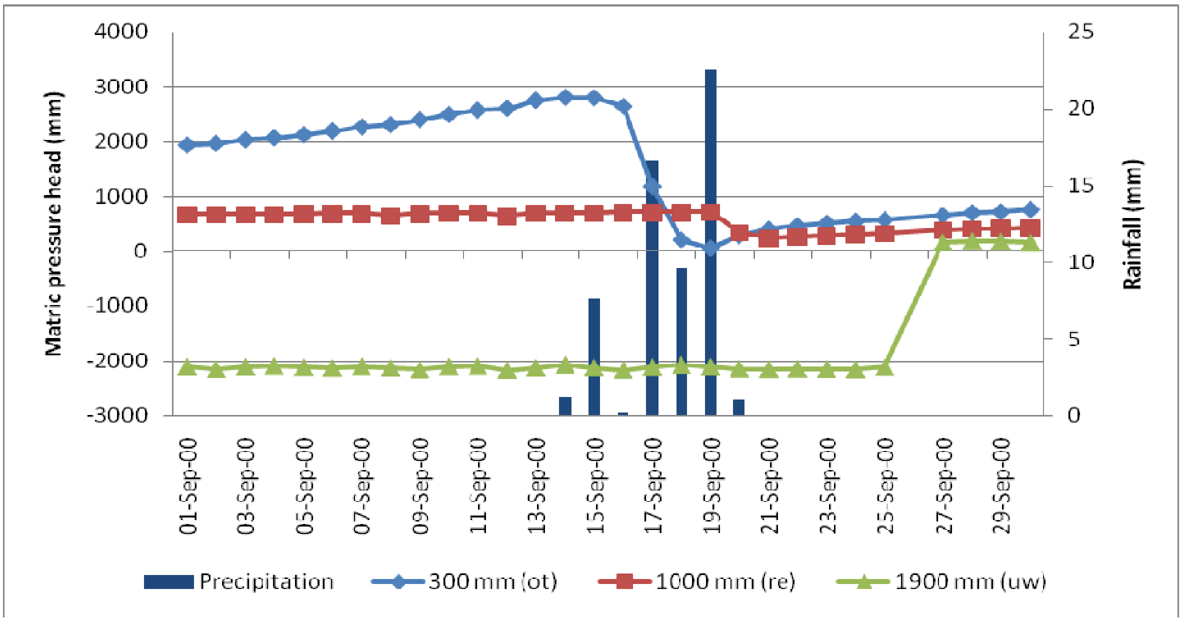


Figure 4.8 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Bd1100 at Uc1 during period 1, describing the response of a recharge soil in the high lying part of the catchment following a dry period.

Uc1 – Bd 1100 or Hu2100 (period 3)

The A horizon during period 3 is only affected by rainfall during the first part of this period (Figure 4.9). It seems that particular events greater than 5 mm affected this horizon on the same day, indicating rapid infiltration (AN-1a). The horizon gradually dries out towards the end of this period, reflecting water extraction through ET by the grass vegetation.

The 1000 mm deep re horizon was only affected by the rain on the 10th of April (>30 mm) and became wetter approximately a day after the particular rain event due to infiltration (AN-1a). It seems that during the smaller rain events, ET extracts the infiltrated water before it reaches this depth. This horizon gradually dried out towards the end of this period, but at a noticeable slower rate, according to the expectation, compared to the A horizon.

During event 3 the uw horizon, at a depth of 1900 mm, was saturated for the entire period but gradually became less saturated presumable due to drainage towards the end (AN-2a) (Figure 4.9). This horizon is only affected by the relative large rain event (33 mm) at the beginning of the event and became wet approximately one day after the rain event due to infiltration (AN-1a). The saturated state throughout the period is an indication of the slow permeability (AN-2a) of the bedrock as well as interflow at the soil/bedrock interface (AN-3a).

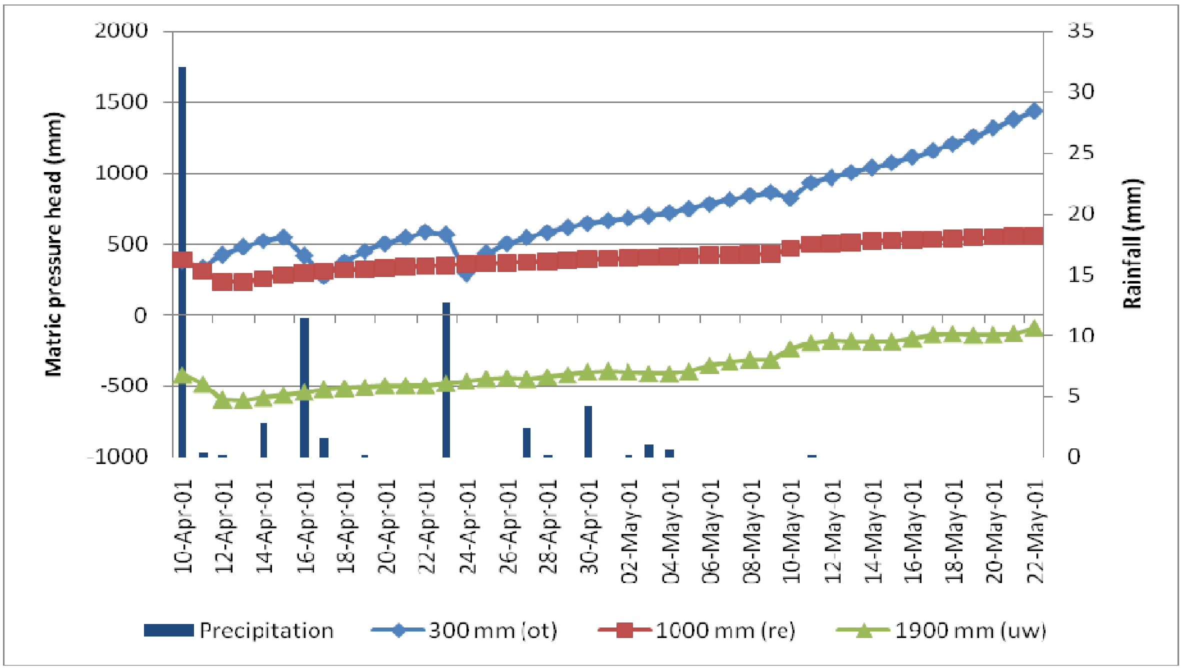


Figure 4.9 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Bd1100 at Uc1 during period 3, describing the response of a recharge soil in the high lying part of the catchment following a wet period.

Uc8 – Lo1000 (Period 1)

The orthic A horizon (300 mm) responded immediately (AN-1a) to the series of rain events starting at the 14th of September 2000 of period 1. This horizon never reaches saturation during this period. After the rain events it gradually dries out (Figure 4.10) due to ET losses.

At the beginning of this period, the sp horizon at 930 mm depth was unsaturated (since m.p.h > 0). This is interesting since the deepest layer (1900 mm) of Uc1 (Figure 4.8) was saturated during this period. This poses a question about the flow at the soil/bedrock interface (AN-3a) from the recharge soils (Uc1) towards this horizon. An explanation for the absence of interflow might be that the catchment must first be recharged following the dry winter periods, i.e. all the cracks and fissures need to be filled up with water until there is enough pressure to force the water to move laterally against the matric forces. The sp horizon responded approximately 4 days after commencement of the rain events (AN-1a). It reached saturation, and would therefore have contributed to process AN-3a.

Therefore it gradually lost water towards the end of this period, due presumable to drainage and possibly some extraction by ET.

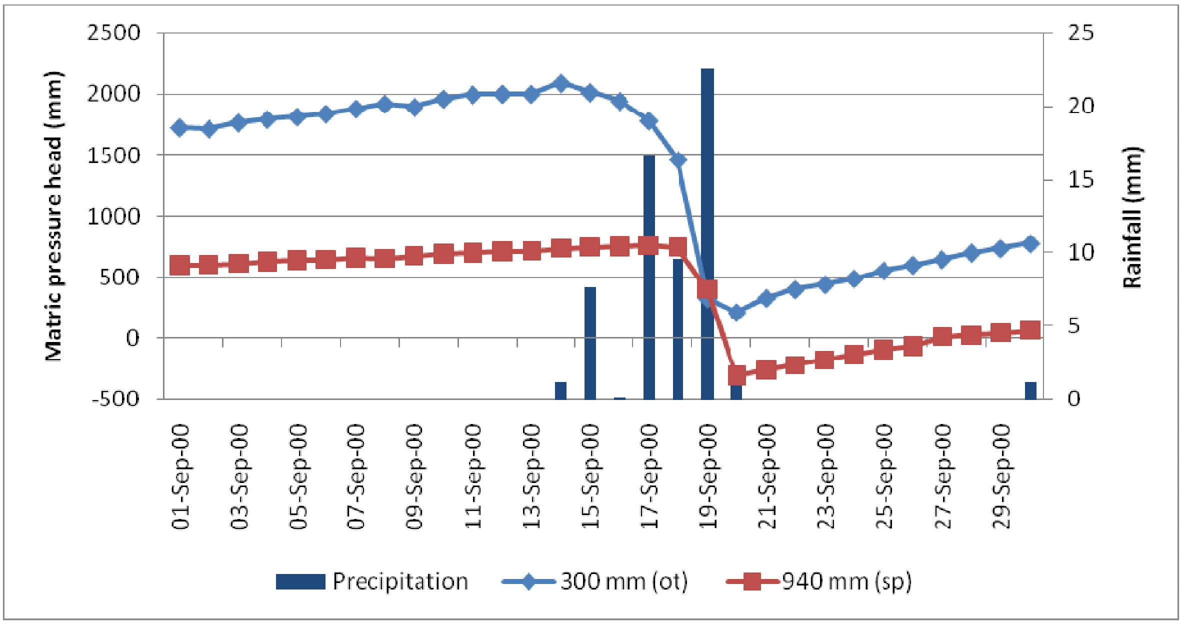


Figure 4.10 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Lo1000 at Uc8 during period 1, describing the response of an interflow soil near the Molteno rock outcrop of the catchment following a dry period.

Uc8 – Lo1000 (Period 4)

The ot horizon responded immediately to the rain during the event on the 9th (Figure 4.11). This horizon was saturated at the beginning of this period and although it dried out towards the end of this period, it remains saturated for approximately 15 days after the specific event. This differs from the response of ot horizon of the recharge soils to specific rain events. Except during the first part of period 2 (which is assumed to be incorrect), the ot horizon of recharge soils only very rarely saturate, and then only for very short periods. This long period of saturation in the ot of this interflow soil is an indication that there is a flow of water towards this horizon (AN-3a). The short term high negative pressure head might be an indication of water exiting the soil (AN-4) and flowing as overland flow on the surface.

The almost constant, very wet tensiometer readings of the sp layer are an indication of recharge through interflow of this horizon (AN-3a). It is therefore fair to assume that, before any significant interflow can occur (Figure 4.11), the catchment first needs to become recharged.

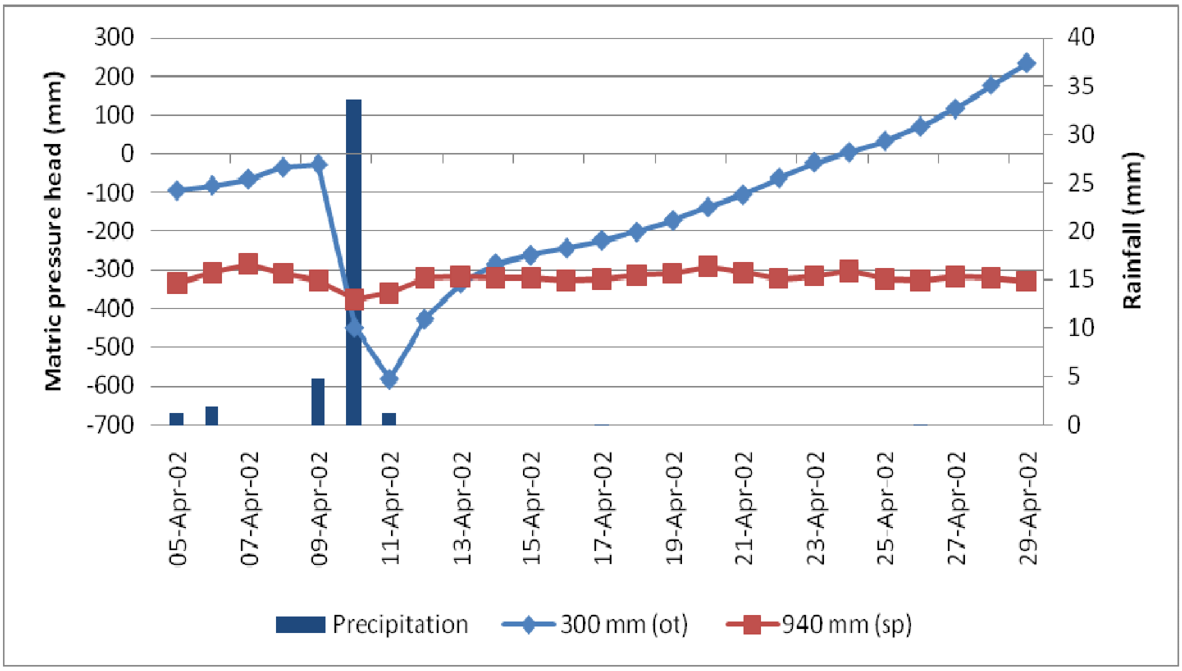


Figure 4.11 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Bd1100 at Uc8 during period 4, describing the response of an interflow soil near the Molteno rock outcrop of the catchment following a wet period.

Uc7 – Tu2220 (Period 1)

During this period the orthic A horizon (300 mm) were saturated from the 1st to the 26th of September 2000, although no rain was recorded during for the 1st two weeks of this period. This might be an indication that there is recharge of the topsoil from another area (AN-4). It seems that the rain on the 14th only affects this horizon 5 days after the rain event (19th); or that this horizon was immediately saturated after the relatively large rain event (22 mm) on the (19th).

The neocutanic B2 horizon (930 mm) of this profile remained dry throughout event 1. A slight response (wetting up) was observed on the 21st. It is unlikely that the small rain events (14 – 16th) reached this depth and it was assumed that the rain events from 17 – 19th (totalling about 49 mm) were responsible for wetting this depth four days after the start of this series of rain events. This was an indication that infiltration and vertical drainage occured in this profile (AN-1b). The diagram indicates that water continues to flow into the ne horizon for about 5 days although the rain has stopped (Figure 4.12), causing a slight increase in water content.

The 1750 mm depth tensiometer was situated in the uw horizon. Judging by the small increase in water content of the overlying ne, too little water evidently infiltrated to reach the 1750 mm depth of the uw. The rainfall was too little.

Uc7 – Tu2220 (Period 3)

During period 3 the ot horizon, initially dry, responded immediately to particular rain events. This suggested that if the horizon was dry, infiltration from precipitation dominate (AN-1b). The horizon gradually dried out towards the end of this period (Figure 4.13).

The ne horizon did not respond to different rain events early in period 3 and were mostly unsaturated. It did however respond rapidly on the 4th of May although no significant rain fell on this day (1 mm). This might be an indication that there was a wave of water from another origin passing through this horizon from the 4th to the 9th of May 2001 (AN-5a).

The 1750 mm depth tensiometer readings indicated that this horizon responded with the same tendency as the neocutanic B2 horizon during period 3. The ‘wave’ of interflow can clearly be seen passing through from the 4th to the 9th in Figure 4.13.

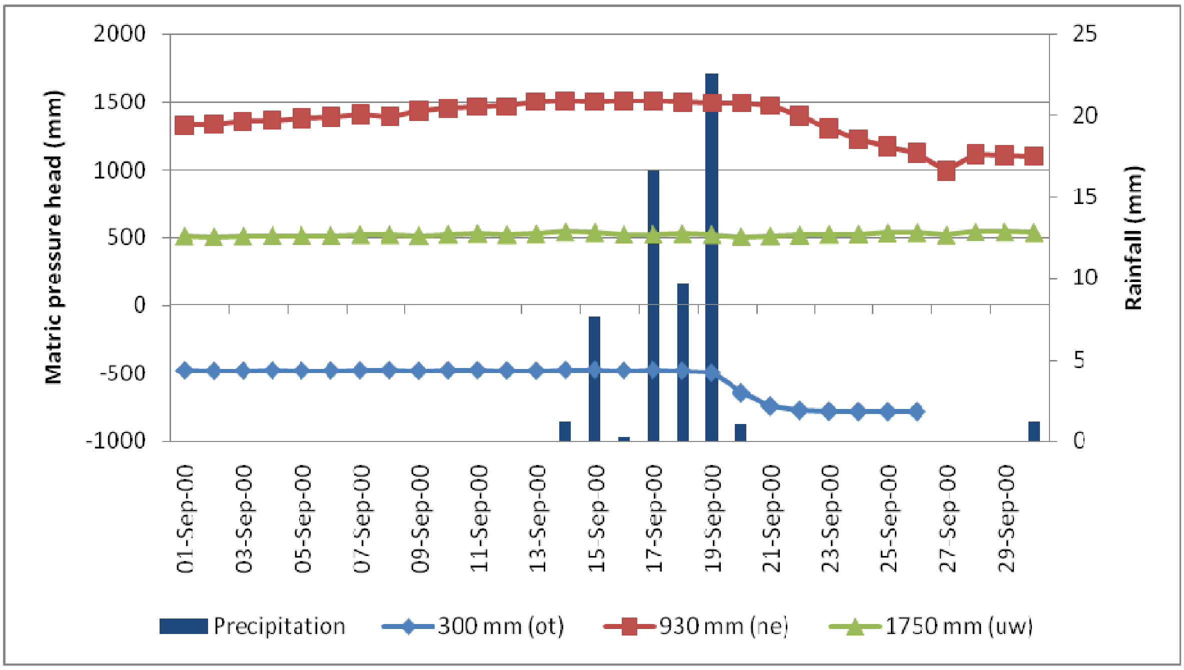


Figure 4.12 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Tu2220 at Uc7 during period 1, describing the response of an interflow soil near in the midslope of the catchment following a dry period.

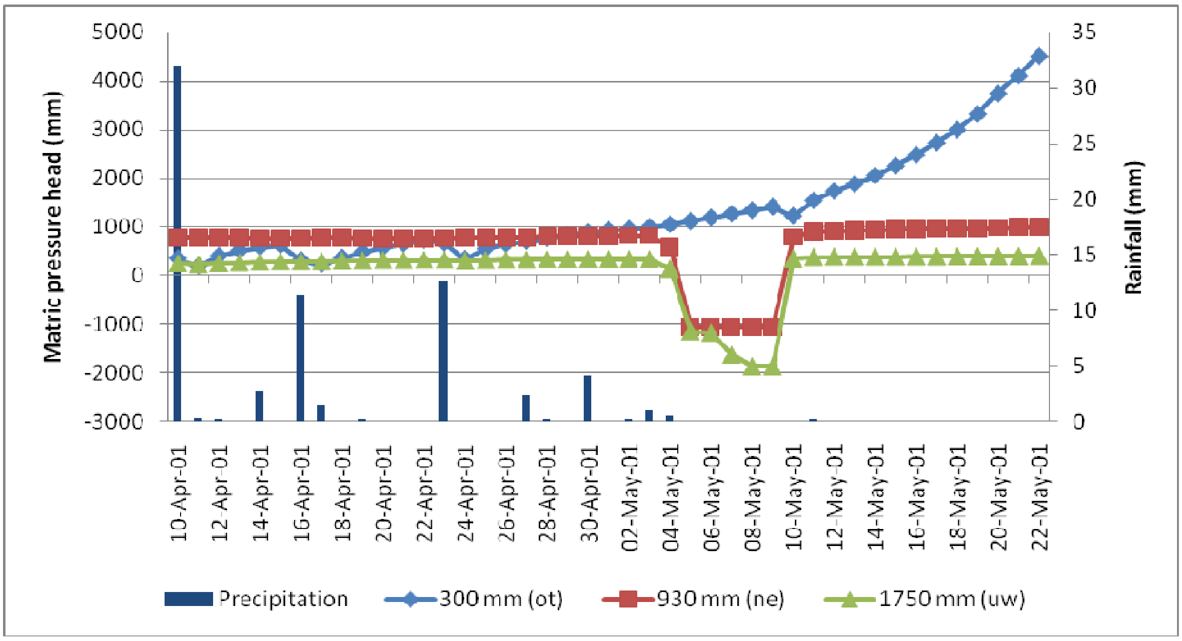


Figure 4.13 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Tu2220 at Uc7 during period 3, describing the response of an interflow soil near in the midslope of the catchment following a wet period.

Uc7 – Tu2220 (Period 4)

During period 4 the ot horizon responded immediately to the rain on the 9th and 10th of April 2002 indicating the dominance of infiltration in this horizon (AN-1b). The horizon came close to but never reached saturation during this event and dries out towards the end (Figure 4.14).

During period 4 the ne horizon responded only slightly to the rain on the 10th of April 2002, but never reached saturation throughout the event (Figure 4.14).

The on horizon is not affected by any rain event during period 4 (similar to period 2) and remained saturated throughout the period. A constant flow of water from the bedrock towards this horizon was postulated (AN-2c).

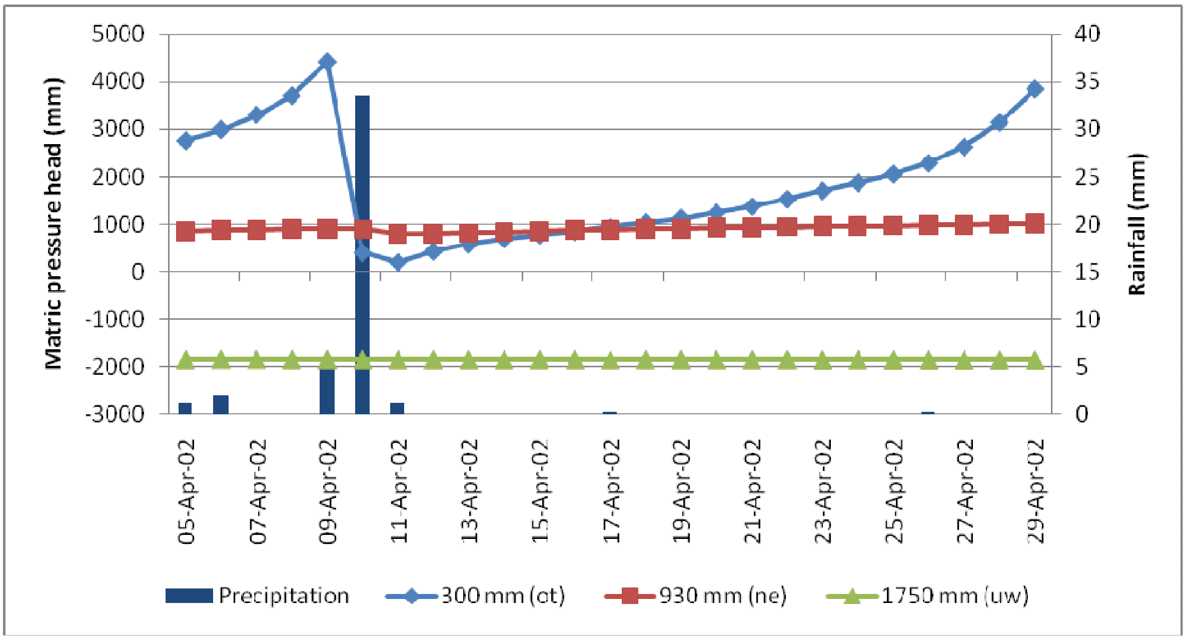


Figure 4.14 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Tu2220 at Uc7 during period 4, describing the response of an interflow soil near in the midslope of the catchment following a wet period.

Uc6 – Kd1000 (Period 3)

The orthic A horizon (300 mm) of this profile responded to rainfall within the same day during period 3 as indicated by a drop in the matric pressure head (Figure 4.15). Towards the end of these events, this horizon dried gradually due to extraction by ET.

During period 3 the G horizon dries out very gradually but remains saturated throughout the period. This is an indication of a constant flow of water towards this horizon (AN-5a and AN-3b). The 'wave' flowing through Uc7 (Figure 4.13) reaches this profile on the 8th of May (approximately 4 days after it first reached Uc7) (AN-5a).

The 1600 mm tensiometer is also situated in the G horizon. This horizon responded in the same way as the 1000 mm depth this period. The 'wave' passing through can also be seen in Figure 4.15.

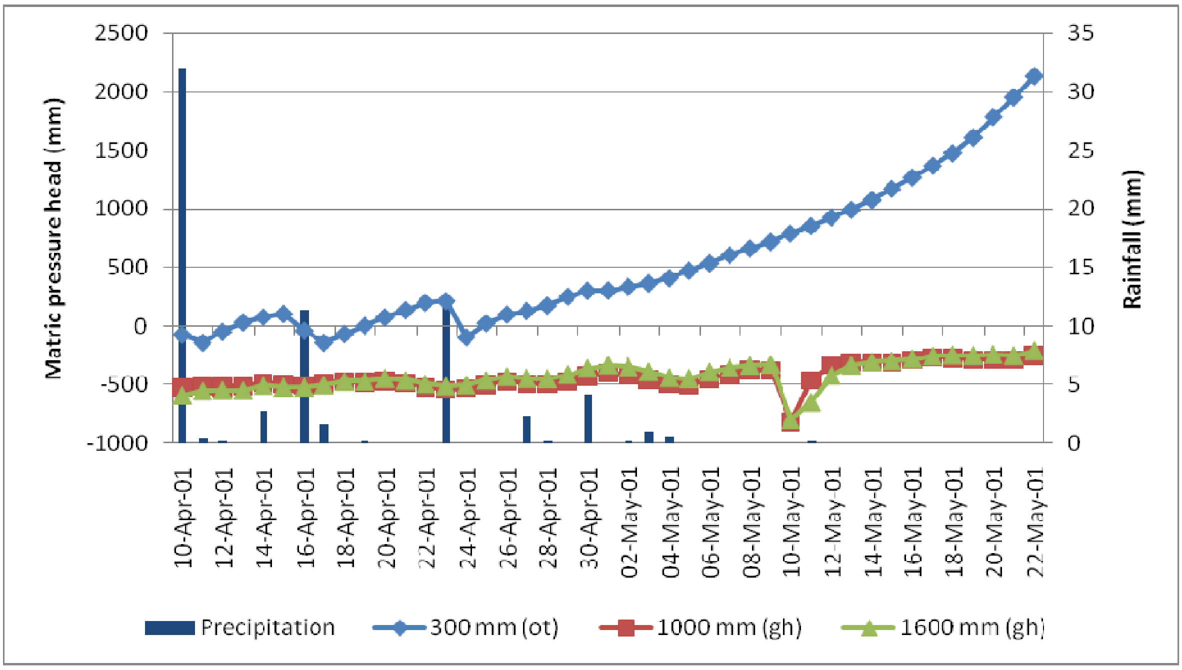


Figure 4.15 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Kd1000 at Uc6 during period 3, describing the reaction of an interflow/responsive soil near the break of slope of the catchment following a wet period.

Uc6 – Kd1000 (Period 4)

The orthic A horizon (300 mm) of this profile responded to rainfall within the same day during period 4 as indicated by the tensiometer readings (Figure 4.16). Towards the end of these events, this horizon dried gradually.

Both the gh horizons (1000 mm and 1600 mm depths) remained saturated throughout this period and were not influenced by individual rain events. A constant supply of water towards these horizons from the bedrock is proposed (AN-2c and AN-3b).

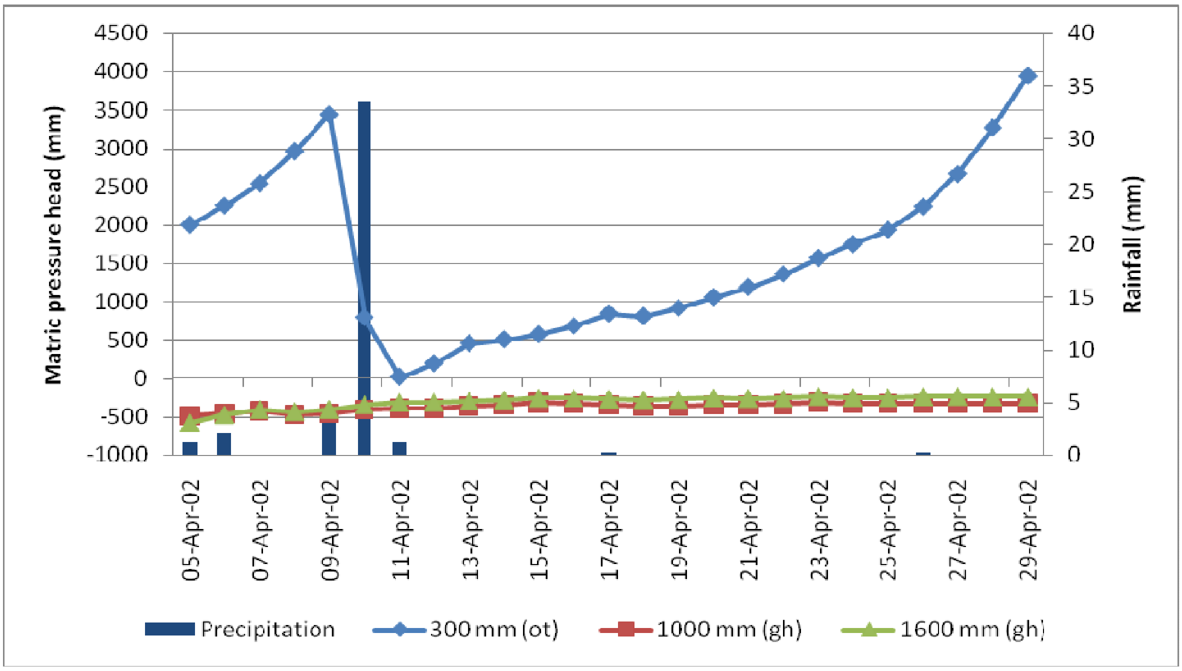


Figure 4.16 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Kd1000 at Uc6 during period 4, describing the reaction of an interflow/responsive soil near the break of slope of the catchment following a wet period.

Uc5 – Ka 1000 (Period 1)

Period 1 (Figure 4.17) is marked by a saturated ot A horizon. The small fluctuations are possibly due to diurnal variations in ET demand, possibly also influenced by similar day/night variations. It is noticeable that the variations disappear after about 40 mm of rain fell between 15 and 19 September. These long times of saturation are interesting, since they followed a relative dry period, with the last significant rainfall at least a month earlier. It is therefore proposed that water flowing in the E horizon of at Uc6, recharges the ot horizon of at Uc5 (AN-5b).

The G1-horizon (1000 mm) responded slightly approximately 24 hours later than the orthic A horizon after the rainfall from 15 – 19 September (Figure 4.17). For the first half of this event these responses occurred without any measured rain and it was assumed that the responses were due to recharge from other regions (AN-5b). The G1-horizon was slightly drier than the orthic A horizon for more than 80% of the period, indicating that the water must be recharged either in the A horizon or at the surface and then drain vertically towards the deeper layer.

The G2-horizon (2000 mm) was saturated throughout the period indicating that there is a constant supply of water from other areas even during the dry winter months (AN-3b) and perennial groundwater activity.

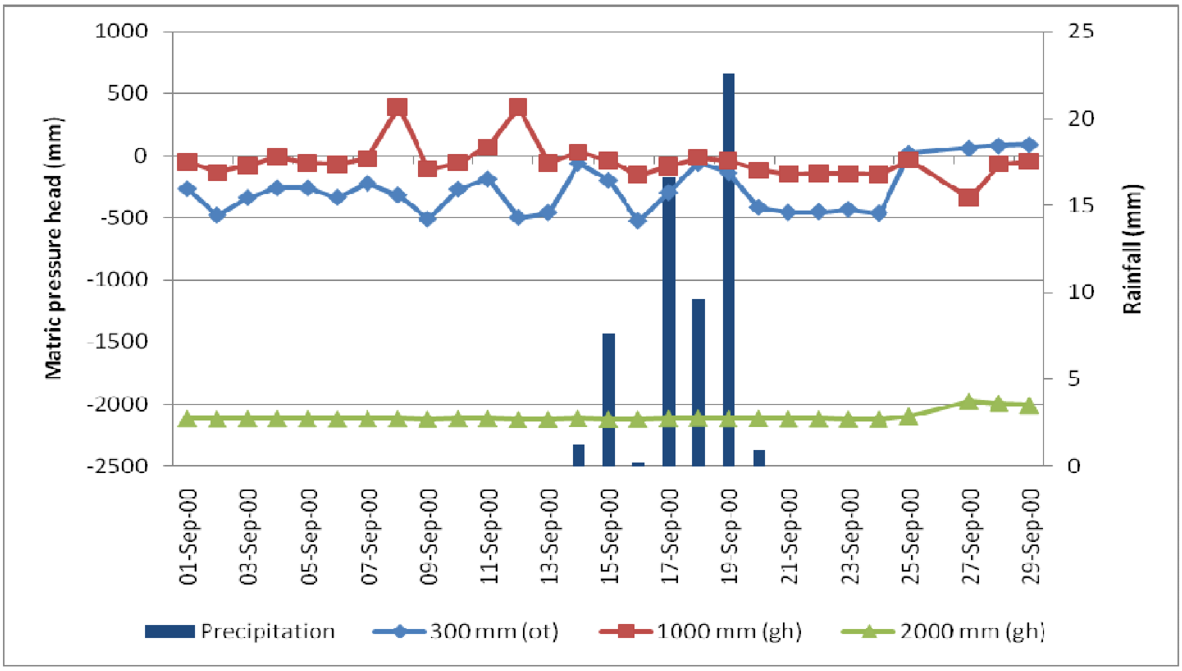


Figure 4.17 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Ka1000 at Uc5 during period 1, describing the response of a responsive soil near the footslope of the catchment following a dry period.

Uc5 – Ka 1000 (Period 4)

Period 4 starts with a dry A horizon (Figure 4.18). The horizon quickly becomes wet after the rain on 9 and 10 April 2002. This can be an indication that infiltration dominates when this horizon is dry. The horizon dries out towards the end of this period due to water extraction by ET.

The G1 and G2 horizon was saturated throughout the period implying a constant supply of water towards these horizons (AN-3b) and perennial groundwater activity. The slight decrease in the matric pressure head in the G2-horizon on the 19th of April can potentially be the time when the rain of the 10th reaches this horizon. This means there was a lag time of approximately 9 days.

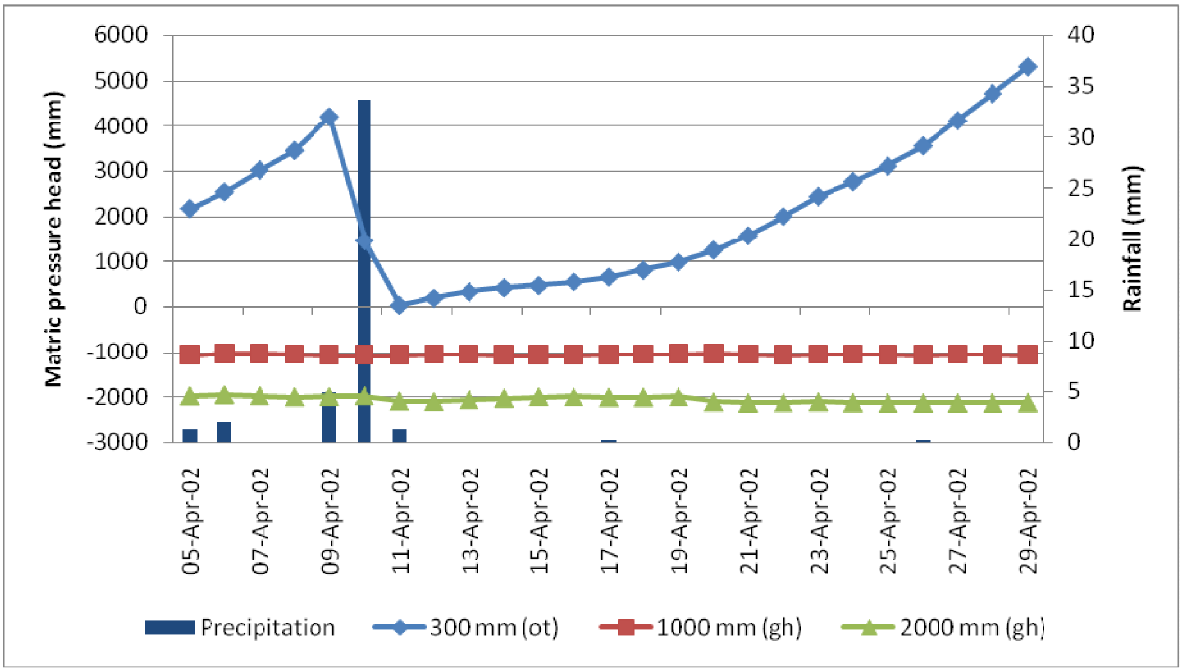


Figure 4.18 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Ka1000 at Uc5 during period 4, describing the reaction of a responsive soil near the footslope of the catchment following a dry period.

Uc4 – Ka 1000 (Period 1)

The orthic A horizon (300 mm) is saturated for long periods during period 1 (Figure 4.19). These saturated conditions of the A horizon during period 1 follow a relatively dry period, indicating that saturation occurred due to recharge from other areas and not from precipitation. Interflow in the E horizon of P-Uc6 might be responsible for this saturation (AN-5b). Saturation excess overland flow (AN-7) was probably dominant on this horizon during the series of rain events, explaining no real response to the particular events.

Other evidence for recharge of this horizon was that after the series of rain events (14 – 20 September 2000), the gh horizon continued to saturate 6 days after the last rain (Figure 4.19) (AN-3b). A two day lag time before the gh horizon responded events were observed in Figure 4.18.

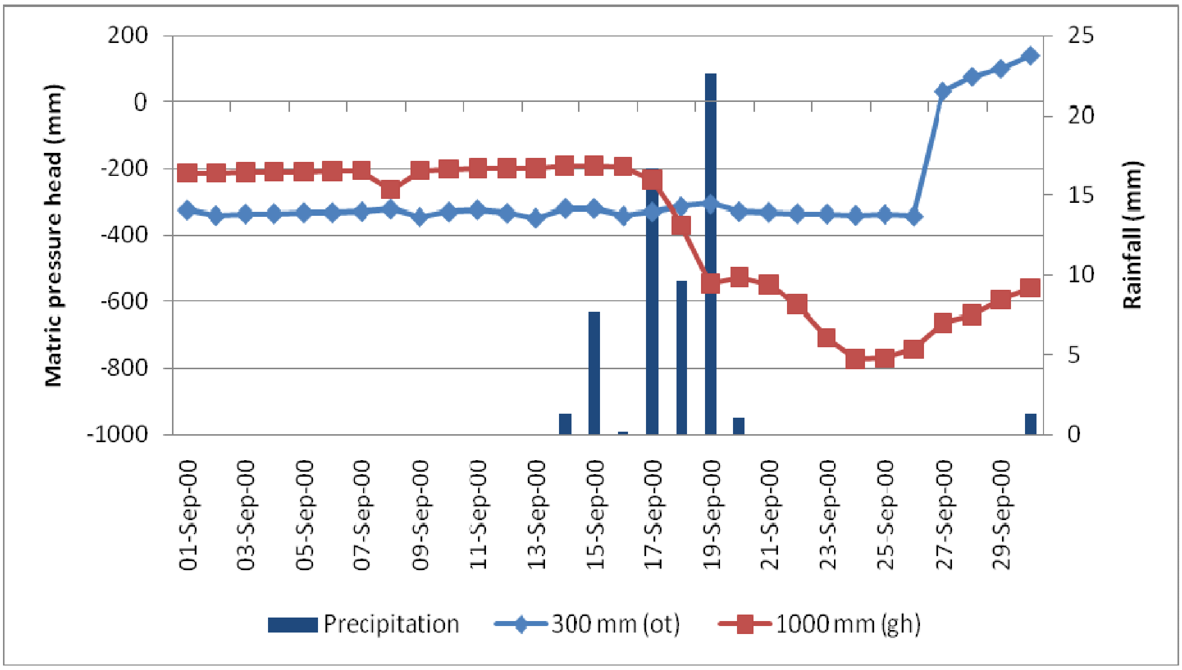


Figure 4.19 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Ka1000 at Uc4 during period 1, describing the reaction of a responsive soil near the toeslope of the catchment following a dry period.

Uc4 – Ka 1000 (Period 3)

The orthic A horizon (300 mm) is saturated for long periods during period 3 (Figure 4.20). Although it gradually dried out, this horizon remained saturated for approximately 20 days after the last significant rain during this period 3. This implies that water seeped towards this horizon (AN-3b) which satisfied the evaporative demand (AN-6) and kept the horizon saturated. It was expected that overland flow would have been dominant following rain events during the period of saturation of this horizon (AN-7).

The gh horizon (1000 mm) remained saturated throughout the event confirming a constant recharge of these horizons (AN-3a) and the presence of perennial groundwater. The slight decrease in matric pressure at the 10th of May might be an indication that the 'wave' of water coming from Uc7 reaches this horizon.

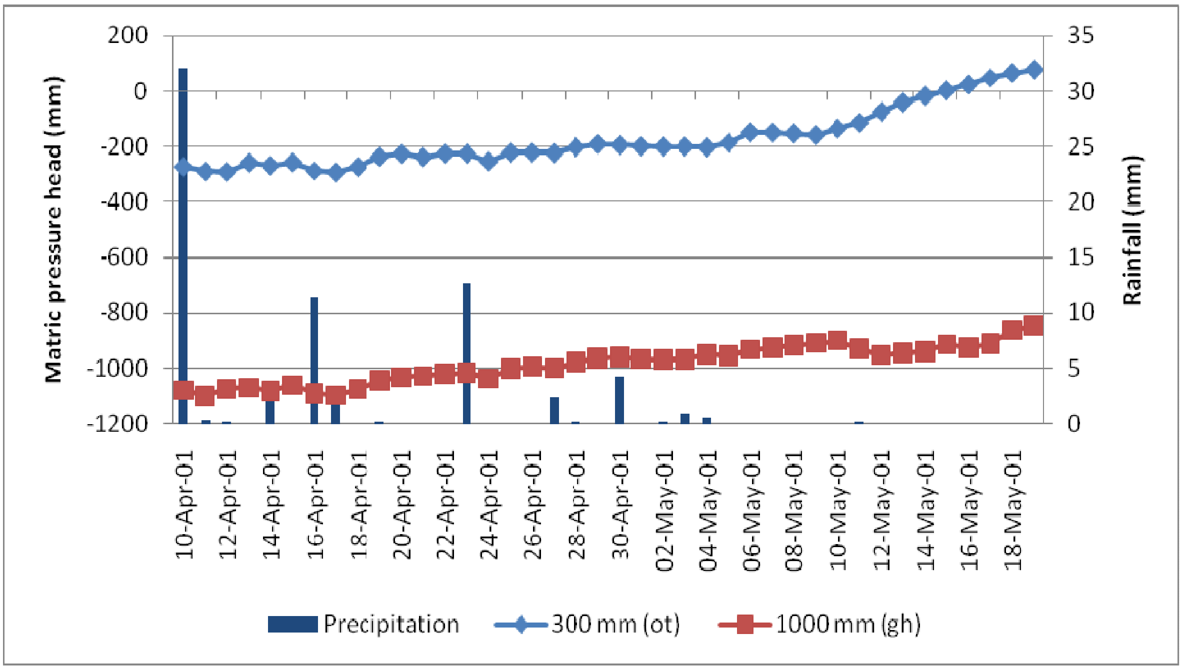


Figure 4.20 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Ka1000 at Uc4 during period 3, describing the reaction of a responsive soil near at the toeslope of the catchment following a wet period.

Uc4 – Ka 1000 (Period 4)

The ot horizon was not saturated, but the small rain event (4 mm) on the 9th of April saturated this horizon (Figure 4.21). This indicated, in an unsaturated state, infiltration dominated in the orthic A horizon of this Katspruit soil form. However, even large precipitation events do not seem to influence the matric pressure head when the horizon is in saturated (34 mm on the 10th of April). This implies that overland flow (AN-7) dominated during the rain event on the 10th. This horizon dried gradually towards the end of this period due to the evaporative demand (AN-6).

The G horizon (1000 mm) was saturated throughout this period (perennial groundwater). This was evidence that there was a supply of water to this horizon from other areas (AN-3b). It seems that the 40 mm rain of 9 – 11 April only affected the G horizon on the 17th, i.e. a lag time of 5 days. The lag time can either be attributed to vertical recharge from the A horizon or to recharge from an upslope source. Since the A horizon remained saturated during this episode, recharge from other areas is more likely (AN-3b).

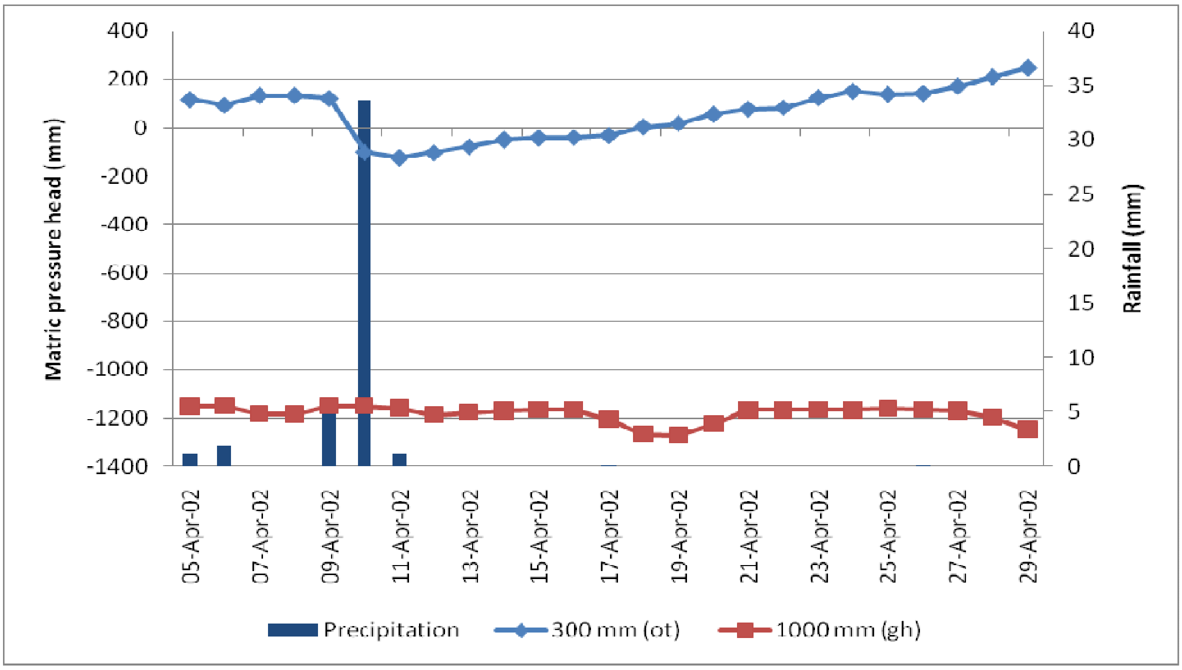


Figure 4.21 Matric pressure head (mm) vs. rainfall (mm) at different depths for the Ka1000 at Uc4 during period 4, describing the reaction of a responsive soil near at the toeslope of the catchment following a wet period.

4.2.2.2 Neutron access tube data (Ad$_{s>0.7}$ values)

AD$_{s>0.7}$ values for three profiles (P211, P212 and P213; see Figures 4.4 and 4.6) in the selected hillslope were available. These values were obtained from Van Huyssteen *et al.* (2005) calculated from 01/07/1997 to 30/06/2003 are presented in Figures 4.22 – 4.24. (The method for calculation of these AD$_{s>0.7}$ is discussed in chapter 3 sect 3.2)

P211 (Katspruit1000)

The A horizon of P211 has an annual duration of saturation of 59% of the year (215 days per year) (Figure 4.22). This implies that rainfall during this 215 day period will contribute to overland flow due to saturation excess (AN-7) and confirms the responsiveness of this profile. There was an increase in the $AD_{s>0.7}$ in the deeper horizons of 363 (99.4%), 357 (97.8%) and 365 (100%) days per year of the G1, G2 and G3 horizons respectively. This long duration of saturation (especially in the lower horizons) was evidence of a constant supply of water to these horizons (AN-3b and AN-5a&b).

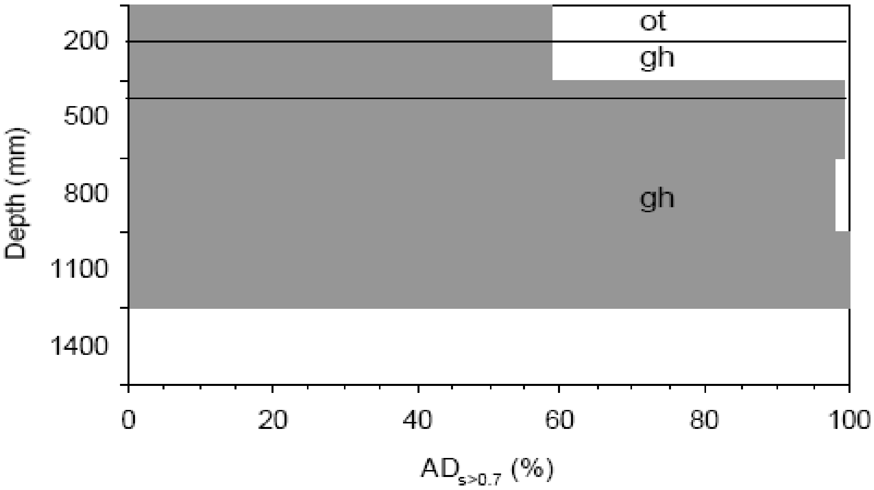


Figure 4.22 Mean $AD_{s>0.7}$ (%) values based on daily soil water content for P211 (taken from Van Huyssteen *et al*., 2005).

The location of the profile (on the toeslope) favours saturation of these horizons, since almost all of the drainage from the catchment must flow through this profile. Perennial groundwater activity is evident in the gh horizons of this profile.

P212 (Tukulu1110)

P212 is located in the upper midslope position, which may be the reason for the infrequent and short duration of saturation. The $AD_{s>0.7}$ values throughout the profile was less than 1.1% of the year (4 days per year). The A horizon was saturated for longer periods than the neocutanic B horizon (Figure 4.23), which confirms AN-4 of the conceptual model (Figure 4.7). Water exiting above the Molteno shelf as return flow, moves as overland flow over the shelf and re-infiltrates into this profile (AN-1b).

The short duration of saturation in the on horizon (1400 mm) was unexpected since tensiometer readings showed that this horizon was constantly saturated during period 4 (Figure 4.14) and remained close to saturation during period 3 (Figure 4.13). This can however be explained: the deepest (1750 mm) tensiometer was inserted at the point of refusal i.e. on the bedrock. This was where the interflow water is expected to flow (AN-5a). The depth of 1400 mm is above the interflow zone and corresponds better with the ne horizons of Figures 4.13 – 4.15.

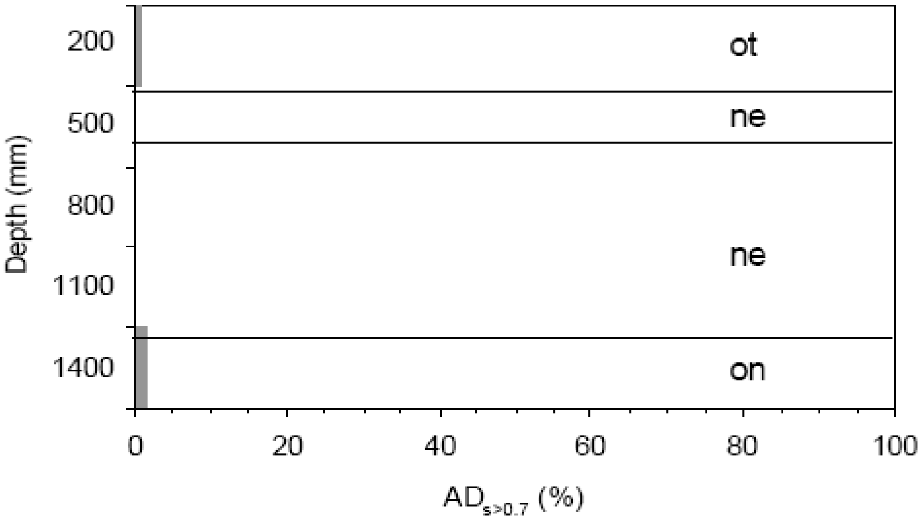


Figure 4.23 Mean AD$_{s>0.7}$ (%) values based on daily soil water content for P212 (taken from Van Huyssteen *et al.*, 2005).

P212 (Ka1000)

The orthic A horizon is saturated 47% of the time (i.e. 171 days of saturation annually) (Figure 4.24). This is shorter than the time of saturation of P211 (Figure 4.22). This is due to a relative smaller area contributing to recharge of this profile compared to P211.

The lower gh horizon (1380 mm) is saturated ($AD_{s>0.7}$) for 358 days per year (i.e. 98% of the time (Figure 4.24). Similar to P211 there must be recharge of this profile especially during the dry months indicating perennial groundwater activity. This recharge path is proposed to be via AN-3b in Figure 4.7.

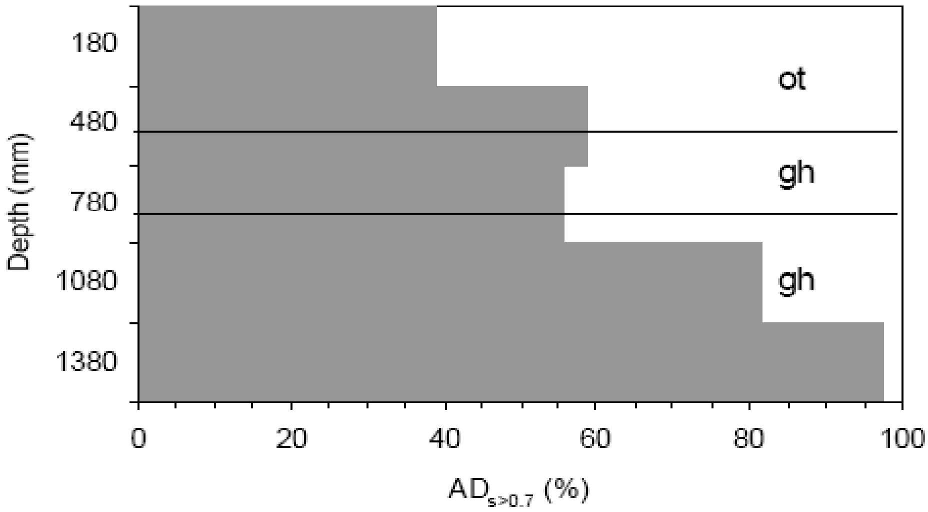


Figure 4.24 Mean $AD_{s>0.7}$ (%) values based on daily soil water contents for P213 (taken from Van Huyssteen *et al.*, 2005).

4.2.2.3 Evapotranspiration

Figure 4.25 presents the average monthly rainfall (mm) vs. the average monthly evapotranspiration (ET, in mm), and potential ET (ET_0), also in mm, over six years for three profiles in the upper catchment. The selected profiles are: P211 (Ka1000), P212 (Tu1110) and P213 (Ka1000) (see Figures 4.4 and 4.6 for location of profiles).

During the first three months the rainfall exceeds the ET in all three profiles. The ET rates for the Katspruit profiles (P211 and P213) were however higher than the rate in the P212 (Tu1110). ET_0 was the same for all the profiles since the same climate data were used.

The average ET from P212 was always less than the average precipitation except during June. This may be due to return flow exiting Longlands soils above the rock outcrop (AN-4) which infiltrates P212 (AN-1b) and contribute to ET. This return flow is expected to end by the end of June.

ET in P211 and P213 are the same from January to June and followed the same tendency as ET_0 (Figure 4.27). Although ET_0 was identical for the profiles, there were differences in ET from June to December. These differences can only be attributed to differences in the soil water content as ET_0 is identical for these profiles. P211 is wetter than P213 (also indicated by morphological differences in sect. 4.2.1 nr. 8) towards the end of the dry season. Since ET is higher than precipitation during this period water possibly came from another source (AN-3a). It seems that there is a constant feed of water to P211 throughout the year, but this feed supplied less water to P213 towards the end of the dry season.

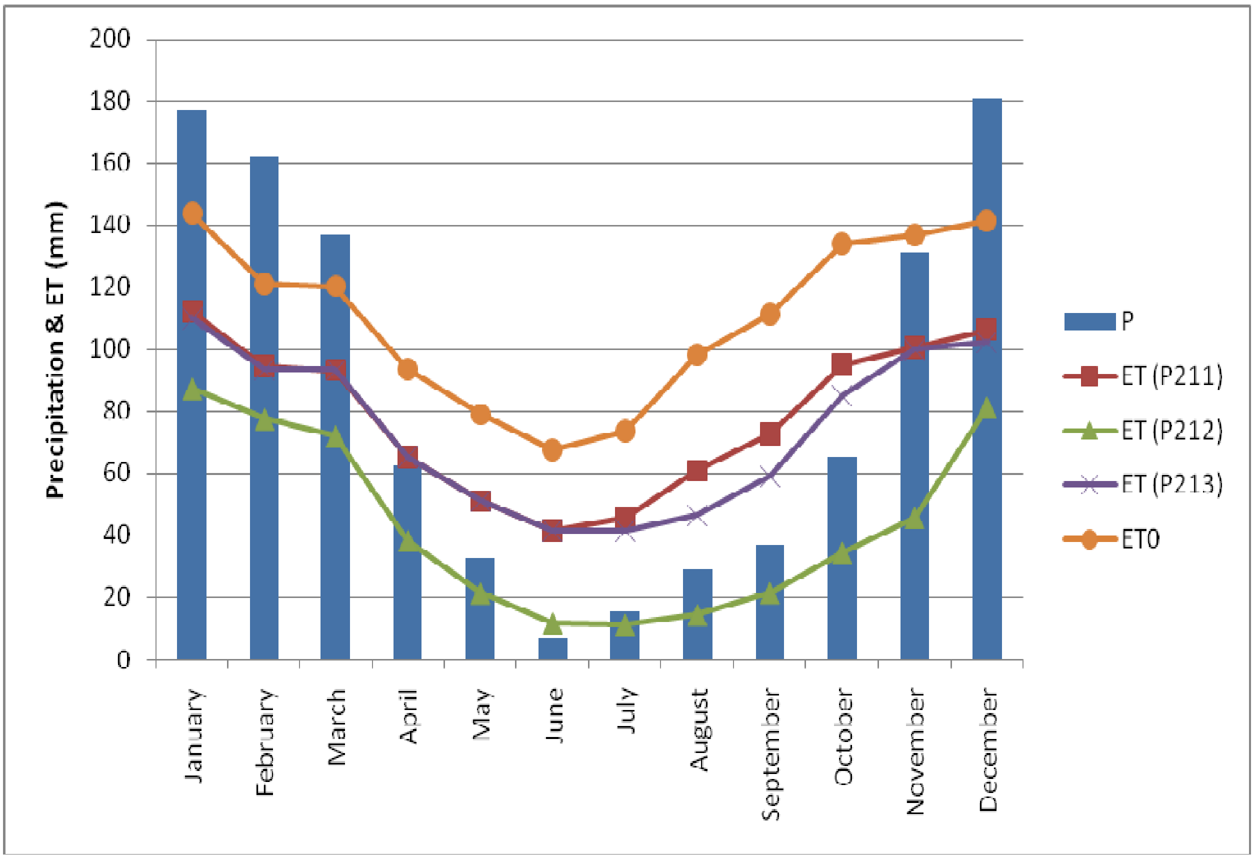


Figure 4.25 Six year mean monthly rainfall (mm), evapotranspiration (mm) and potenstial evapotranspiration (ET_0) of three profiles in the UC of the Weatherley catchment.

4.2.2.4 Hydrograph analysis and streamflow generation

A stream hydrograph was selected for a period which included a number of rain events between 23 March 2001 and 31 May 2001 (Figure 4.26). This hydrograph was then analysed to determine the relative contribution of different streamflow generation mechanisms. For determinations of baseflow the selected period was extended until 4 July 2001.

Peak flow generation

It is hypothesized in the conceptual model, based on soil morphological information, that saturation excess overland flow dominates in the lower lying areas (AN-7). Tensiometer, neutron access tube and evapotranspiration data confirm the saturated state of these soils.

It was assumed that responsive soils next to the stream will be the main contributors to peak flow and was therefore responsible for peak flow generation. These soils occupy approximately 50 000 m^2 of the catchment area (Table 4.2). For this study, peak flow is assumed to stop 24 hours after the end of the particular rain event. Rainfall intensity plays a dominant role in overland flow generation and was therefore taken into account. Table 4.4 presents rainfall and flow volumes as well as rainfall intensities for selected rain events.

Table 4.4 Rainfall volumes on responsive soils adjacent to stream, streamflow volumes and rainfall intensities for six rainfall events

Event	Date	Rain (m^3)	Runoff (m^3)	Rainfall intensity (mm.h^{-1})
1	19-Sep-00	1150	296	1.05
2	13-Sep-01	1190	23	1.26
3	25-Sep-04	3600	77	3.06
4	27-Mar-00	1100	1110	1.4
5	10-Apr-01	1600	1731	79.17
6	10-Apr-02	1650	666	1.74

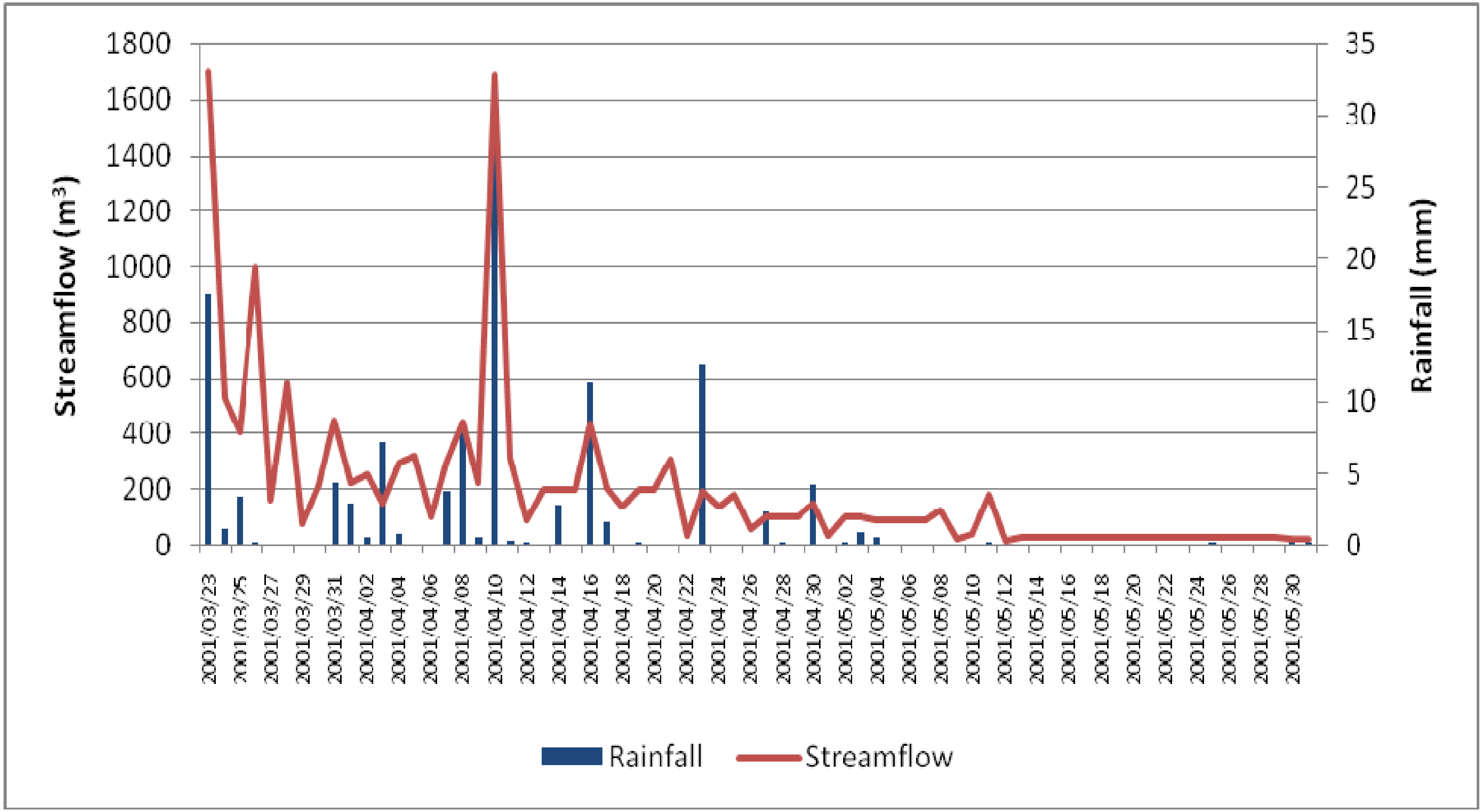


Figure 4.26 Streamflow hydrograph (m^3) vs. Rainfall at W1 (see Figure 4.4) for a selected period (23/03/2001- 31/05/2001).

The first three events followed the dry winter period. The streamflow volume was lower than the rainfall volumes for these events independent of the volume of rain or the intensity. This might be because the orthic A horizon of the responsive soils was dry following extraction by evapotranspiration during the dry winter months and needed to be recharged before any significant overland flow could occur. This process implies that responsive soils had a wetting up phase in the beginning of the rain season.

During event 4, with relatively low rainfall intensity, the rainfall on the responsive soils was almost exactly the same as the runoff for this event, supporting the hypothesis that this area was the main contributor to peak flow with saturation excess overland flow present. During event 5 the runoff exceeds the rainfall, which indicates that a greater area must have contributed to peak flow. This may result from contributions through infiltration excess as the high intensity rainfall exceeds the final infiltration rate of these soils and overland flow dominates. Event 6 follows a period where the evapotranspiration exceeded the rainfall and recharge of the orthic A horizon was needed prior to any overland flow explaining the lower runoff compared to the rainfall.

Baseflow generation

It is hypothesized that all the water contributing to baseflow must flow through the G horizons of Katspruit and Kroonstad soil forms before reaching the stream. If this hypothesis is correct the volume of water lost by these horizons should therefore correspond approximately with the baseflow volume.

The G horizon of P213 was selected as representative of the G horizons. Its water content was taken as the average water content for this horizon during the period 5 May to 4 July 2001. This period was selected since it followed a wet period but no rain was recorded for the duration of the period itself. The volume of water that drained from this horizon was calculated using the Brooks Corey equation and parameter values from Lorentz, Gopa & Pretorius (2001) for a gh horizon in the Weatherley catchment:

$$Se = (\Theta - \Theta_r)/(\Theta_s - \Theta_r) = (h_d/h)^{\lambda} \quad \text{for } h > h_d \ \ldots\ldots\ldots \text{(4.1)}$$

and $$K(h) = K_s(Se)^{(2+3\lambda)/\lambda} \ \ldots\ldots\ldots\ldots\ldots\ldots \text{(4.2)}$$

where: Se = effective degree of saturation
Θ = water content ($m^3.m^{-3}$)
K(h) = unsaturated hydraulic conductivity (mm. h^1)
Θ_s = 0.351 (water content ($m^3.m^{-3}$ at saturation))
Θ_r = 0.264 (residual water content ($m^3.m^{-3}$))
h_d = 30.4 mm (air entry value)
λ = 0.562 (pore size distribution parameter)
K_s = 7.2 mm.h^{-1} (P204 at 500 mm) (saturated hydraulic conductivity)
h = water content measured in 90 mm soil layer

thus: $Se = (30.4/ h)^{0.562}$ ……………………………………..(4.3)

$K(h) = 7.2 \{(30.4/ h)^{0.562}\}^{6.559}$ ……………………………(4.4)

For example If h = 80 then K(h) will be 0.2 mm.h^{-1}

The water retention curve based on this equation is presented in Figure 4.27:

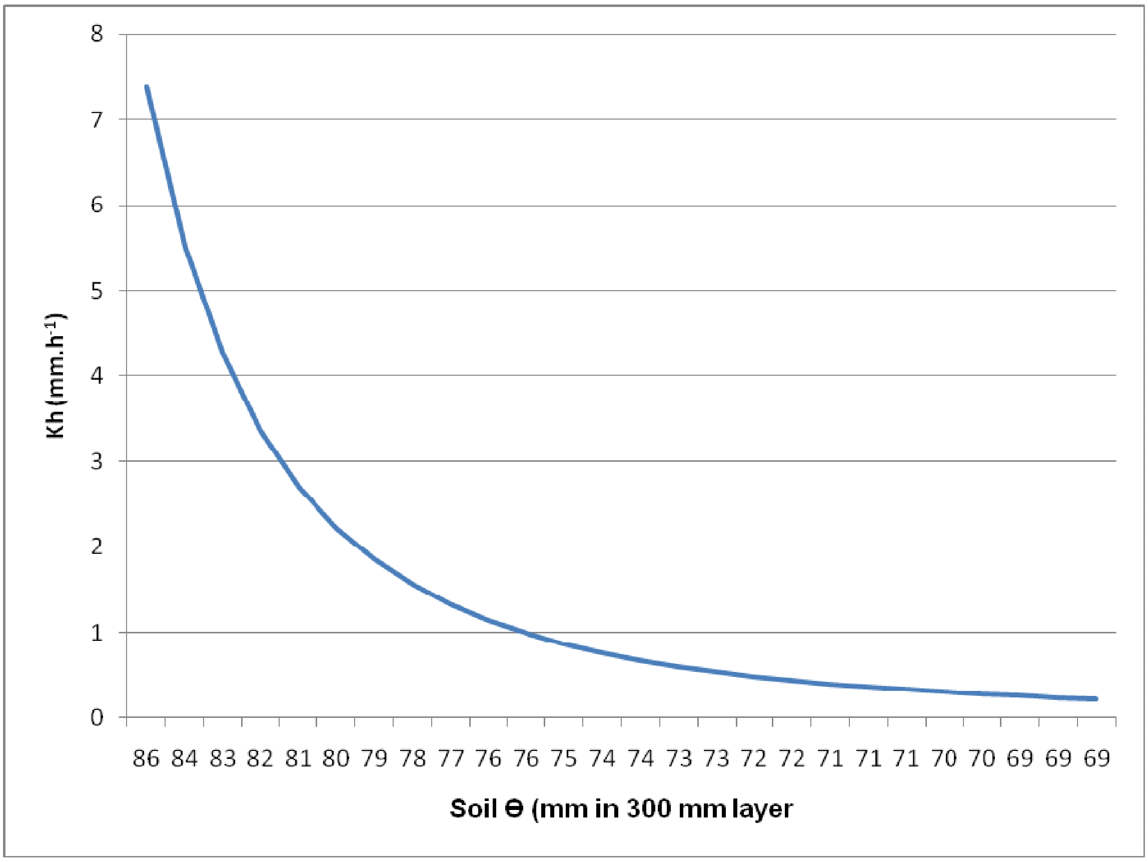


Figure 4.27 ΔK(h) (mm.h^{-1}) with ΔΘ (mm in 300 mm layer) based on equation 4.4.

The unsaturated hydraulic conductivity decreased drastically with a decline in the soil water content (Figure 4.27)

To predict the different K(h) values at different water contents a linear regression line were drawn based on eq. 4.4.

$(\text{Log } K_h + 3) = (39.3 \times \text{Log}\Theta) - 75.5$ in mm.h^{-1}……………$_{(4.5)}$

This equation for P213 is extrapolated to all G horizons of the Uc. These horizons occupy an area of 74 630 m^2 (Table 4.2). The volume of water draining from these soils is expressed in $m^3.day^{-1}$ and compared to the stream runoff ($m^3.day^{-1}$) for the selected period (Figure 4.28)

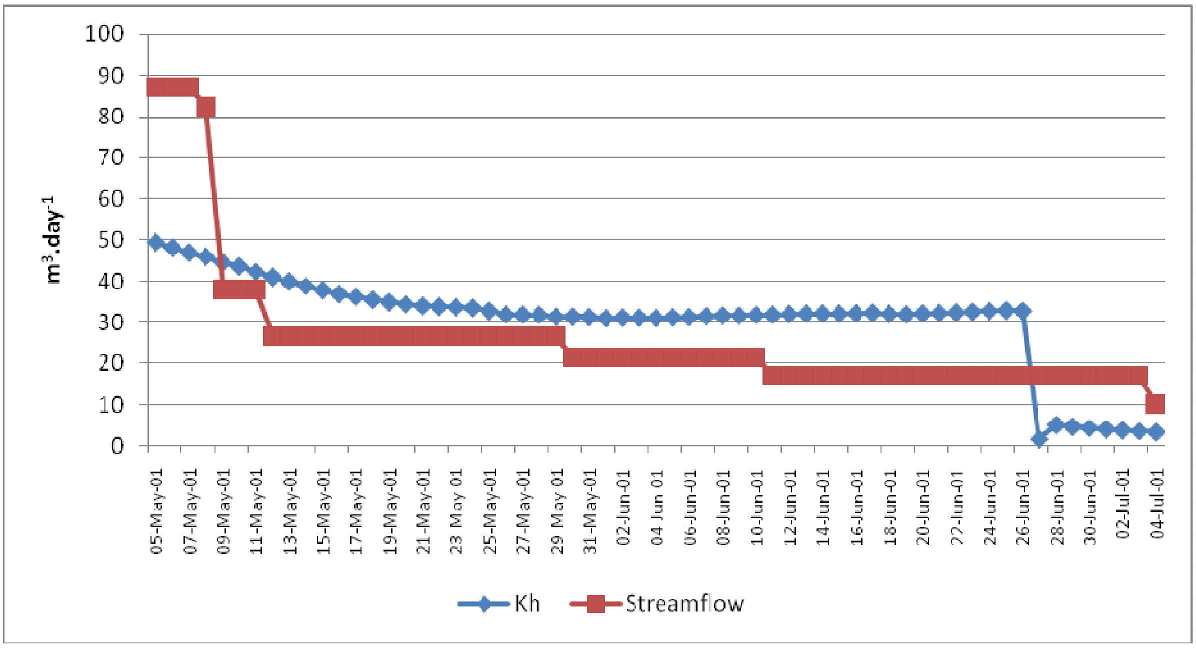


Figure 4.28 ΔK(h) ($m^3.day^{-1}$) vs. streamflow ($m^3.day^{-1}$) for 60 day period starting 5 May 2001.

Baseflow estimated with the drainage equation for P213 gave a very good simulation of the actual streamflow (m^3). The total streamflow estimated for this period is 1875 m^3 and the actual streamflow measured is 1607 m^3 indicating that baseflow is generated through outflow from the G horizons in the lower slopes.

Recharge of marsh

Baseflow is generated through outflow out of the G horizons which occupy the marsh area. According to neutron water metre as well as tensiometer data, this area is saturated for long periods. ET exceeds precipitation during 7 moths of the year (Figure 4.25). The volume of water lost by the soils in this area through outflow and ET must therefore be recharged from other regions. It is postulated that these soils are recharged by interflow and recharge soils in the upper part of this catchment. This hypothesis was tested during the period from 23rd of March to 31st of May 2001. The contribution of macropore flow (interflow) and the shoulder of the hydrograph during this period can also be evaluated since the effect of overland flow as well as baseflow is known.

To test this hypothesis a number of assumptions were made:

- The marsh is recharged through the perimeter surrounding the marsh area.
- Recharge occurred laterally through the whole profile and the average soil depth of the marsh soils (all Ka1000) was taken (Table 4.1).
- The volume of streamflow (m^3) together with the ET (m^3) is the volume lost by the marsh soils and therefore the volume which needs to be recharged.
- Rain on the marsh soils adjacent to the stream (50 000 m^2) (Table 4.2) contributes to overland flow and is not lost by the soils. This volume is therefore subtracted from the total volume of streamflow.
- Baseflow during this period is estimated using the drainage equation of gh horizons (equation 4.5)
- The difference between total streamflow and baseflow together with overland flow is the contribution of interflow (shoulder of the hydrograph).

The contribution of macropore/interflow can be calculated as (Table 4.5):

Streamflow – overland flow – baseflow = interflow... (4.6)

The volume of water lost by the soils in the marsh for the selected period has been calculated as follows:

(Streamflow – Overland flow) + ET = Total water lost by marsh soils.............. (4.7)

where: Overland flow = area of marsh soils next to stream × Rain during selected period

The total streamflow overland flow, ET and water lost by the marsh soils are presented in Table 4.6.

Table 4.5 The contribution volumes (m^3) of total streamflow, overland flow, baseflow and interflow during the selected period

Streamflow (m^3)	**Overland flow (m^3)**	**Baseflow (m^3)**	**Interflow (m^3)**
15150	6100	3952	5098

The total volume of interflow for the selected period is 5098 m^3 which is almost 34% of the total streamflow during this period.

Table 4.6 Volumes (m^3) for streamflow, overland flow and ET as well as the total volume of water lost by the marsh soils during the selected period

Streamflow (m^3)	**Overland flow (m^3)**	**ET (m^3)**	**Total lost (m^3)**
15150	6100	976	10027

The total volume of water that is recharged through the perimeter of the marsh is calculated as 10027 m^3. The area of this perimeter is calculated using the measured circumference of the marsh and the average depth of Katspruit soil forms (Table 4.1). The circumference is approximately 2200 m and the average depth of the soil form 1.06 m (0.71 m for gh horizons and 0.35 m for ot horizon). The area through which recharge can occur is therefore 2200 m × 1.06 m = 2332 m^2.

The lateral recharge expressed in $mm.h^{-1}$ can be calculated as follows:
{[(Volume recharged ÷ area through which recharge occurs) × 1000] ÷ 69 days ÷ 24 hours} = lateral recharge ($mm.h^{-1}$).. (4.8)
Therefore:
$10027\ m^3 \div 2332\ m^2 = 4.3$ m in 69 days
$(4.3\ m \times 1000) \div 69 = 62\ mm.day^{-1}$
62 mm ÷ 24 = **2.6 $mm.h^{-1}$**
The estimate K*s* for gh is 7.2 $mm.h^{-1}$. The calculated value 2.6 $mm.h^{-1}$ is therefore a relatively good estimation for lateral recharge into these layers.

4.3 Conclusions

The conceptual model based solely on soil morphological properties gave an acceptable indication of the hillslope hydrology for the selected hillslope in the Uc of the Weatherley catchment. Tensiometer readings, $AD_{s>0.7}$ values, evapotranspiration and stream hydrograph confirmed the conceptual model.

This model serves as a basis for distinguishing between different streamflow generations mechanisms. Soil information was used to estimate different streamflow generation mechanisms (peakflow, baseflow and recharge). Results produced estimates which are comparable with the actual streamflow volumes obtained from the stream hydrograph.

CHAPTER 5

BEDFORD CATCHMENTS

5.1 Introduction

Soil properties play a major role in hydrology, to the extent that they can influence the hydrograph significantly (Chorley, 1978).

Soil information is useful in gauged basins (i.e. catchments with weirs and hydrologic measurement data) as it facilitates the understanding of hydropedological processes. The need for predictions of these processes in ungauged basins (PUB) (i.e. catchments without weirs and hydrologic measurement data) is becoming increasingly more important (Park & Van de Giesen, 2004; Ticehurst *et al*., 2007).

The distribution of soil indicators, related to hydrological pathways, storage mechanisms and duration of water in a hillslope, serve as a window to subsoil behaviour (Wysocki, Schoeneberger & LaGarry, 2005).

In this chapter the aim is firstly to examine and interpret soil indicators occurring in three semi-arid catchments to try to elucidate hydrological response characteristics, and secondly, to determine if soil information at different levels of detail influence hydrologic modelling with the Pitman hydrological model.

5.2 Methodology

5.2.1 Study area

Three sub-catchments (B3, B4&5) of the Bedford catchment in the Eastern Cape (Figure 5.1) were surveyed for soil distribution and related features for hydropedological purposes. The Bedford catchment is drained by the eNyara River and covers about 670 km^2. The areas of B3 , B4&5 are 40.3, 31.1 and 17.7 km^2 respectively. They are located in the semi-arid grassland areas of the Eastern Cape some 150 km from the coast, at the foot of the Winterberg escarpment. The vegetation consists of a mixture of grass, bush and trees and is classified as Grasslands with False Thornveld in the valley bottom. Land use is restricted to grazing by cattle, sheep and a limited amount of game. These catchments are representative of large semi-arid areas in South Africa (Hughes and Sami, 1993).

The climate of the three catchments is more or less uniform with an annual rainfall of about 460 mm. The type of rainfall varies between short high intensity storms during the summer and long duration events which can occur any time of the year. The annual evaporation is approximately 1400 mm a year, based on regionalized Symons pan data. The parent material forms part of the Middleton Formation and consists of sub horizontally bedded sandstone and shale’s (Johnson, 1976). Catchments B4&5 lie on the northern boundary of the Koonap Formation, while B3 is located in the transition to the Balfour Formation. Together these three Formations make up the Adelaide Sub-Group of the Beaufort Group of sediments in the Karoo Sequence (Truswell, 1977). The majority of the area has gentle slopes (>80% of the area has slopes less than 8%) and a relief of 90 – 150 m (Land Type Survey Staff, 2002)

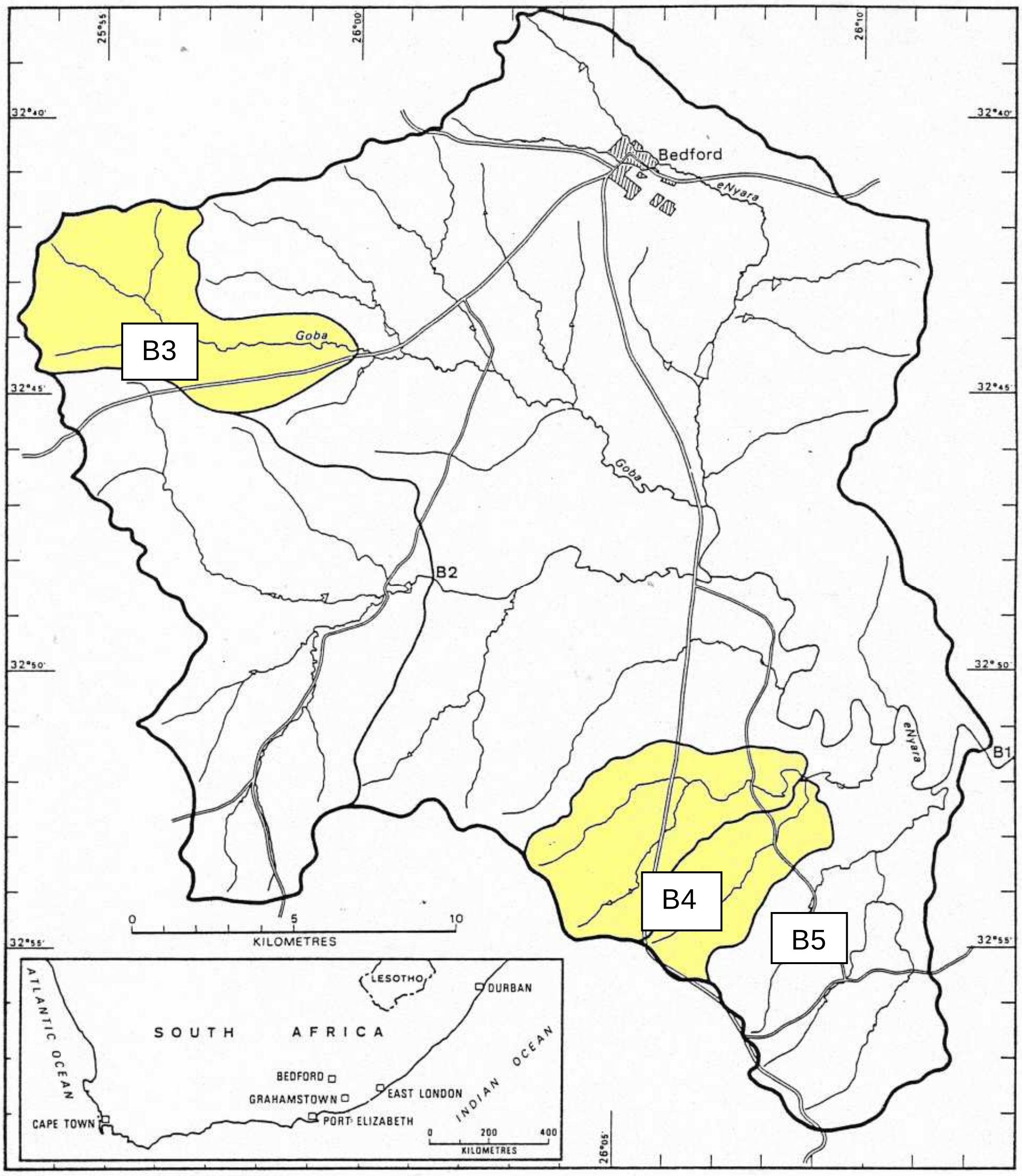


Figure 5.1 Location of the surveyed catchments (Hughes & Sami, 1993).

5.2.2. Soil survey

5.2.2.1 Field procedure

An extrapolation survey method of soil survey was followed (Le Roux *et al*., 1999) using hand and hydraulic augers. Representative hillslopes in terms of profile and planform curvature were identified from a 1: 50 000 ortho map. The transects were marked. These transects and others selected visually in the field were surveyed.

Approximately 240 observations were made on 30 transects. The observations were made by hand and hydraulic auger. Observations were made as deep as possilbe. The distance between auger observations varied between 50 and 300 m depending on changes in topographical features. Penetrometer (depth probe) measurements were made in-between to monitor the depth of the soil. The soils were identified in accordance with the Soil Classification: A taxonomic system for South Africa (Soil Classification Working Group, 1991). Profiles pits were opened at representative sites, described, sampled and analysed (Appendix 1). The observations for the three sub catchments are presented in Appendix 2.

5.2.2.2 Laboratory procedure

Laboratory preparation

Soil samples were air dried at 30℃, and then sieved through a 2.0 mm mesh sieve and stored in dry area until analyzed using methods prescribed by the Non – Affiliated Soil Analysis Work Committee (1990).

Physical methods

The clay (<0.002 mm), fine silt (0.02 - 0.002 mm) and coarse silt (0.05 – 0.02 mm) fractions were determined by sedimentation, pipette sampling, oven-drying and weighing. Very fine sand (0.1 – 0.05 mm), fine sand (0.25 – 0.1 mm), medium sand (0.5 – 0.25 mm) and coarse sand (2.0 – 0.50 mm) fractions were determined by dry sieving and weighing.

Chemical methods

The $pH_{(H2O)}$ and $pH_{(KCl)}$ were measured in a 1:2.5 water and 1 M KCl suspension respectively. The exchangeable cations (Ca, Mg, K & Na) and CEC were determined by NH_4OAC extraction with a Atomic Absorption spectrophotometer (AA). Fe & Mn were extracted using CBD and determined with the AA.

5.2.3 Pitman hydrological model

5.2.3.1 Introduction

The Pitman hydrological model (Pitman, 1973) was used in this study by a post-graduate hydrology student at Rhodes University, E. Kapangaziwiri, to evaluate the contribution of soil information. The Pitman model is comparable to many other conceptual models, consisting of storages, linked by functions, developed to represent the major hydrological processes prevailing in catchments. The model comprises of three conceptual storages: interception, soil water and groundwater. The model simulates infiltration-excess, saturation excess, overland flow and bedrock flow. It is a monthly rainfall-runoff model using monthly rainfall data and evapotranspiration estimates as input (Kapangaziwiri & Hughes, 2008). As it was designed for water resource assessment purposes in managed catchments, it also includes functions to account for losses and abstractions from small dams and direct abstractions from the river itself. Its data requirements are relatively limited, with the minimum needed being a time series of monthly rainfall and mean monthly reference evaporation. It is usually quite straightforward to calibrate and Pitman (1973) provides some guidelines for initial parameterization (Hughes 1996).

5.2.3.2 Procedure

The hydrological and related properties of the soils of the catchments were calculated for two levels of detail:

1. Land Type data
2. Extrapolation survey data

These two levels of data were incorporated in the Pitman hydrological model. The procedures for obtaining these properties were:

Soil depth

For the Land Type level of detail, soil depths were obtained from Land Type Data (Land Type Survey Staff, 2002). The depth of each soil form was obtained from the inventory. The average depth of the specific soil form was then calculated.

For level two the average observed horizon depth was calculated for each soil form. The average profile depth for each soil form was then taken as the sum of the average horizon depths in mm. The mean soil depth for the catchment is the average depth over all the soil forms weighted according to their aerial distribution.

Horizon differentiation

Note that hydrological models refer to soil horizons as the “structure” of the soil. The soils of all the catchments were classified according to Soil Classification: A taxonomic system for South Africa (Soil Classification Working Group, 1991). A short description of the dominant soil forms encountered during the surveys, their horizons and horizon thickness were recorded and will be discussed.

Bulk density (D_b) and therefore porosity (P_o)

Bulk density and porosity were determined on undisturbed core samples from the horizons taken during the field survey.

Infiltration rates

These were determined in the field using a sprinkle infiltrometer as described by Reinders & Louw (1984). It is, however, advised that the data of Hughes & Sami (1993) should rather be used since they made a larger number of determinations using the same procedure.

Texture classes

The particle size distributions were determined with the pipette method (The Non-Affiliated Soil Analysis Work Committee, 1990).

Storativity of rock formations

The range of porosity values for different materials (Table 5.1) will be used to determine the storativity of the rock formation. Note that these are only estimated values.

Table 5.1 Range of porosity values (%) (Dominico & Schwartz, 1990)

Rocks		**Unconsolidated sediments**	
Sandstone	5-10	Gravel	25 – 40
Limestone	0 - 20	Sand	25 – 50
Karstic limestone	5 - 50	Silt	35 - 50
Shale	0 - 10		
Basalt, fractured	5 - 50		
Crystalline rock	0 - 5		
Crystalline rock, fractured	0 – 10		

5.2.3.4 Determining water storage and water release characteristics

The water storage and water release characteristics of the soils in a catchment provide information on how the water recharge and discharge processes occur in a catchment. It is therefore important to define these characteristics. A method for predicting these characteristics is proposed. These results can also facilitate the evaluation of the conceptual models formulated about these processes.

The water storage release characteristics were based on measured drainage curves of similar soils determined elsewhere in South Africa (Hensley *et al.,* 1997 and Hensley *et al*., 2000). From these curves it was possible to obtain suitable factors for relating field saturation (*f* sat.) and drained upper limit (DUL) to D_b. Appropriate values will be given for the soils of all the catchments.

A weighted mean D_b value for the profile was calculated and used to determine an estimated mean P_o value of the whole soil profile. For example if the mean D_b value of an 800 mm deep Sw soil was 1.5 $Mg.m^{-3}$, the P_o value would be 43.4% or 347 mm and the estimated *f* sat. and DUL values would be (0.85 × 347) and (0.70 × 347) mm, respectively. The factors 0.85 and 0.7 are those that experience has shown are suitable values for estimations of *fsat*. and DUL from P_o. Appropriate values for these factors are incorporated in the results presented in Tables 5.18 and 5.20. The estimated “maximum drainable water” (m.d.w.) would therefore be: *f* sat. – DUL = 295 –

243 = 52 mm. As defined here m.d.w. does not take the ET into account. The rate at which this water is expected to drain from the bottom of the solum was obtained by differentiating the drainage curve equation describing the appropriate for the particular soil. This equation will be presented for each soil or soil group. For example:

The field determined drainage curve for a duplex soil similar to the Sw/Va/Se soils in the Bedford catchments was well described ($r^2 = 0.90$) by the following equation:

$\Theta = 442 - 11.43 (\ln t)$ mm.................................. (5.1)

where Θ = water content of the profile (mm)

442 = measured *f* sat. value (mm)

t = drainage time from *f* sat. (hours)

i.e. $d\Theta/dt = -11.43 \times 1/t$ $mm.h^{-1}$..........................(5.2)

Differentiating equation 5.1 gave the drainage rate at different times after drainage starts, and therefore an estimate of the effective drainage rate (K) of the profile at any stage. Taking t as 1 hour therefore gave an estimate of K close to field saturation, in this case, 11.4 $mm.h^{-1}$ during the 1st hour. For the 24th hour K is therefore estimated at 0.5 $mm.h^{-1}$. Based on equation 5.2 it is estimated that the cumulative amount of water (excluding the ET demand) that would have drained from the profile at 1, 2, 4, 6, 15 and 20 days after *f* sat., would be 36, 44, 52, 37, 67 and 71 mm, respectively.

5.3 Results and discussion: soil formation and distribution

Soil genesis and behaviour is a product of the climate impact over time on the geological parent material of the soil manipulated by the topography, and the interactive impact of these factors on the vegetation. Some features of the soils, supported by topographical, geological and vegetation features related to the soil type, reflect the hydrological behaviour of the dominant hillslopes of the catchments. The soil distribution pattern is the same for B4&5 but differs from that of B3. The soil distribution pattern influences the hillslope hydrology of these catchments and the hillslope hydrology influences the soil.

5.3.1Soil depth

Soil depth is mainly a result of the balance between the rate of weathering and the rate of erosion/deposition. Under similar climate and hydro-topographical conditions the rate of weathering of rock is controlled by the nature of the bedrock. The soils in the Bedford catchments are generally shallow, with an average of 215 mm for the selected catchments. There was however a major difference between the average depths of B3 (450 mm) compared to B4&5 (190 mm). The depths of the soils occurring on TMU's varied, (Table 5.2) (Land Type Survey Staff, 2002). These differences may be due to local variation in the rock fractures, both the density and the size of the cracks. The degree of layering and formation of bedding planes may also differ although none of these are easily observed.

Table 5.2 Average soil depths on different TMU's of the hillslopes of catchments B3, B4&5

	Catchment B3		**Catchment B4&5**	
TMU	**% of catchment**	**Average soil depth (mm)**	**% of catchment**	**Average soil depth (mm)**
1	19	251	17	183
2	5	154	1.6	145
3	49	311	63.5	202
4	15	740	10.4	446
5	12	3223	7	606

The deeper soils in B3 can store more water than the soils of B4&5. This promotes more water infiltration, a greater water holding capacity, a greater drainable porosity, a greater volume of water contained at saturation and at drained upper limit. The overall result is more interflow on the A/B horizon boundary and/or the soil/rock interface, with more water contributing to bedrock flow and more plant extractable water in the profile. More available plant extractable water results in more water used for transpiration, more plant growth and a denser plant cover. The soil indicates that the water released to interflow and bedrock flow contributes to perched and regional water tables. The deeper soils on TMU's 4 and 5 of all these catchments are expected to increase these effects. The effect of deeper soils on TMU's 4 and 5 will also be more pronounced in B3 than in B4&5. In B3 the valley bottom is a large, alluvial body of soils of the Oakleaf form. The absence of preferred flowpaths indicates that this soil body serves as a store rather than a conduit of water. It blocks the river channel from the upper part of the catchment. The channel starts again lower down the catchment.

Soil depth is an important factor determining flowpaths and it influences residence times. This influence can be more important in determining residence time than that of the upslope contribution length (Asano *et al*., 2002). The shallow soils, with a small water storage capacity become saturated quickly and overland flow will play a more dominant role due to saturation excess, especially on the steeper slopes of the TMU 3's. More overland flow is associated with a shorter residence time and high peak flow volumes.

5.3.2 Soil type

The degree of physical weathering of the parent rock, visible as cracks, varies between the catchments. An increased degree of physical, and chemical weathering, results in soils of the Glenrosa form to occur in catchment B3 (Figure 5.2 & 5.3). The parent rock in B4&5 are rarely cracked and as a result the soils of the shallow Mispah form shows dominance (Figure 5.4 and Table 5.3). Although the soil fraction is subdominant the cracks in the lithocutanic B horizon serve as a flowpath for drainage water as the underlying rock is fractured. The cracks also serve as channels for preferred flow in recharging the phreatic zone of the hillslope cracked rocks.

Figure 5.2 Soil present in the fissures of the physically weathered rock; typical of the lithocutanic B horizons of catchment B3.

Figure 5.3 A piece of saprolite in an advanced state of chemical weathering observed in TMU 4 of B3.

Table 5.3 Distribution of soils on TMU 1 and 3 of catchments B3 and B4&5

TMU	Soil Form	B3	B4&B5
1	Glenrosa	44%	14%
	Mispah	54%	71%
3	Glenrosa	40%	67%
	Mispah	30%	22%

In catchments B4&5 the bedrock underneath the Mispah soils is impermeable. Thin hair cracks were observed. In a simple field observation no infiltration of water into these hair cracks could be measured. After a rainfall event water was flowing from the Mispah form in small streams (Figure 5.4). It was also flowing the soil at the surface (Figure 5.5). The water infiltrated the soil higher up in the landscape, moved unrestricted vertically through the shallow Mispah soil profile until it encountered the impermeable bedrock. Lateral flow occurred at the soil/bedrock interface. The soil/bedrock interface is an important flowpath in this catchment. It has enhanced erosion in sensitive areas and caused removal of the A horizon, leaving the bedrock exposed. This will increase overland flow during rain events.

Figure 5.4 Return flow visible after rain from Mispah soils (catchment B5).

Figure 5.5 Water was flowing overland as return flow in the area encircled here after a rainfall event in catchment B5.

The presence of trees in shallow soils might be an indication of the existence of cracks serving as conduits towards recharge of regional water tables. The low storage capacity of the shallow soils inhibits tree growth because of their deep rooting inclination and high water consumption. The deep roots of the trees penetrate the cracks and extract water from a phreatic zone (Figure 5.6). This conclusion is supported by the observation in this catchment of rapid recharge of the regional water table as the water levels of boreholes increased immediately after rain, and water flowing into boreholes could be heard, indicating that recharge of the regional water table is from a local origin (Hughes and Sami, 1993).

Mottled sub-soil on TMU 5 in catchment B3 close to the streambed implied that saturated conditions occur in these soils long enough at times to form mottles. Low annual rainfall and high evapotranspiration demand exclude the possibility that these wet conditions could be caused by vertical drainage of local rainfall without additions by interflow. Recharge from upslope through the bedrock is a more likely explanation for the intermittent water table and development of these signs of periodic subsoil saturation. It is therefore seen as a perennial groundwater occurring in peak rain seasons and probably in wet years only.

Figure 5.6 Shrubs and trees growing in the bare rock with cracks near catchment B3.

5.3.3 Local variation in soil depth

Deeper Glenrosa soils and shallow Mispah soils alternate down the hillslopes of both the Bedford catchments B3 and B4&5 to form a stepwise terrain profile (downslope) curvature. This weathering pattern of the sedimentary rocks of the Beaufort Group results in a shelving bedrock character. These shelves influence the redistribution of water in the hillslope. Three weeks after rain it was visible as horizontal streaks of dry vegetation and vegetation with active growth due to the variation in water, profile extractable water and vegetation vitality.

The individual sedimentary layers (shelves) also vary in hardness resulting in a corrugated planform curvature (horizontal). Reddish Mispah soils occur on the ridges and slightly deeper grey Mispah and Glenrosa soils in the hollows. The difference in colour can be attributed to the duration of saturation of the soils during rain events. It is hypothesised that saturation excess water flows diagonally downslope from the shallow Mispah's on the ridges towards the deeper Mispah soils in the hollows.

Longer duration of saturation of the soils in the hollows results in reduction of Fe^{3+} and formation of a bleached colour. An increased vitality of the vegetation on the deeper, bleached soils in the hollows is visible as downslope green streaks (with trees on the lower TMU 3) in the landscape three weeks after the rain (Figure 5.7). Water would tend to move down the slope in the corrugated channels as soil/bedrock interflow.

Figure 5.7 The influence of variation in soil depth is visible as downslope green streaks where the soils are deeper.

Soils of the Cartref form (orthic A / E / lithocutanic B horizon) are evidently expected to occur more frequently in B3 than B4&5 (Land Type Survey Staff, 2002) (Figure 5.8). This could not be confirmed in the survey as very few soils of the Cartref form were observed. The presence of an E horizon is an indication of the presence of a perched water table due to interflow on the A/B horizon interface. It is an indication that at least in some areas the lithocutanic B horizon restricts flow, resulting in transient groundwater on the B horizon and interflow.

Figure 5.8 Cartref soil form in catchment B4. The E horizon is indicated by arrow.

5.3.4 Distribution of lime in the soils and landscape

Calcium carbonate (lime) forms from Ca released from weathering rock and CO_2 dissolved in water. Dissolved lime leaches with draining water and concentrates and precipitates where water evaporates. The limited solubility of lime in water makes it an important indicator of the preferred flowpaths in a hillslope. The redistribution of lime after being released by chemical weathering depends on the leaching factor and presence of water tables. In this environment the leaching factor is controlled by the interaction between climate (precipitation and evaporative demand), permeability of underlying rock, soils (mainly depth and texture) and topography (mainly slope gradient and shape). Lime was absent from the soils on TMU 1 and upper TMU 3 and present in the sub-soils of the lower lying soils in all the catchments. Leaching of lime is effective in the higher lying soils in spite of the impermeable rock in B4&5, implying interflow. However, lime accumulated in the lower lying soils due to interflow water containing an increased amount of $CaCO_3$ in solution reaching these soils, prolongs this process. The lime precipitates in these soils during drying. Lime is also present in bedrock cracks in the transition between TMU 3 and TMU 4 of catchment B4&5. Because lime dissolves where water flows, and precipitates where it evaporates, it is an indication of the storage of small volumes of $CaCO_3$ rich water rather than the cracks being conduits for phreatic water. This observation supports the supposition that perennial groundwater does exist in the lower landscape, but does not play a significant role in hillslope behaviour in B4&5.

The occurrence of soils of the calcareous Augrabies form in the TMU 4 and 5 positions indicate the presence of a perennial groundwater in these and similar arid climates. Interflow water draining downslope is enriched with calcium. Calcium carbonate accumulates in the lower terrain positions as a water table and precipitates during evapotranspiration. The water table is presumably also the cause of mottles in the deep subsoil. Calcareous character was more prominent in the alluvial body of catchment B3. In these soils $CaCO_3$ probably precipitates by capillary action. Interpedal pores serve as aeration channels and dry the soil out, resulting in precipitation of lime on the surface of soil ped faces and the walls of root channels (Figure 5.9). The perennial groundwater probably occurs only in the rain season of extremely wet years. It is not considered transient as it is not rain event driven but rather seasonal. It only leaves signatures where it occurs for significant periods.

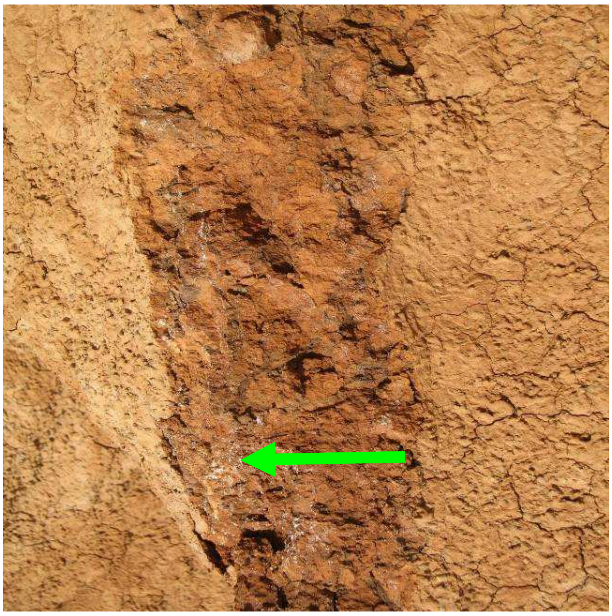


Figure 5.9 Lime precipitated on ped faces in interpedal pores serves as an indicator of the presence of perennial groundwater on TMU 5 of catchment B3.

5.4 Results and discussions: Conceptual models of hillslope hydrology

The hillslope hydrology of the catchments differs. Shallow Mispah soils and impermeable underlying bedrock are the dominant governing factors of flowpaths in catchments B4&5 (Figure 5.10). These factors favour overland flow **(1)** as saturation excess water is added to infiltration excess water and adds to peak flow. This implies short residence times. Infiltrated water flows at the soil/bedrock interface **(2)** and may return to the surface **(3)** in some areas enhancing overland flow. Interflow in the soil plays an important role shortly after rain as indicated by the presence of lime downslope. Infrequent perennial groundwater (**4)** in TMU 5 is indicated by the presence of lime.

Deeper Glenrosa soils and permeable bedrock are the dominant factors governing flowpaths in catchment B3 (Figure 5.11). These factors favour bedrock flow **(1)** recharging the regional water table **(2)** and perennial groundwater **(3)** in the lower part of the hillslope. The presence of E horizons indicates the existence of interflow **(4)** at the A/B horizon interface. This implies longer residence times in the hillslopes. More active perennial groundwater **(5)** is therefore expected. The latter is indicated by the presence of more lime than in B4&5 and the presence of mottles, proof of periodic redox conditions.

These conceptual models of the hydrological behaviour of the hillslopes of catchments B3 and B4&5 are in harmony with the results of Hughes & Sami (1993) and field observations (personal communication Hughes, 2007).

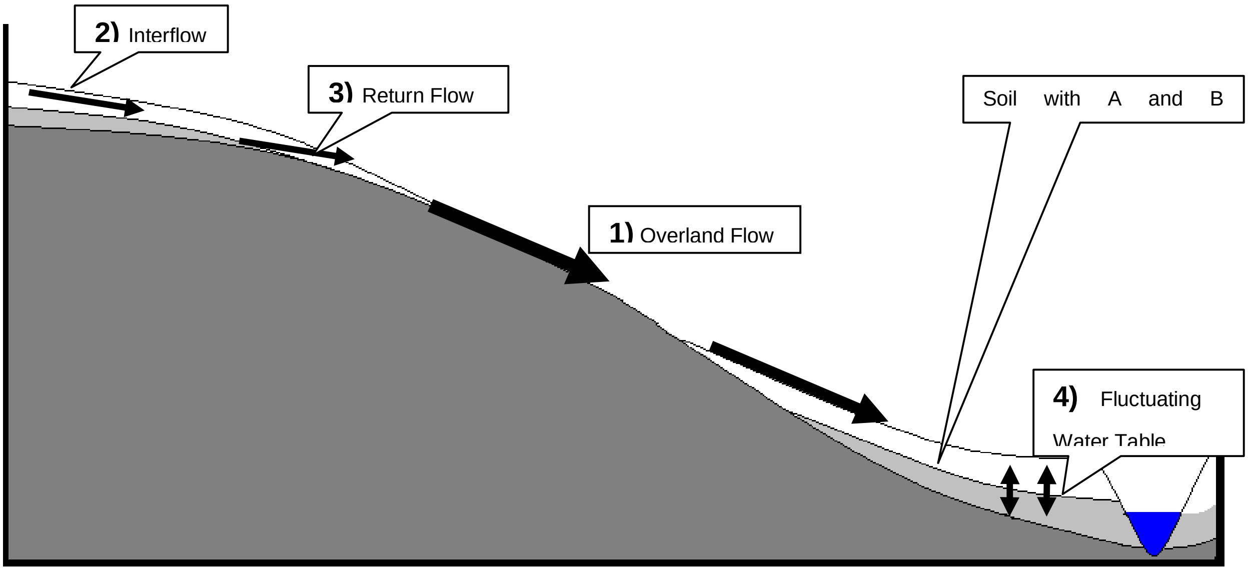


Figure 5.10 Conceptual hillslope behaviour of catchments B4&5.

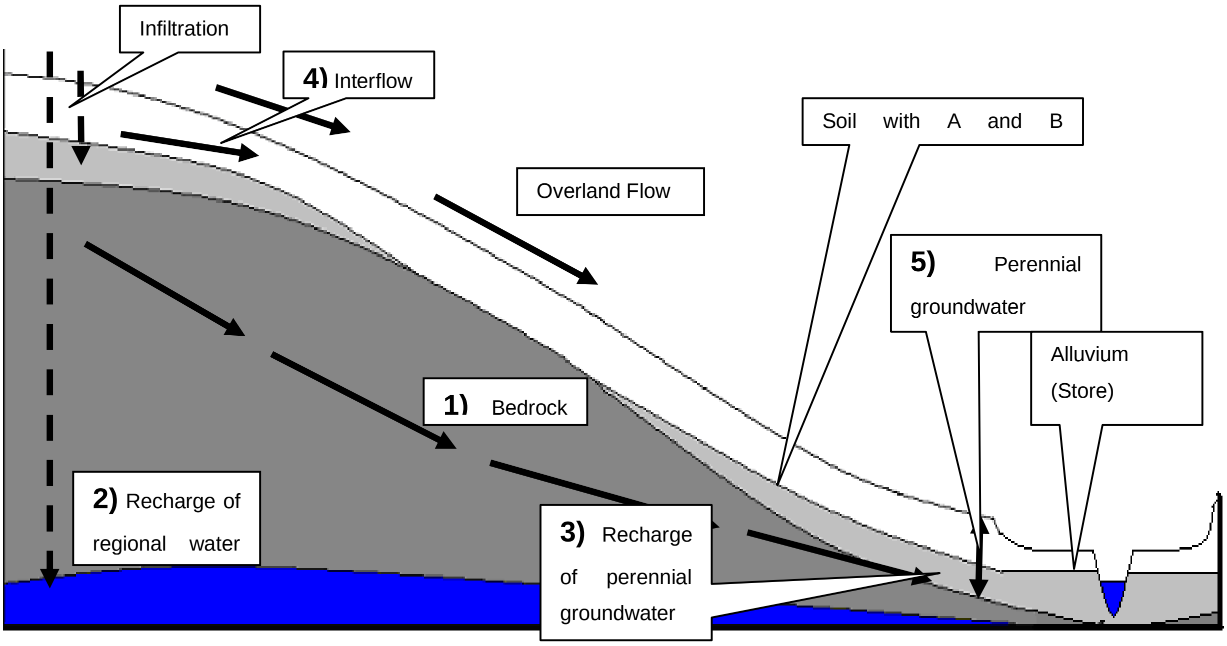


Figure 5.11 Conceptual hillslope behaviour of catchment B3.

5.5 Results and discussion: Evaluation of conceptual models and contribution of soil data to the efficiency of the Pitman model

5.5.1 Soil information for the Pitman model

Soil information obtained by the procedures discussed in section 5.2.3.4 is presented in this section. This information is then used in the Pitman hydrological model.

5.5.1.1 Results (B3)

Input level 1: Land Type data

Soil forms and soil form distribution

Table 5.4 Soil form, TMU distribution and soil depths of Land Type Db 167 (Land Type Survey Staff, 2002) which occupies approximately 50% of catchment B3

TMU		Extent (%)	Soil Form	%	Depth (mm)
1			R	5%	0
			Sw	35%	250
			Ss	30%	350
			Gs	15%	200
			Ms	10%	150
			Hu	5%	350
	Total	**35%**			
3			Sw	35%	250
			Ss	30%	300
			Gs	20%	200
			Ms	5%	150
			Hu	10%	350
	Total	**50%**			
4			Sw	5%	250
			Ss	20%	250
			Gs	5%	200
			Hu	10%	350
			Va	25%	250
			Oa	35%	800
	Total	**10%**			
5			Gs	10%	250
			Va	55%	250
			Oa	35%	800
	Total	**5%**			

Table 5.5 Soil form, TMU distribution and depths of Land Type Fc 537 (Land Type Survey Staff, 2002) which occupies 50% of catchment B3

TMU		**Extent (%)**	**Soil Form**	**%**	**Depth (mm)**
1			Gs	60%	400
			Cf	20%	400
			Ms	20%	250
	Total	**10%**			**350**
3			Gs	68%	400
			Sw	15%	400
			Cf	10%	400
			Ms	5%	250
			Hu	2%	550
	Total	**75%**			**400**
4			Gs	20%	400
			Sw	30%	400
			Oa	30%	900
			Hu	10%	550
			Va	10%	800
	Total	**10%**			**610**
5			Gs	5%	400
			Sw	20%	400
			Oa	40%	900
			Hu	5%	550
			Va	30%	800
	Total	**5%**			**610**

Table 5.6 Weighted average soil form distribution (%) in Land Type Db 167 (50% of catchment B3) and Fc 537 (50% of catchment B3) (Land Type Survey Staff, 2002)

Soil Form	Extent (%)
R	1
Sw	22
Ss	13
Gs	38
Ms	6
Hu	5
Va	4
Oa	5
Cf	5

Soil depth

Table 5.7 Mean soil depth of Land Type Db 167 and Fc 537 (Land Type Survey Staff, 2002)

Soil Form	Mean depth (mm)
R	0
Sw	325
Ss	250
Gs	300
Ms	200
Hu	450
Va	500
Oa	850
Cf	400

The weighted mean soil depth according to the Land Type Data is **335 mm.** This is calculated as the mean soil depth of the specific soil form multiplied by the percentage of coverage of that form. Since the Land Type Data does not distinguish between the depths of different horizons, it is assumed in this study that the depth of the A horizons are 200 mm; E horizons are 100 mm and B & C horizons are the remaining depth of the profile.

Final infiltration rates

Infiltration rates are controlled by slope, soil cover and antecedent water content besides soil properties. It is therefore recommended that the final infiltration values of Hughes & Sami (1991) be used. Their most dependable mean value will be obtained under Korroid vegetation on crusted Mispah and Glenrosa forms i.e. 1.73 mm.h^{-1}.

Texture classes unconsolidated

Table 5.8 Average particle size distribution for different horizons

	Particle size distribution (%)						
Horizon	**CoSa**	**MeSa**	**FiSa**	**veFiSa**	**CoSi**	**FiSi**	**Cl**
ot	5	3.6	17.9	20.8	10.0	13.9	27.8
vp	3.7	3.6	14.8	24.5	10.5	9.3	32.9
ne	5.9	4.7	15.7	16.3	12.7	10.8	32.7
so	2	2.2	17.4	19.5	9.5	2.5	46.5
Mean	4.9	4.0	16.1	20.5	11.1	11.3	31.1

Storativity of subsurface formations

A value of 2-5% is estimated for the porosity of catchment B3.

Input level 2: Transect survey data

Soil forms and soil form distribution

Table 5.9 Distribution of observed soil forms on different TMU's and their depths in catchment B3

TMU		Extent (%)	Soil Form	%	Depth (mm)
1			Ms	54%	217
			Gs	41%	249
			Pn	4.50%	700
	Totaal	**19%**			
2			Ms	62.50%	164
			Gs	25%	205
			R	12.50%	0
	Totaal	**6.80%**			

Table 5.9 continued

3			Ms	31.50%	114
			Gs	40.50%	296
			Sw	16%	546
			Va	5.20%	850
			Cf	3.50%	450
			Se	1.70%	450
			R	1.70%	0
	Totaal	**49%**			
4			Gs	5%	150
			Sw	29%	714
			Va	23.50%	865
			Se	12%	435
			Oa	5%	530
			Ag	12%	700
			Du	12%	1325
	Totaal	**15%**			
5			Sw	7%	628
			Du	8.00%	1163
			Pn	6.60%	1000
			Oa	80.00%	5000
			Ss	2.00%	1000
	Totaal	**12%**			

Table 5.10 Weighted mean distribution of observed soil forms, catchment B3

Soil form	Extent
Ms	29%
Gs	30%
Sw/Va/Se	22%
Cf	2%
Oa	10%
Ag	4%
R	2%

Soil depth

Table 5.11 Weighted mean depth of soil forms and horizons, catchment B3

Soil form	Profile depth (mm)	Horizon	Horizon depth (mm)
Sw/Va/Se	900	ot	200
		vp	600
		ud/uw	100
Gs	400	ot	200
		li	200
Cf	500	ot	200
		E	100
		li	200
Ms	200	ot	200
		R	0
Oa	2200	ot	200
		ne	2000
Ag	1300	ot	200
		nc	1100
R	0	R	0

The mean soil depth according to observed data of this catchment is **658 mm.** This was calculated as the mean depth of the different soil forms as a fraction of the area which is covered by a specific form

5.5.1.2 Results (B4&5)

Although the observed soil forms in these catchments were the same as in B3 (Table 5.6), there were differences in the mean depth (Table 5.7) and distribution of soil forms between the catchments. There will therefore be differences in the m.d.w. and the mean soil volume between catchment B3 and B4 & B5.

Input level 1: Land type data

Soil forms and soil form distribution

Table 5.12 Distribution of soil forms, TMU's and depths in Land Type Fc 545 (Land Type Survey Staff, 2002) representing catchments B4&5

TMU		Extent (%)	Soil Form	%	Depth (mm)
1			Gs	70%	250
			Ms	20%	250
			Cf	10%	250
	Totaal	**5%**			
3			Gs	80%	250
			Sw	8%	400
			Ms	5%	250
			Cf	5%	250
			Hu	2%	550
	Totaal	**80%**			
4			Gs	20%	250
			Sw	20%	400
			Oa	30%	900
			Va	20%	800
			Hu	10%	550
	Totaal	**10%**			
5			Gs	5%	250
			Sw	20%	400
			Oa	40%	900
			Va	30%	800
			Hu	5%	550
	Totaal	**5%**			

Table 5.13 Weighted mean soil form coverage in Fc 545 (Land Type Survey Staff, 2002), representing catchments B4&5

Soil form	Extent (%)
Gs	70%
Ms	5%
Cf	5%
Sw	9%
Hu	3%
Oa	5%
Va	4%

Soil depth

Table 5.14 Weighted mean depth of soils in Land Type Fc 545 (Land Type Survey Staff, 2002) representing catchments B4&5

Soil form	Mean depth (mm)
Gs	250
Ms	250
Cf	250
Sw	400
Hu	550
Oa	900
Va	800

The weighted mean depth of the soils in B4&5 according to Land Type Data is **330 mm.** This value was obtained by multiplying the mean depth of a specific soil form with the relative coverage in the Land Type. Since the Land Type Data does not distinguish between the depths of different horizons, it is assumed in this study that the depth of the A horizons are 200 mm; E horizons are 50 mm and B & C horizons are the remaining depth of the profile.

Final infiltration rates

See final infiltration values for catchment B3.

Texture classes

The particle size distribution is the same as for B3 (Table 5.10).

Storativity of subsurface formations

A value of 0-1% is estimated for the porosity of catchments B4 & B5

Input level 2: Transect survey data

Soil forms and soil form distribution

Table 5.15 Distribution of observed soil forms on different TMU's and soil depths in catchments B4&5

TMU		Extent (%)	Soil Form	(%)	Depth (mm)
1			Ms	71%	158
			Gs	14%	403.33
			Sw	4.70%	300
			R	9.50%	0
	Total	**17%**			
2	**Total**	**1.60%**	**Ms**	**100%**	
3			Ms	70.80%	136
			Gs	21.50%	278
			Sw	2.53%	600
			Oa	2.53%	600
			Va	2.53%	600
	Total	**63.50%**			
4			Ms	38.50%	218
			Gs	15%	330
			Sw	30.70%	725
			Oa	15%	600
	Total	**10.40%**			
5			Ms	11%	400
			Oa	11%	750
			Sw	11%	520
			Va	11%	800
			Se	11%	900
			Ka	22%	560
			Ag	22%	510
	Total	**7%**			

Table 5.16 Weighted average coverage (%) of observed soil forms in catchment B4 & B5

Soil form	Extent (%)
Ms	60.00
Gs	18.00
Sw/Va	8.00
Oa	4.00
Ag	2.00
R	8.00

Soil depth

Table 5.17 Weighted mean depths of observed soil forms and horizons in catchments B4&5

Soil form	Profile depth (mm)	Horizon	Horizon depth (mm)
Ms	200	ot	200
		R	0
Gs	400	ot	150
		li	250
Sw/Va	700	ot	300
		vp	300
		ud/uw	100
Oa	700	ot	300
		ne	400
Ag	500	ot	200
		nc	300

The weighted mean soil depth of these catchments is **286 mm.** This is expressed as the product of the mean depth of a soil form and the percentage of the catchment covered by this soil form.

Final infiltration rates

See final infiltration values for catchment B3.

Texture classes

The particle size distribution is the same as for B3 (Table 5.10).

Storativity of subsurface formations

A value of 0-1% is estimated for the porosity of catchments B4 & B5

5.5.1.3 Summary of soil information for Pitman model

Table 5.18 presents a summary of the different levels of soil information incorporated in the Pitman model.

Table 5.18 Summary of the two different levels of inputs for the different catchments used by the Pitman model

	Characteristic	B3	B4&5
	Soil texture	SaCl	SaLm
Level 1	Mean soil depth	335 mm	330 mm
	Mean porosity	38.8 %	46.6%
	Infiltration rate	1.73 mm.h^{-1}	1.73 mm.h^{-1}
	Subsurface storativity	5 %	1%
	Soil texture	SaClLm	SaLm
Level 2	Mean soil depth	658 mm	286 mm
	Mean porosity	43.9 %	42.6 %
	Infiltration rate	1.73 mm.h^{-1}	1.73 mm.h^{-1}
	Subsurface storativity	5%	1%

5.5.2 Results from the Pitman hydrological model

The soil information was incorporated into the Pitman hydrological model. The results of the simulations run on the gridded Bedford basin to assess the influence of the differences in the soils data between B3 and B4&B5 are presented in Figure 5.12. Since there are no historical flow records for the catchments a ‘best guess’ time series estimate was used as basis for assessment. This ‘best guess’ estimates is basically a lumped weighted average of the data of the 3 sub catchments. The appropriateness of the soil data for the model would thus be judged by its ability to produce identifiable, hydrologically plausible parameters.

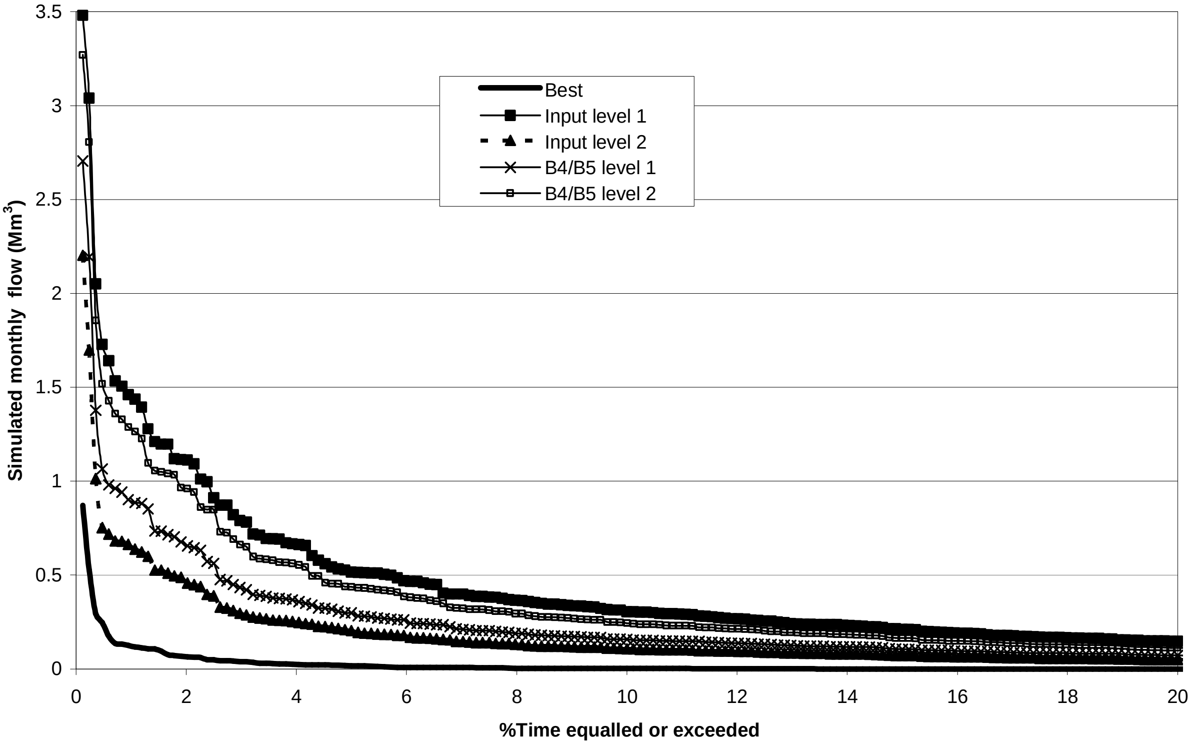


Figure 5.12 Flow duration simulations for catchment B3 using different types of input levels. The first two levels of input refer to those for catchment B3 (After Kapangaziwiri, personal comunication, 2008).

The scale issue as well as topographical influences are illuminated with this method of simulation. This is because the different input levels are applied for the same catchment. Differences in the simulations are therefore the result of different soil inputs.

It can be seen from the diagram that the simulation derived from using input level 1 for B3 to estimate parameters resulted in much higher outflow than when using input level 2 for the catchment. For example the model predicts that a similar monthly outflow of 0.5×10^6 m^3 is only equalled or exceeded 2% of the time on B3 when level 2 (soil survey) data is used, whereas using level 1 (Land type) data the equivalent volume is around 6% of the time. The difference between the simulated outflows for this catchment is caused by the differences in the average soil depths (335 mm for level 1 and 658 mm for level 2). It is clear that the Pitman model identifies the fact that the deeper soils will absorb more of the rainfall and therefore depress the amount of runoff.

The difference between the simulated outflows between the different input levels of B4&5 can also be attributed to differences in the average soil depth. The average depth of level 1 inputs for B4&5 is 330 mm whereas the average depth for level 2 is 286 mm. Compared to B3 the comparison is reversed here as level 1 data predicts a deeper average soil depth than level 2 for catchment B4&5. Here it is predicted that a simulated monthly outflow of 0.5 × 10^6 m^3 is only equalled or exceeded about 2.6% of the time using level 1 data whereas the equivalent figure using level 2 data is about 4.2%. More outflow can therefore be expected using level 2 inputs compared to level 1 as infiltration and storage is enhanced in the slightly deeper soils.

It is interesting to note that although the average soil depth according to level 1 inputs for catchment B3 is the second highest (i.e. 335 mm), the highest flow volumes is simulated using these inputs. This might be due to the low porosity values associated with this level of input. The mean porosity for the Land type data (level 1) of B3 was incorrectly calculated by the hydrologist. The mean porosity obtained, 38.8% (Table 5.18) did not take into account the porosity of the Sterkspruit soil forms which occupy approximately 13% of this catchment according to the Land type data (Table 5.6). If the porosity of this additional soil form had been taken into consideration the mean porosity of the soils of this catchment would have been 44.9% (based on Tables 5.6 and 5.7 and a mean weighted bulk density of 1.52 $Mg.m^{-3}$). This causes the simulated curve to move closer to the horizontal axis, i.e. predicting fewer outflows because of the greater capacity of the soils to absorb rainfall. The simulated outflow curve will therefore be very similar to that of level 1 input data of catchment B4&5 since the mean porosity (44.9% for B3 and 46.6% for B4&5) and the mean soil depths (335 mm for B3 and 330 mm for B4&5) are very similar. The influence that porosity values have on the simulation model is noteworthy and accentuates the importance of correct input values.

The best guess parameters used for the relevant outflow curve in Figure 5.12 include the storativity of the subsurface layers (5%), which explains the very low simulated outflow. The influence of the storativity is magnified in Figure 5.13, where the low storativity of catchment B4&5 (1%) resulted in much higher simulated streamflow compared to catchment B3.

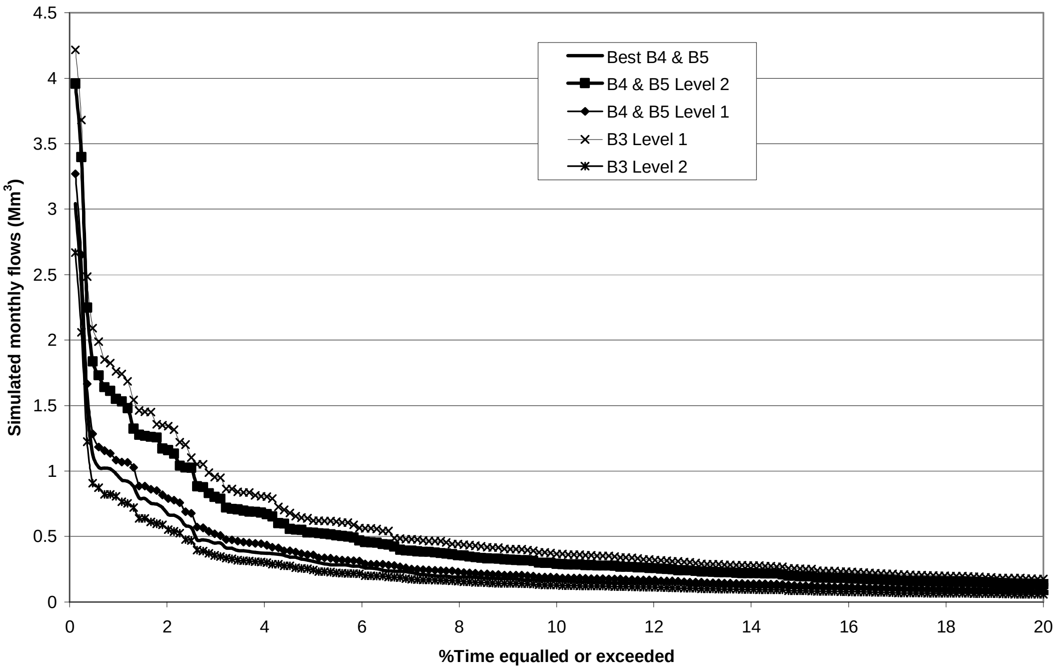


Figure 5.13 Flow duration curves for catchment B4&5 using different soil input levels for different catchments (After Kapangaziwiri, personal comunication, 2008).

The results presented in Figure 5.13 are very similar to that obtained for catchment B3. The only difference is the lower storativity of the subsurface formations. The lower storativity of B4&5 correspond with the higher simulated streamflow.

5.5.3 Results of the predicted water storage and release characteristics

Water storage and release characteristics can aid in the evaluation of the conceptual models since they reveal how the recharge and discharge will take place in the catchment. They are also useful for determining the storativity of catchments. These characteristics, based on observed soil observations in the three sub-catchments are presented in Tables 5.19 – 5.22.

Table 5.19 Description of selected "weighted average" characteristics of observed soil profiles in catchment B3

Soil form	**Horizon**	**Depth (mm)**	**D_b (mg.m^{-3})**	**Weighted mean D_b (mg.m^{-3})**	**Po (%)**	**Po (mm)**	***fsat* (mm)**	**DUL (mm)**	**m.d.w. (mm)**
Sw/Va/Se	ot	200	1.39	1.52	42.6	383	326	268	58
	vp	800	1.56						
	vd/uw/on	900	1.56						
Gs	ot	200	1.39	1.50	43.4	174	104	70	34
	li	400	1.60						
Cf	ot	200	1.39	1.53	42.3	212	127	85	42
	E	300	1.65						
	li	500	1.60						
Ms	ot	200	1.39	1.39	47.5	95	81	57	24
	R								
Oa	ot	200	1.39	1.35	49.1	1080	864	724	140
	ne	2200	1.34						
Ag	ot	200	1.39	1.35	49.1	638	511	427	84
	nc	1300	1.34						

*m.d.w = maximum drainable water

Table 5.20 Estimated drainage rates of different profiles of catchment B3

Soil form	**Drainage equation**	**Drainage rate (mm.h^{-1})**	
		1st hour	**24th hour**
Sw/Va/Se	**$-11.43 \times 1/t$**	11.4	0.5
Gs	**$-10.3 \times 1/t$**	10.3	0.5
Cf	**$-10 \times 1/t$**	10.0	0.4
Ms	**$-10 \times 1/t$**	10.0	0.4
Oa	**$-15.3 \times 1/t$**	15.3	0.8
Ag	**$-15.3 \times 1/t$**	15.3	0.8

Table 5.21 Description of selected “weighted average” characteristics of the observed soil profiles in catchments B4&5

Soil form	**Horizon**	**Depth (mm)**	**D_b (mg.m^{-3})**	**Weighted mean D_b (mg.m^{-3})**	**Po (%)**	**Po (mm)**	***fsat* (mm)**	**DUL (mm)**	**m.d.w. (mm)**
Sw/Va/Se	ot	300	1.39	1.49	43.88	307	261	215	46
	vp	600	1.56						
	vd/uw/on	700	1.56						
Gs	ot	150	1.39	1.52	42.59	170	102	68	34
	li	250	1.60						
Ms	ot	200	1.39	1.39	47.5	95	81	57	24
	R								
Oa	ot	300	1.39	1.36	48.63	340	272	228	44
	ne	700	1.34						
Ag	ot	200	1.39	1.36	48.68	243	195	163	32
	nc	500	1.34						

*m.d.w = maximum drainable water

Table 5.22 Estimated drainage rates of different profiles B4&5

Soil form	**Drainage equation**	**Drainage rate (mm.h^{-1})**	
		1st hour	**24th hour**
Sw/Va	**-11.43 × 1/t**	11.4	0.5
Gs	**-10.3 × 1/t**	10.3	0.5
Ms	**-10 × 1/t**	10.0	0.4
Oa	**-15.3 × 1/t**	15.3	0.8
Ag	**-15.3 × 1/t**	15.3	0.8

The storage capacity of the soil is considered as the water content of the soil between *fsat* and the lower limit (LL) of plant available water. It is assumed that water held below LL does not drain out of the catchment and is not extracted by evapotranspiration. LL values have been estimated for different depths under grassland vegetation using data from other studies. They are expressed as a fraction of porosity i.e. S. The estimated values where:

0 – 200 mm → S ≈ 0.2

200 – 1000 mm → S ≈ 0.3

> 1000 mm → S ≈ 0.5

These values were then used to determine the storage capacity of the different soil forms (using the depths and *fsat* values of Tables 5.19 and 5.21) of the different catchments as presented in Table 5.23. A calculation example is given as follows for the Ms soil in Table 5.19: Po for the soil is 95 mm; since the soil is 200 mm deep the appropriate S value at LL is 0.2; 0.2 × 95 mm = 0.019 m. The storage capacity for the catchments was then calculated using the LL values in Table 5.23, the *fsat* values for each soil in Tables 5.19 and 5.21, and the areas of each soil in Tables 5.10 and 5.16. An example of the calculation procedure, in this case for the contribution of Sw/Va/Se to B3, is as follows:

$$\text{Storage } (m^3)\ fsat\ (m) - LL\ (m) \times \text{area covered by soil form } (m^2) \ldots\ldots_{(5.3)}$$

$$\text{i.e } 0.326 - 0.105 \times (0.22 \times 40300000) = 1959386\ m^3$$

Results are presented in Table 5.24. The storage capacity estimated for the Pitman model was provided by the cooperating hydrologist (Kapangaziwiri, personal comunication, 2008). Estimates of the maximum water which can possibly drain from the catchments (m.d.w) based on our observations, are also presented in Table 5.24.

Table 5.23 Estimated Lower limit (LL) values of water storage capacity (m) for different soil forms in catchments B3 and B4&5

	Weighted LL values (m)	
Soil forms	B3	B4&5
Ms	0.019	0.019
Gs	0.043	0.043
Sw/Va/Se	0.105	0.081
Cf	0.054	
Oa	0.418	0.093
Ag	0.212	0.064

Table 5.24 The weighted storage capacity (based on observed and data that are estimated for the Pitman model) and maximum drainable water (m^3) for catchments B3 and B4&5

Catchment	Area (km^2)	m.d.w (m^3)	Observed data Storage capacity (m^3)	Pitman model Storage capacity (m^3)
B3	40.3	1939236	5759676	10518300
B4&5	48.8	1298080	3513600	6148800

Although the area is smaller, the storage capacity of the soil is 49% greater in B3 compared to B4&5. Since the bedrock in catchment B4&5 is assumed to be impermeable the porosity of the soil can serve as an indication of the storage capacity of the catchment. This implies that when catchment B4&5 is at LL, 72 mm ($0.072 \times 48.8 \times 10^6 = 3513600$) rain will bring the catchment, if no runoff occurs, to the full storage capacity of the catchment (ET not taken in account). Similarly assuming that the storativity of the bedrock in catchment B3 is also zero, 143 mm rain will be needed to bring this catchment to field saturation. This difference in the storage capacity is due to deeper soils in catchment B3 compared to B4&5 and especially to the contribution of the Oakleaf and Augrabies soil forms in the alluvial layer which contributes to approximately 40% of the storage capacity of catchment B3.

The Pitman model over estimated the storage capacity for both catchments. This might be because during the parameterisation of the maximum storage capacity (ST), the porosity instead of field saturation (*fsat*) values were used. The equation for ST_{soil} according to Kapangaziwiri *et al.,* (2008):

$$ST_{soil} \text{ (mm)} = \text{POR (\%)} \times \text{VVAR (\%)} \times \text{Soil depth (m)}/10 \ldots\ldots\ (5.4)$$

where: POR = porosity

VVAR = correction factor for vertical variations in POR (0.9 used during this study)

We know that under field conditions soils never saturates to 100% of porosity and it is therefore advised that *fsat* values instead of porosity be used. It is evident from the results in Tables 5.19 and 5.21 that the maximum value of the ration *fsat/*Po (i.e. equivalent to VVAR in equation 5.4) used for observed data is 0.85, and sometimes only 0.6. The choice of these factors is based on field experience. The LL value has also not been taken into account for the Pitman estimate. This influences the storage capacity to a great extent especially in the deeper soils of catchment B3 (> 1000 mm) where this value is estimated to be more than 50% of the porosity.

Figure 5.12 presents the outflow based on the area of catchment B3 using the soil parameters of both catchments B3 and B4&5 to produce the separate graphs. The difference between the outflow curves are therefore due to the difference in the storage capacity of the catchments since the area used for both simulations was 40.3 km^2. The mean slope of these curves differs and it is postulated that the ratio between the mean slopes of the curves should be correlated with the ratio between the storage capacities of the catchments. Linear regression lines were created to obtain the mean slopes. Outflows lower than 0.05 × 10^6 m^3 were not taken into account. The linear regression lines and equations are presented in Figure 5.14.

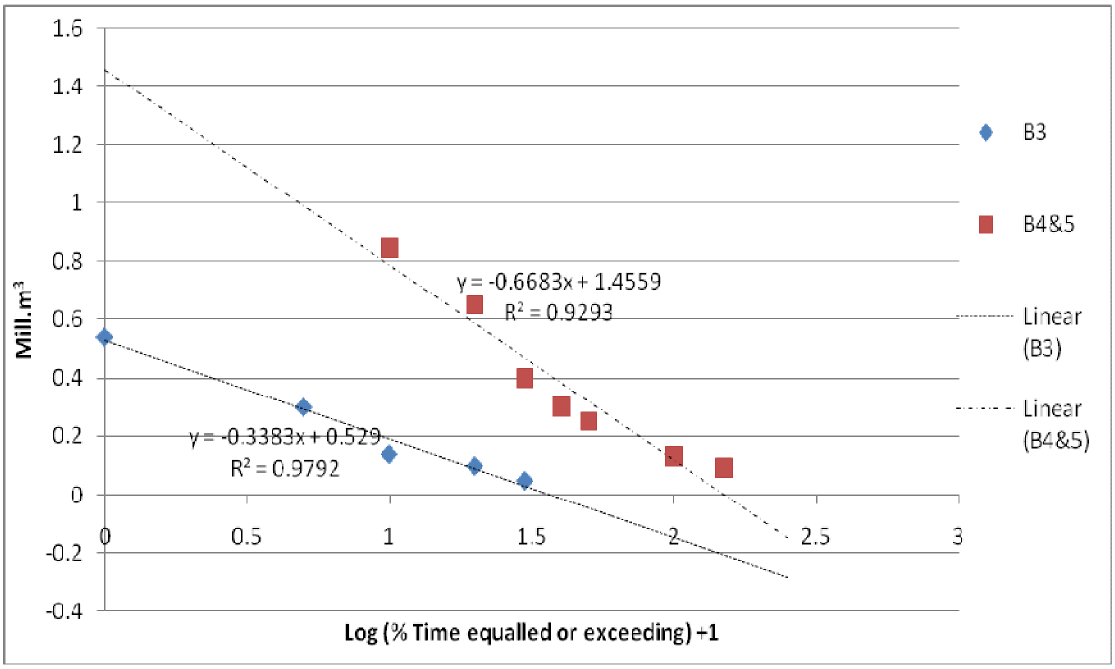


Figure 5.14 Linear regression lines for the outflow of catchment B3 > 0.05 × 10^6 m^3, predicted by the Pitmain model and interpreted from the results in Figure 5.12.

Thes slope of the two regression lines are 0.668 and 0.338 when using soil data from B4&5 and B3, respectively.

The ratios between these slopes and the ratios of the storage capacities of the two catchments are presented in Table 5.25. The storage capacity of B4&5 is expressed in terms of the area of B3 (40.3 km^2) since that is the area used for the predicted outflows in Figure 5.12 and 5.14, i.e. 2901600 = 40.3/48.8 × 3513600.

Table 5.25 Ratios between mean slopes of outflow curves and storage capacities of catchments B3 and B4&5.

Catchment	Mean slope	Ratio	Storage capacity (m^3)	Ratio
B3	-0.668	1.98	5759676	1.99
B4&5	-0.338		2901600	

There is a very good correlation between ratios of the storage capacities and the mean slopes of the outflow curves (Table 5.24). This illustrates the influence of the storage capacity of the catchment on outflow from the catchment. The greater capacity of catchment B3 to store water, results in lower simulated outflow associated with this catchment because of the deeper soils being able to absorb more of the rainfall than the shallower soils of B4&5.

The m.d.w. data in Table 5.24 shows that the volume of water which can possibly drain from catchment B3 is 49% more than that of catchment B4&5. This is due to a greater average soil depth in catchment B3.

It is postulated that the drainage equations in Tables 5.20 and 5.22 can reveal information on how, under certain circumstances, water would drain out of the catchment. The following assumptions were made to simplify the catchment's hydrological characteristics and define the relevant 'particular set of circumstances':

- The catchments became saturated by continuous low intensity rainfall which caused no runoff and then the catchments drained from *fsat* and no rain fell during the drainage period.
- The drainage network is simplified to one stream flowing in a straight line through the entire catchment.
- The area contributing directly to streamflow is assumed to be the mean depth of the soils in the TMU 5 position multiplied by the length of the stream.
- Topographical differences were ignored, since runoff has been excluded as a factor in this hypothesized exercise.
- There is a constant interflow of water towards this contribution area as long as there is drainable water in the catchment (i.e. until m.d.w. = 0).
- The daily ET is estimated as 87% of potential ET divided by 365 (based on findings of Liu, Graham & Jacobs (2005) on sandy and clayey soils under different vegetations).

- The drainage equation (Tables 5.20 and 5.22) used is the average equation for all soils present in the TMU 5 position.

Based on these assumptions the areas contributing to streamflow and the daily ET were calculated and are presented in Tables 5.26 and 5.27

Table 5.26 The areas (m^2) contributing to streamflow in catchments B3 and B4&5

Catchment	Stream length (m)	Weighted mean soil depth (m)	Contribution area (m^2)
B3	10200	1.844	**37618**
B4&5	16000	0.557	**17824**

Table 5.27 The estimated average daily ET (m^3) for catchments B3 and B4&5

Catchment	Area (m^2)	Potential ET ($mm.year^{-1}$)	Estimated actual ET ($mm.year^{-1}$)	Daily ET (m)	Daily ET (m^3)	ET ($m^3.h^{-1}$)
B3	40300000	1400	1218	0.00334	134481	5603
B4&5	48800000	1400	1218	0.00334	162845	6785

The equations used to determine the outflow from the different catchments are presented in Table 5.28.

Table 5.28 Drainage equations for streamflow contribution areas of catchments B3 and B4&5

Catchment	Weighted mean equation	Equation for contribution area
B3	$d\Theta/dt = -14.48 \times 1/t\ mm.h^{-1}$	$d\Theta/dt = -544.7 \times 1/t\ m^3.h^{-1}$
B4&5	$d\Theta/dt = -13.75 \times 1/t\ mm.h^{-1}$	$d\Theta/dt = -245.1 \times 1/t\ m^3.h^{-1}$

These equations were used to simulate the outflow from the catchments in hours after *fsat* (Figure 5.15). Water losses from the catchment by ET were accounted for using the estimates in Table 5.27.

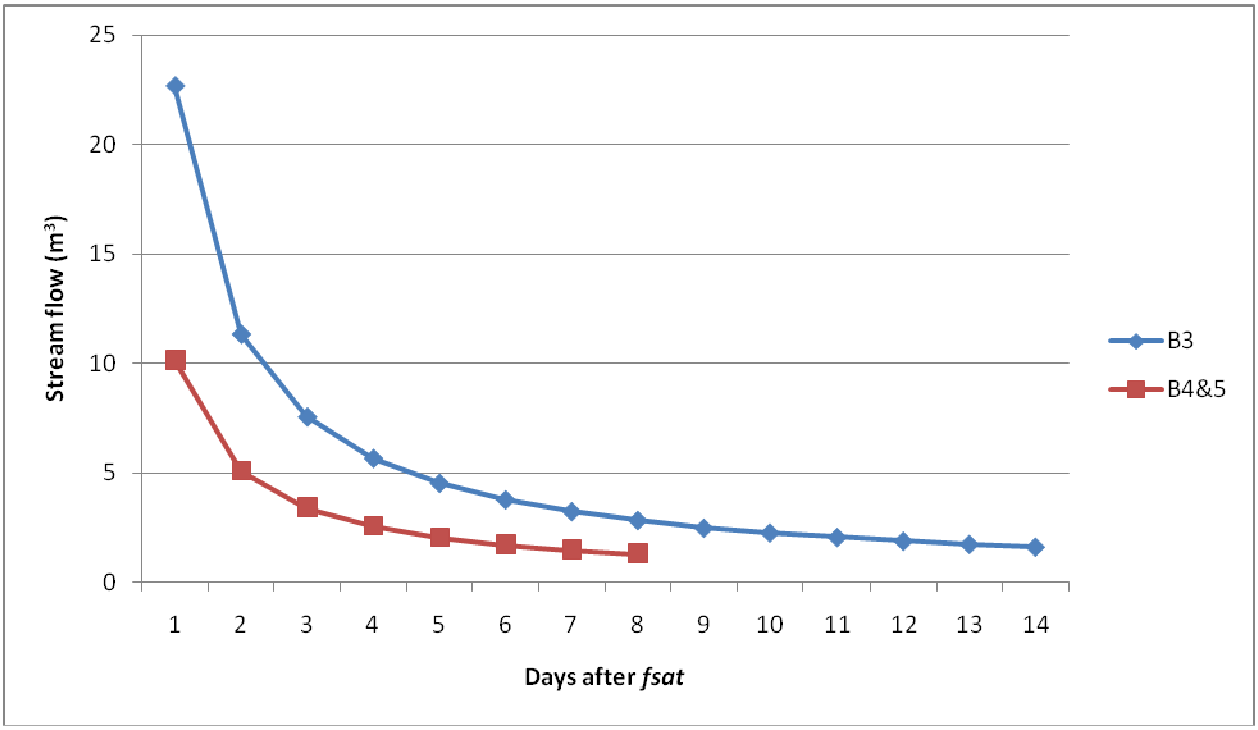


Figure 5.15 Estimated streamflow (m^3), all of it originating from interflow, i.e. interflow water only, from catchments B3 and B4&5 in days after *fsat* based on the drainage equations presented in Table 5.28.

Figure 5.15 is the predicted shoulder of a typical hydrograph of the catchments. The deeper soils of catchment B3 facilitate longer and a greater volume of streamflow from this catchment compared to B4&5. Since ET was taken into account, this graph indicates that the contribution to evaporation is higher in B3 than in B4&5. This is in harmony with the conceptual models in section 5.4, which are based solely on morphological properties. It is necessary to understand clearly that the differences between the graphs in Figure 5.12 (Pitman predictions) and 5.15 are due to the fact that the formers focus was on overland flow only and the latter is on in interflow only.

5.6 Conclusions

Soil indicators and their links with bedrock and topographical characteristics revealed information on hillslope hydrological processes. Soil indicators of flowpaths, residence times and storage mechanisms may be useful in developing conceptual models of characteristic hillslope behaviour. It has been demonstrated that these conceptual models contributed to improved prediction of the hydrological behaviour of hillslopes and catchments. Although interpretations of soil indicators can play a role in understanding the hydrology of gauged catchments, they may be much more valuable in predictions of the hydrological behaviour in ungauged catchments.

Evaluation of the conceptual models via the Pitman hydrological model reveals the accuracy of the models. The storage capacity is one of the dominant factors influencing simulated outflow (through overland flow) from the catchment. There is an indirect correlation between the storage capacity and the volume of outflow (overland flow).

A method for determining interflow from an ungauged catchment is proposed. The estimated outflow (through interflow) obtained from this method is in harmony with the conceptual model.

CHAPTER 6
THE WAY FORWARD

6.1 Introduction

Soil properties can serve as indicators of hillslope hydrological behaviour. Although these properties are not dynamic in nature, as the hydrological processes responsible for their formation, they nevertheless have a governing influence on the hydrological processes and/or give an indication of dynamic hydrological processes. The existence of soil bodies implies that variation of the soil properties is not random. This enables the interpretation of hydrological behaviour of soil properties to facilitate the prediction of key hydrological processes, especially useful in ungauged basins.

The soil forms of the South African soil classification system (Soil Classification Working Group, 1991) carry valuable information regarding soil properties and their hydropedological significance. This is also true for the diagnostic soil horizons which play the major role in the definition of forms. For example, it is accepted in soil science that wet soils occur in landscapes. The nature of these wet horizons, is described in non-quantitative terms in the classification system of South Africa as follows:

- **G horizon** is defined as *“saturated with water for long periods”*;
- the **E horizon** as *“a temporary build up of water above the B horizon …discharge in a predominantly lateral direction”*;
- the **soft plinthic B horizon** has redox morphology that formed *“under conditions of a fluctuating water table”*;
- the **hard plinthic B horizon** is referred to as a mature equivalent of the soft plinthic B horizon;
- **unconsolidated material with signs of wetness** is defined by soil morphology *“that is evidence of wetness”*;
- **unspecified material with signs of wetness** is defined as a morphology *“has grey, low chroma matrix colours that have been caused by wetness”*;.

Interpretations of these properties are useful in the understanding of hillslope hydrology as was shown with the development of conceptual hillslope hydrological response models for Bedford and Weatherley. Improved qualitative and quantitative definitions could enhance the soil science contribution to the understanding of hillslope hydrological processes and hydrological modelling, especially with PUB. The current classification system has not been appropriately adapted for application in hydrological modelling as the focus has traditionally been predominantly towards agricultural. An appropriately adapted system, which can be understood and applied by hydrologists, focussing specifically on the hydrological behaviour of soils is needed.

This chapter describes preliminary ideas on a hydrological classification of the soil types of South Africa. Related pioneering work in this direction is presented in the publication 'Hydrology of soil types (HOST): a hydrologically based classification of the soils of the United Kingdom' (Boorman, Hollist & Lilly, 1995). This is a hydrological classification system of the soils based on their predicted hydrological response. It has evidently made a dramatic impact on the hydrological modelling in the UK. An example of the application of HOST is presented in Figure 6.1. This study, conducted by Soulsby *et al.* (2007), in Girnock, Scotland, illustrates the influence of soil properties and their position in the landscape on hydrological processes. The main soils were peaty gleys and peaty podzols (HOST class 15). These soils occur on the lower slopes and concave areas with small gradients. They are typical of the soils that occur on midslopes and lower slopes according to Figure 2.1 (Ticehurst *et al*., 2007). They are saturated for most of the year and generate shallow lateral flow in organic surface horizons as well as saturation excess overland flow. The contribution to groundwater recharge of the peaty gleys is limited.

In Figure 6.1, the second most extensive soils were freely drained brown soils, humus iron podzols and deeper sub-alpine soils (HOST class 17). They are found on the steeper slopes. Vertical water movement in these soils causes groundwater recharge and in some cases deep sub-surface flow at the soil bedrock interface that can be expected to contribute to interflow. In this study, freely drained alluvial deposits and soils (HOST class 5), were found in the main river valley. Recharge of groundwater was limited due to the inclined nature of the upper slopes.

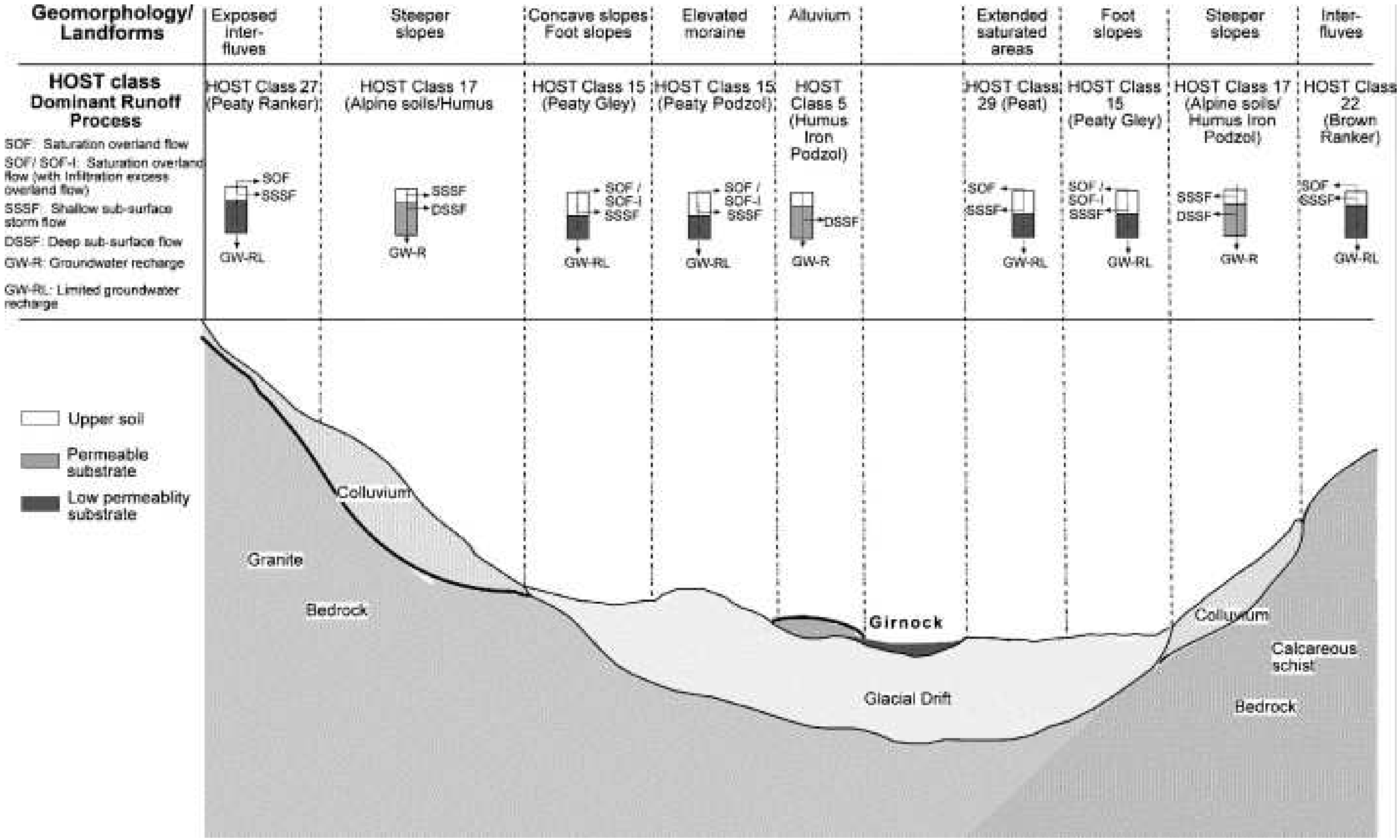


Figure 6.1 Conceptual model of the distribution of soil hydrological properties according to HOST in the Girnock (Soulsby *et al.*, 2007).

The hydrology of the soils of South Africa is very different from that of the United Kingdom and a radically different approach is proposed. The hydrology of soil types in South Africa has been researched for several years. Since 2000 the focus has moved from agriculture to the nature of soil as a natural entity. Progress in this connection has been made in the Weatherley catchment. Two useful parameters were defined to describe degrees of wetness, viz. $AD_{s>0.7}$ = duration of s>0.7 (days per year) and $D_{s>0.7}$ = mean duration of s>0.7 events (days per event), (Van Huyssteen *et al*., 2005). This idea is similar, but more quantitative, than USA Department of Agriculture's (USDA) way of describing the "soil moisture regime" (Soil Survey Staff, 1999). In their system, changes in soil water content are defined as the duration of soil conditions, with plant available water and without. The USDA describe the condition of drainable water in terms of degree of drainage, varying from excessively drained to poorly drained, and using soil morphology as an indicator of the degree of drainage. Van Huyssteen *et al.* (2005) quantified the duration of drainable water.

6.2 Describing the hydrology of soils

The hydrology of soils is, more than the duration of wetness above DUL (degree/duration of drainage) or between DUL and LL (soil water regime), although that is a major part. In general the hydrology of South African soils can be described by the unique interaction of the following factors:

1. The soil water regime of each diagnostic horizon in terms of:
    a. the duration of specific degrees of wetness;
    b. seasonal phases of these specific degrees of wetness.
2. The influence of evapotranspiration on the soil water regime of the rootzone.
3. The drainage curve.
4. The hydraulic conductivity curve (vertical flow) between field saturation (*f sat*) and the drained upper limit (DUL) of recharge horizons.
5. The hydraulic conductivity curve (lateral flow and vertical flow) between f*sat.* and DUL of diagnostic horizons that have morphological signs of wetness.
6. Morphological features related to preference flow paths.
7. Flow paths and storage mechanisms in hydropedosequences.

6.2.1 Soil water regime

6.2.1.1 The duration in specific wetness degrees of certain horizons

A protracted duration of conditions wetter than DUL is an indication that water is held in the soil against gravity aided by a layer with impaired permeability. The implication is that a perched water table is present (sect. 2.1.3.2). This condition is well known in soil science and is built into the South African soil classification system as E, G and plinthic horizons and materials with signs of wetness. These wet conditions impact on natural vegetation and cultivated crops, both in irrigated and non-irrigated land. Variation in plant species composition is visible in natural environments. In the dry semi-arid areas of the western Free State and Northwest Provinces, the plinthic B horizon facilitates water storage for maize production. However, in the wetter areas of KwaZulu-Natal, water accumulation in plinthic soils may result in crop failure during wet years.

Recharge soils release the ET excess water from the soil to recharge groundwater and do not saturate. Interflow soils are soils that hold drainable water in the soil for some time. Wetland saturation excess soils do not adsorb rainwater readily, as they are usually already saturated with water.

Hillslope soil horizons with high $AD_{s>0.7}$ values indicate the presence of drainable water in the hillslope. Theoretically, this water can drain slowly towards the stream and contribute to streamflow. Such soils can be grouped in two classes. The first group is characterized by short durations of wetness (low $D_{s>0.7}$ values) and relatively high frequency. These conditions occur in E and soft plinthic B horizons of soils in more elevated (TMU 3) positions. However, where these horizons occur in lowland (TMU 4 or 5) positions $D_{s>0.7}$ values are expected to be high. At Weatherley, for example, the $D_{s>0.7}$ of these horizons sometimes exceed 200 days (Van Huyssteen *et* al., 2005). The long-term duration of drainage in the Longlands soil (P225) is typical of this characteristic (Figure 3.4). The mean long term $D_{s>0.7}$ value for the E horizon in this soil is, for example, 36.5 days per year compared to the equivalent value for the E horizon of P201 (TMU3 with 10% slope) of 4.0 days per year. Conversely, long periods of wetness occur in subsoils classified as G, and in unspecified and unconsolidated materials with signs of wetness. A typical example is the Katspruit soil profile (P235) of Weatherley (Figure 3.6), with $D_{s>0.7}$ value of 365 days per year in the G-horizon.

6.2.1.2 Seasonal phases of specific degrees of wetness

In the Weatherley catchment, the duration of drainable water in the E and soft plinthic B horizons varies from three weeks to twelve months (Van Huyssteen *et al*., 2005). This is an indication that lateral drainage or interflow in soils is actively and continuously contributing to streamflow. Recognising this, developments in hydrological modelling have recently improved the soil water subroutine of ACRU (Lorentz *et al*., 2007b). The subroutine has been expanded to include a deep subsoil layer. The results indicate that this soil layer contributes to base flow until the end of July in the Weatherley catchment (Figure 6.2). The contribution is represented by the volume of water between the groundwater line and intermediate line in the graph.

Due to the nature of the hydrology of soil types, the soils have different soil water regime phases. Four phases were identified, namely, a wetting up phase, a wet phase, a draining phase and a drying phase. Not all phases are present in all soil types. The wetting up phase is prominent in recharge soils. It is generally limited to interflow soils and negligible in the wetland responsive soils. The amount of water taken up by the recharge soil is equal to the profile extractable water content, i.e. the amount extracted from the root zone by ET during the dry season. The duration of wetting up depends on the amount of extracted water and the rainfall pattern. In the Weatherley catchment, for most of the years, the recharge soils wet up within two weeks.

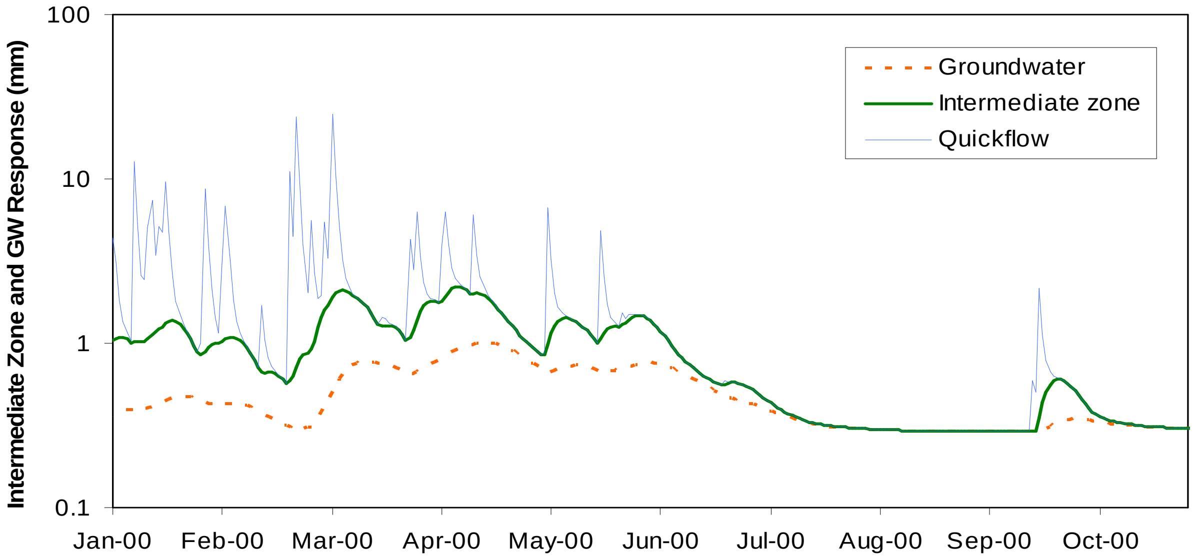


Figure 6.2 Hydrograph of outflow at Weatherley as predicted by ACRU equipped with an additional deep soil layer in the soil subroutine (Lorentz *et al.*, 2007b).

During the raining season, the wetness of recharge soils does not exceed DUL for any significant period. For example, for the true re and ye horizons up to a depth of 1 m at Weatherley the long term $D_{s>0.7}$ values (days per year) were generally <3. The amount and distribution of rainfall controls the water content of recharge soils in the wet phase and the wet phase therefore lasts as long as the rain season. The wet season of the interflow soils is paralleled by a draining phase delivering water to lower lying soils. Reduction in rainfall towards the end of the rain season results in a slowly decreasing amount of drainage as these soils go into a draining phase. During the interflow process, water is draining to and from the interflow soils. This process can theoretically last until the beginning of the next rain season. In the Weatherly catchments it seems to make a significant contribution for about 8 months of the year (Figure 6.2).

As the wetland responsive soils contains drainable water for the largest part of the year (Figure 3.5), the draining phase, which withers after the rain stops, dominates in these soils. Although the draining phase is most prominent in the interflow, it lasts longer in wetland soils.

ET has a continuous drying-out influence on all soils. During the rain season this influence tends to be neutralised in all soils. After the rain stops a well defined drying out phase starts in the recharge soils. This drying out phase is more gradual in the interflow soils because of their protracted draining phase. Defined drying only commences after interflow has stopped.

Variations in the contribution of outflow water from the intermediate zone (Figure 6.2) are expected to be transient in nature due to the different kind of E and soft plinthic B horizons in the soil types of the Weatherley catchment. The variation in water contents measured in a Longlands soil (P225) at Weatherley is typical of the temporal variability of the water regime in these soils (Figure 3.4).

6.2.2 The influence of evapotranspiration on the soil water regime of the root zone

Evapotranspiration (ET) is driven by atmospheric demand but restricted by the available water in the soil. Under highly demanding atmospheric conditions, typical of the subtropics, the availability of soil water controls ET. The seasonal change in soil water contents differs in recharge, interflow and wetland saturation excess responsive soils (Figure 4.27).

At Weatherley the wetland responsive soils act as a mechanism that pumps ET water into the atmosphere all year round, resulting in large water losses that can exceed annual rainfall (Zere, 2005). The amounts lost from interflow soils are typically somewhat less than that from responsive soils. ET losses from recharge soils have two phases. It is fast in the rain season and decreases significantly after the rain season.

6.2.3 The drainage curve

Traditionally a drainage curve describes the decrease in water content of a soil profile as water drains out between *f sat*. and DUL. In the definition of the hydrology of soil types it can also serve as a water release curve. It serves as a measure of the drainable porosity, DUL, rate and rate of change of drainage, and permeability of the underlying material/degree of interflow. If suitable instruments have been installed a drainage curve can also provide reliable data for the calculation of the unsaturated hydraulic conductivity curve for each horizon. The influence of soil morphology on a drainage curve can be clearly seen by comparing drainage curves of an Avalon soil and a Hutton soil (Hensley *et al.*, 1997).

The value of drainage curves of the different hydrological soil types has been exploited to a very limited extent in the past. This is seen as an important instrument to quantify the hydrology of soil types in the future.

6.2.4 The hydraulic conductivity curve between *f sat.* and DUL for recharge soils.

The hydraulic conductivity (K) of the soils in a catchment is of primary importance to hydrologists (Lorentz *et al*., 2001). Because of the prohibitive cost of repeatedly making detailed K measurements in ungauged basins, and the large spatial variation always encountered, it is considered a valid objective to attempt to develop ‘ball park’ values for specific textural ranges within specific diagnostic horizons. Such results should be useful to hydrologists.

6.2.5 The hydraulic conductivity curve (lateral flow and vertical flow) between *f sat.* and DUL of diagnostic horizons that have morphological signs of wetness.

The hydrological behaviour of interflow soils is influenced by the rate of lateral drainage at water contents between *f sat*. and DUL. Little research has been done in South Africa in this field but results and field observations show that the flow rates can be rapid. The rate of lateral movement in interflow horizons is important for quantifying the hydrology of different interflow soils, and therefore for hydrological modelling.

6.2.6 Morphological features related to preference flow paths

The hydrology of soil types is influenced by preference flow. Apedal soils have a small preference flow factor. However, it may be significant in the dry state. The hydrology of structured soils, especially vertic soils, may be dominated by preference flow. Typical summer storms are short and most of the rain falls in the second quartile of the year. Recharge ratios may be significantly affected by preference flow. Some degree of quantification of this factor and the relationship with soil morphology should be useful to hydrologists.

6.2.7 Flow paths and storage mechanisms in hydropedosequences

Flow paths, storage mechanisms and the interaction between draining soil water and fractured rock and other types of aquifers are important aspects of hydropedology that needs to be studied in greater detail to improve the understanding of the hydrology of soil types and the role the soil map plays in understanding the soil/rock interanction.

6.3 Hydrology of soil types of South Africa

In chapter 3 preliminary results on three different soil types, based on the water regime of these soils were discussed. However, all 7 factors listed above describing the hydrology of soils need to be studied with the aim of differentiating between different soil types based on their hydrological behaviour. These studies should be conducted over a wide range of soils with different climates and geology to be representative of South African conditions. The objective of these studies should be to provide a useful and easy to use database for a wide range of hydrological applications.

The development of such a data base may not only enhance water management in South Africa, but also improve our understanding of soil as natural entity and the associated improvement of the soil classification system of South Africa.

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APPENDIX A

PROFILE DESCRIPTIONS AND ANALYSIS DATA FOR BEDFORD CATCHMENTS

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SOIL PROFILE DESCRIPTION

NATIONAL SOIL PROFILE NO : 1

Map/photo : 3226CA Bedford

Latitude + Longitude: 32° 43' 56.3" / 26° 56' 15.6"

Land Type No : Db167

Climate Zone : 1207S

Altitude : 795 m

Terrain Unit: Footslope

Slope: 2 %

Slope Shape : Concave

Aspect : North-east

Microrelief : Dongas 1.0m, 50% coverage, profile within features

Parent Material Solum : Origin binary, local colluvium, solid rock

Underlying Material : Shale/mudstone/siltstone(unspecified)

Soil form and family : Swartland adelaide

Surface rockiness : None

Surface stoniness : <2% exposed surface, round, stones

Occurence of flooding : Occasional

Wind erosion : None

Water Erosion : Gully moderate, partially stabilized

Vegetation / Land use : Grassveld, open

Water table : None

Described by : J.J. van Tol

Date Described : 04/2007

Weathering of underlying material: Unknown

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 350	Dry state; dry colour: weak red 7.5R5/4; texture: sandy loam; structure: apedal fine granular; consistence: loose, friable, non-sticky, non-plastic; clear wav transition.	Orthic
B	350 - 800	Pedocutanic: horizon undisturbed; dry colour: weak red 5R5/4; texture: fine sandy clay loam; structure: moderate medium subangular blocky; consistence: hard, firm, sticky, plastic; few fine normal pores, medium cracks; common sesquioxide cutans; diffuse wavy transition.	Pedocutanic
C	800 - 1000	Saprolite: horizon disturbed; texture: fine sandy clay loam; few fine distinct red and yellow reduced iron oxide mottles; structure: moderate fine angular blocky; consistence: slightly hard, slightly firm, slightly sticky, slightly plastic.	Saprolite

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Described by : J.J. van Tol **Date described :** 04/2007

Nasionale Nr / National No : 1

Breedtegraad / Latitude: 32° 43' 56.3" **Landtipe / Land Type:** Db167

Soil form and family Swartland adelaide Sw2111 **Kaart / Map :** 3226CA Bedford

Lengtegraad / Longitude: 26° 56' 15.6" **Klimaatsone / Climate Zone:** 1207S

Lab nr/no	Diepte Depth	Hor	Particle Size < 2mm							CBD			**Mineralogie / Mineralogy	
			coSand	meSand	fiSand	vfiSand	coSilt	fSilt	Clay	Fe	Al	Mn	2 - 50 µm	< 2 µm
	mm		%							%				
C 1	0 - 350	A	2.9	2.4	21.6	22.0	11.0	10.9	28.4	0.01				
C 2	350 - 800	B	2.8	2.8	19.5	23.6	8.6	10.1	31.6	0.01				
C 3	800 - 1000	C	2.0	2.2	17.4	19.3	9.5	2.5	46.5	0.02				

Lab nr/no	Org C	KUK CEC	Katione / Cations * Uitruilbaar / Exchangeable # Ekstraheerbaar / Extractable						Ekstr. suurheid Extractable acidity		pH		Versadigingsekstrak / Saturation Extract Oplosbare Katione / Soluble Cations								Vers. Satur.	NAV SAR	Weerst. Resist.	EG EC
				Na	K	Ca	Mg	Tot	Total	Al	H2O	KCl	Na	K	Ca	Mg	Na	K	Ca	Mg				
	%	cmol (+)/kg soil							cmol (+)/kg soil				cmol (+)/dm³				cmol (+)/ kg soil				%		ohms	mS/m
C 1	0.21		#	4.89	0.44	9.06	3.35				8.10	7.03												180
C 2	0.18		#	6.67	2.76	8.10	3.42				8.57	7.63											390	
C 3	0.20		#	5.51	1.71	10.37	4.10				6.83	6.35											250	

Lab nr/no	Mikrovoedingselemente Micro nutrients					P			Waterretentiwiteit Water Retentivity				MR	AWR	Atterberg Limiete / Limits			
						Status		Sorpsie Sorption										
	Zn	Mn	Cu	Co	B	P	Bray		-33 kPa	-80 kPa	-500 kPa	-1500 kPa			Vloeigrens Liquid limit	Plastisiteitsgrens Plastic limit	Liniêre krimping Linear shrinkage	Plastisiteitsindeks Plasticity index
	mg / kg					mg/kg		%	%				kPa		%			
C 1	0.65	9.04	0.93			3.48	2.67											
C 2	0.60	3.40	1.18			9.40	5.23											
C 3	0.55	10.37	1.13			12.50	5.87											

Lab nr/no	METODE GEBRUIK / METHOD USED							
	Status		Sorpsie / Sorption	Boron	KUK / CEC	Katione / Cations	CBD	Mikro Elemente Micro Elements
	P	P-Bray						
C 1		Phosphorus - Bray			CEC (Amm. Acet.) Atomic Absorption	Na,K,Ca,Mg Amm. Acet. Atomic A	CEC (Amm. A	Ammonium EDTA ICP-MS
C 2								
C 3								

SURVEY NAME : **Bedford Catchments** **Profile No / Field No :** 710

ARC • LNR

SOIL PROFILE DESCRIPTION

NATIONAL SOIL PROFILE NO : 1

Map/photo : 3227BC Bolo

Latitude + Longitude: 32° 43' 0" / 24° 56' 11"

Land Type No : Fc545

Climate Zone : 1206S

Altitude : 792 m

Terrain Unit: Lower Midslope

Slope: 2 %

Slope Shape : Straight

Aspect : South-west

Microrelief : Anthill mounds, 0.4m, 15% coverage, profile between features

Parent Material Solum : Origin binary, local colluvium, solid rock

Underlying Material : Shale/mudstone/siltstone(unspecified)

Geological Group / Formation : Mudstone, shale and sandstone of the Middleton Formation, Beaufort Group

Soil Type : Swartland

Soil form and family : Swartland beaufort

Surface rockiness : None

Surface stoniness : None

Occurence of flooding : Occasional

Wind erosion : None

Water Erosion : Gully moderate, stabilized

Vegetation / Land use : Grassveld, closed

Water table : None

Described by : B. Kuenene

Date Described : 04/07

Weathering of underlying material: Moderate physical

Alteration of underlying material : Normal weathering

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 180	Dry state; horizon undisturbed; dry colour: white 5YR8/1; moist colour: dark reddish brown 5YR3/2; texture: clay loam; structure: moderate, secondary structure: moderate medium granular; consistence: slightly hard, firm, slightly sticky, slightly plastic; many fine normal pores, common medium & coarse pores, fine cracks; continuous slight massive cementation of unknown agent; many roots; abrupt transition.	Orthic
B	180 - 730	Dry state; horizon undisturbed; dry colour: very dark grey 5YR3/1; moist colour: dark reddish brown 5YR2/1; texture: clay loam; structure: strong, secondary structure: strong coarse subangular blocky; consistence: hard, very firm, sticky, plastic; many fine normal pores, many medium & coarse pores, coarse cracks; continuous slight laminar cementation of unknown agent; non-hardened free lime, slight effervescence; few slickensides; common clay cutans; many roots; no observed transition.	Pedocutanic

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Described by B. Kuenene **Date described** 04/07

Nasionale Nr / National No : 1 **Breedtegraad / Latitude** 32° 43' 0" **Landtipe / Land Type:** Fc545

Soil form and family Swartland beaufort Sw2112 **Kaart / Map :** 3227BC Bolo **Lengtegraad / Longitude** 24° 56' 11" **Klimaatsone / Climate Zone:** 1206S

Lab nr/no	**Diepte Depth**	**Hor**	**Particle Size < 2mm**							**CBD**			****Mineralogie / Mineralogy**	
			coSand	**meSand**	**fiSand**	**vfiSand**	**coSilt**	**fSilt**	**Clay**	**Fe**	**Al**	**Mn**	**2 - 50 µm**	**< 2 µm**
	mm		%							%				
b 1	0 - 180	A	7.2	3.0	14.4	18.7	8.9	18.6	28.6	0.61		0.05		
b 1	180 - 730	B	5.9	4.7	15.7	16.3	12.7	10.8	32.7	0.75		0.05		

Lab nr/no	**Org C**	**KUK CEC**	**Katione / Cations** *** Uitruilbaar / Exchangeable** **# Ekstraheerbaar / Extractable**						**Ekstr. suurheid Extractable acidity**		**pH**		**Versadigingsekstrak / Saturation Extract** **Oplosbare Katione / Soluble Cations**								**Vers. Satur.**	**NAV SAR**	**Weerst. Resist.**	**EG EC**
				Na	**K**	**Ca**	**Mg**	**Tot**	**Total**	**Al**	**H2O**	**KCl**	**Na**	**K**	**Ca**	**Mg**	**Na**	**K**	**Ca**	**Mg**				
	%	cmol (+)/kg soil							cmol (+)/kg soil				cmol (+)/dm³				cmol (+)/ kg soil				%		ohms	mS/m
b 1			#	0.50	3.70	41.10	1.90				9.00	7.00												
b 1			#	0.20	3.20	7.30	1.20				9.00	8.00												

Lab nr/no	**Mikrovoedingselemente Micro nutrients**					**P**			**Waterretentiwiteit Water Retentivity**				**MR**	**AWR**	**Atterberg Limiete / Limits**			
						Status		**Sorpsie Sorption**							**Vloeigrens Liquid limit**	**Plastisiteitsgrens Plastic limit**	**Liniêre krimping Linear shrinkage**	**Plastisiteitsindeks Plasticity index**
	Zn	**Mn**	**Cu**	**Co**	**B**	**P**	**Bray**		**-33 kPa**	**-80 kPa**	**-500 kPa**	**-1500 kPa**						
	mg / kg					mg/kg		%	%				kPa		%			
b 1																		
b 1																		

Lab nr/no	**METODE GEBRUIK / METHOD USED**							
	Status		**Sorpsie / Sorption**	**Boron**	**KUK / CEC**	**Katione / Cations**	**CBD**	**Mikro Elemente Micro Elements**
	P	**P-Bray**						
b 1					CEC (Amm. Acet.) Atomic Absorption	CEC (Amm. Acet.) Atomic Absorptio	CBD	
b 1					CEC (Amm. Acet.) Atomic Absorption	CEC (Amm. Acet.) Atomic Absorptio	CBD	

ARC • LNR

SOIL PROFILE DESCRIPTION

NATIONAL SOIL PROFILE NO : 2

Map/photo : 3227BC Bolo

Latitude + Longitude: 32° 43' 59" / 25° 56' 13"

Land Type No : Fc545

Climate Zone : 1206S

Altitude : 786 m

Terrain Unit: Lower Midslope

Slope: 2 %

Slope Shape : Concave

Aspect : South-west

Microrelief : Anthill mounds, 0.3m, 15% coverage, profile between features

Parent Material Solum : Origin single, solid rock

Underlying Material : Shale/mudstone/siltstone(unspecified)

Geological Group / Formation : Beaufort Group/Middleton formation

Soil Type : Oakleaf

Soil form and family : Oakleaf patrysdal

Surface rockiness : None

Surface stoniness : None

Occurence of flooding : Occasional

Wind erosion : None

Water Erosion : Gully moderate, stabilized

Vegetation / Land use : Grassveld, closed

Water table : None

Described by : B. Kuenene

Date Described : 5/2007

Weathering of underlying material: Moderate physical

Alteration of underlying material : Normal weathering

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 270	Dry state; horizon undisturbed; dry colour: white 5YR8/1; moist colour: dark reddish brown 5YR3/3; texture: sandy clay loam; structure: apedal massive, secondary structure: moderate granular; consistence: slightly hard, friable, sticky, plastic; common fine normal pores, few medium & coarse pores; very few ; common roots; clear smooth transition.	Orthic
B	270 - 1170	Dry state; horizon undisturbed; dry colour: very dark grey 5YR3/1; moist colour: dark reddish brown 5YR2/1; texture: sandy clay loam; structure: moderate fine subangular blocky, secondary structure: moderate fine subangular blocky; consistence: hard, firm, very sticky, very plastic; many fine normal pores, many medium & coarse pores, coarse cracks; non-hardened free lime, slight effervescence; few clay cutans; very few ; many roots; no observed transition.	Neocutanic

INSTITUTE FOR SOIL, CLIMATE AND WATER
INSTITUUT VIR GROND, KLIMAAT EN WATER

Described by B. Kuenene **Date described** 5/2007

Nasionale Nr / National No : 2

Breedtegraad / Latitude 32° 43' 59" **Landtipe / Land Type:** Fc545

Soil form and family Oakleaf patrysdal Oa2120 **Kaart / Map :** 3227BC Bolo

Lengtegraad / Longitude 25° 56' 13" **Klimaatsone / Climate Zone:** 1206S

Lab nr/no	Diepte Depth	Hor	Particle Size < 2mm							CBD			**Mineralogie / Mineralogy	
			coSand	meSand	fiSand	vfiSand	coSilt	fSilt	Clay	Fe	Al	Mn	2 - 50 µm	< 2 µm
	mm		%							%				
C 1	0 - 270	A	4.9	5.3	17.8	21.6	10.0	12.3	26.5	0.80		0.06		
C 2	270 - 1170	B	4.6	4.3	10.1	25.3	12.4	8.4	34.2	0.62		0.06		

Lab nr/no	Org C	KUK CEC	Katione / Cations * Uitruilbaar / Exchangeable # Ekstraheerbaar / Extractable						Ekstr. suurheid Extractable acidity		pH		Versadigingsekstrak / Saturation Extract Oplosbare Katione / Soluble Cations								Vers. Satur.	NAV SAR	Weerst. Resist.	EG EC
				Na	K	Ca	Mg	Tot	Total	Al	H2O	KCl	Na	K	Ca	Mg	Na	K	Ca	Mg				
	%	cmol (+)/kg soil							cmol (+)/kg soil				cmol (+)/dm³				cmol (+)/ kg soil				%		ohms	mS/m
C 1			#	0.20	2.90	9.60	0.90				8.00	7.00												
C 2			#	0.20	2.70	14.10	1.20				9.00	8.00												

Lab nr/no	Mikrovoedingselemente Micro nutrients					P			Waterretentiwiteit Water Retentivity				MR	AWR	Atterberg Limiete / Limits			
						Status		Sorpsie Sorption							Vloeigrens Liquid limit	Plastisiteitsgrens Plastic limit	Linière krimping Linear shrinkage	Plastisiteitsindeks Plasticity index
	Zn	Mn	Cu	Co	B	P	Bray		-33 kPa	-80 kPa	-500 kPa	-1500 kPa						
	mg / kg					mg/kg		%	%				kPa		%			
C 1																		
C 2																		

Lab nr/no	METODE GEBRUIK / METHOD USED							
	Status		Sorpsie / Sorption	Boron	KUK / CEC	Katione / Cations	CBD	Mikro Elemente Micro Elements
	P	P-Bray						
C 1					CEC (Amm. Acet.) Atomic Absorption	CEC (Amm. Acet.) Atomic Absorptio	CBD	
C 2					CEC (Amm. Acet.) Atomic Absorption	CEC (Amm. Acet.) Atomic Absorptio	CBD	

SURVEY NAME : Hydropedology 07 **Profile No / Field No :** 002

APPENDIX B

OBSERVATION DESCRIPTIONS OF THE BEDFORD CATCHMENT

B4 & B5

GPS No	Location	Elevation	Form	Horizon	Depth (mm)	Clay (%)	TMU	SS	Lime	Rock
108	S32 53 16.7 E26 08 10.5	626 m	Ms	ot	90	11-15%	3	VV	-	4
109	S32 53 18.1 E26 08 10.4	620 m	Gs	ot	150	11-15%	4	CC	-	2
				so	460					
110	S32 53 20.9 E26 08 10.3	620 m	Ms	ot	220	11-15%	3	VV	-	3
111	S32 53 22.6 E26 08 10.5	630 m	Ms	ot	450	0-6%	3	VV	-	1
112	S32 53 25.2 E26 08 10.8	633 m	Ms	ot	120	0-6%	3	VV	-	3
113	S32 53 29.0 E26 08 11.8	638 m	Ms	ot	50	0-6%	3	VV	-	4
114	S32 53 31.7 E26 08 11.9	641 m	Ms	ot	60	0-6%	3	VV	-	4
115	S32 53 35.5 E26 08 13.4	648 m	Ms	ot	10	0-6%	3	VV	-	4
117	S32 53 35.5 E26 08 13.4	649 m	Gs	ot	100	0-6%	3	CC	-	1
				so	420					
118	S32 53 37.6 E26 08 13.7	652 m	Gs	ot	200	0-6%	3	CC	-	1
				so	500					
119	S32 53 38.5 E26 08 13.5	652 m	Ms	ot	140	0-6%	3	CC	-	3
120	S32 53 41.5 E26 08 13.2	658 m	Ms	ot	100	0-6%	3	CC	-	3

GPS No	Location	Elevation	Form	Horizon	Depth (mm)	Clay (%)	TMU	SS	Lime	Rock
121	S32 53 44.9 E26 08 13.6	666 m	Ms	ot	90	11-15%	1	VV	-	2
122	S32 53 36.5 E26 07 14.1	678 m	Ms	ot	180	11-15%	3	VV	-	3
123	S32 53 35.6 E26 07 18.6	671 m	Ms	ot	70	11-15%	3	LV	-	3
124	S32 53 34.7 E26 07 24.7	664 m	Ms	ot	100	5-10%	3	VV	-	4
125	S32 53 34.8 E26 07 31.6	653 m	Ms	ot	100		4	CC	-	3
126	S32 53 35.9 E26 07 39.0	639 m	Oa	ot	250	5-10%	5	CC	-	2
				ne	750				Y	
127	S32 53 39.2 E26 07 43.3	630 m	Sw	ot	200	5-10%	5	LC	-	3
				vp	520				Y	
128	S32 54 08.3 E26 07 11.0	648 m	Gs	ot	100	5-10%	4	LL	-	2
				so	200					
129	S32 54 07.7 E26 07 07.0	654 m	Gs	ot	100	5-10%	3	LC	-	2
				so	230					
130	S32 54 08.5 E26 07 00.3	661 m	Gs	ot	50	5-10%	3	CC	-	2
				so	50					
131	S32 54 08.7 E26 06 46.7	681 m	Gs	ot	100	5-10%	3	VV	-	2

GPS No	Location	Elevation	Form	Horizon	Depth (mm)	Clay (%)	TMU	SS	Lime	Rock
				so	100					
132	S32 54 10.0 E26 06 36.6	696 m	Ms	ot	80	5-10%	1	CC	-	2
133	S32 54 09.7 E26 06 36.8	694 m	Gs	ot	150	5-10%	1	CC	-	2
				so	420					
134	S32 54 09.3 E26 06 37.6	694 m	Ms	ot	70	5-10%	1	CC	-	2
135	S32 54 08.6 E26 06 38.1	693 m	Gs	ot	70	5-10%	1	CC	-	2
				so	390					
201	S32 53 18.7 E26 07 55.6	618 m	Va	ot	400	15%	5		-	
				vp	800	30%			-	
				ud	800+	30%			-	
202	S32 53 19.7 E26 07 56.9	618 m	Oa	ot	400	15%	4		-	
				ne	700	25%			-	
				unsp.	700+	25%			-	
203	S32 53 20.8 E26 07 59.0	624 m	Sw	ot	150	15%	upper 4		-	
				vp	350	30%			-	
				unsp.	350+				-	
204	S32 53 22.1 E26 08 01.2	634 m	Ms	ot	150	15%	3		-	

GPS No	Location	Elevation	Form	Horizon	Depth (mm)	Clay (%)	TMU	SS	Lime	Rock
205	S32 53 25.0 E26 08 04.0	636 m	Sw	ot	100	15%	upper 3		-	
				vp	150	20%			-	
				unsp.	150+				-	
206	S32 53 27.6 E26 08 06.2	634 m	Gs	ot	150	15%	3		-	
				so	150+	20%			-	
207	S32 53 31.0 E26 08 08.9	641 m	Ms	ot	210	15%	2		-	4
				R					-	
209	S32 53 33.6 E26 08 10.6	646 m	Ms	ot	110	15%	1		-	4
210	S32 51 39.0 E26 06 49.1	674 m	Gs	ot	200	15%	3	LL	-	
				so	450+				-	
211	S32 51 42.6 E26 06 49.6	675 m	Ms	ot	200	15%	3	CV	-	4
				R	200+				-	
212	S32 51 45.8 E26 06 49.1	662 m	Ms	ot	50	15%	upper 3	CL	-	4
				R					-	
213	S32 51 49.1 E26 06 48.8	652 m	Sw	ot	400	15%	3	CC	-	
				pd	600	30%			-	

GPS No	Location	Elevation	Form	Horizon	Depth (mm)	Clay (%)	TMU	SS	Lime	Rock
				unsp.	600+				-	
214	S32 51 52.6 E26 06 48.5	642 m	Ms	ot	100	15%	3	CC	-	3
				R					-	
215	S32 51 56.3 E26 06 48.2	636 m	Ms	ot	400	15%	4	CC	-	3
216	S32 51 57.3 E26 06 48.5	636 m	Sw	ot	260	15%	4	CC	-	
				pd	860	30%			-	
				unsp.	860+				-	
217	S32 52 01.1 E26 06 48.3	629 m	Pn	ot	300	10%	5	CC	-	
				ye	600	15%			-	
				uw	840+	15%			-	
218	S32 52 02.8 E26 06 47.1	626 m	Ka	ot	400	10%	5	CC	-	
				G	400+	20%			-	
219	S32 52 08.3 E26 06 47.6	631 m	Ms	ot	100	15%	lower 3	VL	-	
				R					-	
220	S32 52 41.2 E26 05 20.5	704 m	Sw	ot	200	15%	1	LL	-	
				pd	300	25%			Y	
				unsp.	300+				-	

GPS No	Location	Elevation	Form	Horizon	Depth (mm)	Clay (%)	TMU	SS	Lime	Rock
221	S32 52 41.3 E26 05 26.0	695 m	Gs	ot	300	15%	1	LL	-	
				so	440+				Y	
224	S32 52 35.2 E26 05 26.3	691 m	Ms	ot	100	15%	1	LL	-	3
				R					-	
225	S32 52 31.1 E26 05 26.0	686 m	Ms	ot	180	15%	1	LL	-	
226	S32 52 27.7 E26 05 25.8	679 m	Ms	ot	400	15%	1	LL	-	1
				R						
227	S32 52 24.1 E26 05 25.7	675 m	Oa	ot	400	11-15%	U3	L	Y	
				ne	600	25-30%			Y	
				unsp.	600					
228	S32 52 20.2 E26 05 26.0	670 m	Va	ot	300	11-15%	3	CC	Y	
				pd	500	25%			Y	
				ud	600				Y	
229	S32 52 16.5 E26 05 25.3	666 m	Ms	ot	300	11-15%	U4	L	Y	1
230	S32 52 12.8 E26 05 24.3	661 m	Oa	ot	200	11-15%	L4	L	Y	
				ne	400	25-30%			Y	
				unsp.	500				Y	

GPS No	Location	Elevation	Form	Horizon	Depth (mm)	Clay (%)	TMU	SS	Lime	Rock
231	S32 52 11.0 E26 05 23.9	662 m	Se	ot	400	11-15%	5	CC	Y	
				pd	700	30%			Y	
				uw	900	25-30%			Y	
232	S32 52 08.5 E26 05 25.9	660 m	Ms	ot	400	11-15%	5	CC	Y	
233	S32 52 06.9 E26 05 22.3	669 m	Ms	ot	150	11-15%	4	CV	Y	2
234	S32 52 04.5 E26 05 18.9	676 m	Ms	ot	360	11-15%	3	CV	Y	2
235	S32 52 01.8 E26 05 15.8	683 m	Ms	ot	140	11-25%	3	CV	Y	2
236	S32 52 00.1 E26 05 12.8	688 m	Ms	ot	160	11-25%	1	CV	Y	2
301	S32 51 34.4 E26 06 47.3	681 m	Ms	ot	130	15%	1	VV	-	2
302	S32 51 37.2 E26 06 45.3	682 m	Ms	ot	180	15%	1\3	VV	-	2
303	S32 51 39.8 E26 06 44.1	679 m	Ms	ot	180	15%	3	VL	-	2
304	S32 51 42.6 E26 06 43.4	672 m	Ms	ot	80	10%	2\3	VV	-	4
305	S32 51 44.3 E26 06 42.9	665 m	Sw	ot	300	10%	4	CL	-	4
				pd	820	20%				
306	S32 51 47.5 E26 06 41.4	658 m	Ms	ot	320	15%	3	LV	-	2
307	S32 51 50.8 E26 06 40.3	649 m	Sw	ot	300	15%	3\4	LL	-	2
308	S32 51 54.1 E26 06 38.5	641 m		vp	480	25%	3	VV	Y	4

GPS No	Location	Elevation	Form	Horizon	Depth (mm)	Clay (%)	TMU	SS	Lime	Rock
309	S32 51 58.1 E26 06 37.3	635 m	Sw	ot	300	15%	4	CL	-	1
				Vp	820	30%				
310	S32 52 00.2 E26 06 38.0	630 m	Ag	ot	200	15%	5	LL	Y	2
				nc	500	25%			Y	
311	S32 52 00.2 E26 06 38.0	630 m	Ka	ot	200	15%	5	CL	-	1
				G	520	20%			-	
312	S32 52 01.5 E26 06 07.2	646 m	Rock		0		4\3	LL		4
313	S32 52 02.5 E26 06 06.4	647 m	Ms	ot	180	10%	3	LL		3
314	S32 52 06.2 E26 06 03.5	654 m	Ms	ot	20	10%	3	VV	-	4
315	S32 52 10.0 E26 06 00.6	662 m	Ms	ot	15	10%	3	VV	-	3
316	S32 52 14.2 E26 05 57.9	669 m	Ms	ot	0		3	VV	-	4
317	S32 52 16.9 E26 05 55.0	673 m	Rock		80	10%	1	VV	-	2
318	S32 52 55.9 E26 05 15.4	723 m	Ms	ot	80	10%	1	VV	-	2
319	S32 52 57.1 E26 05 15.3	724 m	Ms	ot	190	10%	1	LV	-	1
320	S32 53 00.2 E26 05 12.3	737 m	Ms	ot	130	10%	1	LV	-	3
321	S32 52 59.3 E26 05 17.0	733 m	Rock		0		1	VV	-	4

GPS No	Location	Elevation	Form	Horizon	Depth (mm)	Clay (%)	TMU	SS	Lime	Rock
322	S32 52 57.2 E26 05 17.4	733 m	Ms	ot	130	10%	1	VV	-	3
323	S32 52 34.7 E26 04 28.4	728 m	Ms	ot	120	10%	1	LV	-	3
324	S32 52 32.4 E26 04 33.8	718 m	Ms	ot	90	10%	3	LV	-	4
325	S32 52 29.8 E26 04 39.6	711 m	Ms	ot	80	10%	3	LV	-	3
327	S32 52 25.2 E26 04 51.0	699 m	Ms	ot	90	10%	3	LV	-	3
328	S32 52 22.0 E26 05 00.1	693 m	Ms	ot	80	10%	3	VV	-	2
329	S32 52 18.9 E26 05 05.7	685 m	Ms	ot	120	15%	3	VV	-	2
330	S32 52 15.7 E26 05 11.9	677 m	Ms	ot	120	15%	3	VV	-	2
331	S32 52 12.9 E26 05 16.9	669 m	Ms	ot	140	15%	4	CV	-	2
332	S32 52 12.1 E26 05 21.3	664 m	Ag	ot	200	15%	5		-	0
				nc	520	30%			Y	

B3

GPS No.	Location	Elevation	Soil form	Horizon	Depth (mm)	Clay	TMU	SS	Lime	Rocks
501	S32 42 46.3 E25 56 20.5	931 m	Ms	ot	110	7-10%	1	LV	-	1
502	S32 42 54.8 E25 56 15.1	901 m	Gs	ot	200	11-15%	3	LV	-	1
				so	580					
503	S32 42 51.3 E25 56 16.4	894 m	Ms	ot	160	7-10%	3	LV	-	1
504	S32 42 48.6 E25 56 19.0	889 m	Ms	ot	80	0-6%	3	LV	-	1
505	S32 42 58.7 E25 56 14.3	890 m	Ms	ot	150	7-10%	2	CV	-	4
506	S32 41 46.0 E25 56 12.5	888 m	Ms	ot	100	7-10%	2	VV	-	1
507	S32 43 22.1 E25 56 11.8	864 m	Gs	ot	100	7-10%	3	LV	-	2
				so	230					
508	S32 41 37.9 E25 56 11.1	856 m	Oa	ot	200	11-15%	4	LL	-	1
				ne	530					
509	S32 43 26.6 E25 56 08.2	849 m	Sw	ot		16-20%	5	LL	-	1
				Vp	1000					
510	S32 43 32.9 E25 56 05.5	844 m	Pn	ot	300	16-20%	5	LL	-	1
				ye	1000					

GPS No.	Location	Elevation	Soil form	Horizon	Depth (mm)	Clay	TMU	SS	Lime	Rocks
511	S32 43 21.2 E25 56 10.6	830 m	Gs	ot	200	11-15%	3	LC	-	3
				so	500					
512	S32 43 20.7 E25 56 15.2	797 m	Gs	ot	200	11-15%	3	LC	-	2
				so	470					
513	S32 43 20.5 E25 56 16.9	796 m	Sw	ot	250	11-15%	4	LL	-	2
				vp	1000	31-35%				
514	S32 43 15.3 E25 56 20.6	795 m	Sw	ot	150	11-15%	4	LL	-	4
				vp	670	26-30%				
515	S32 43 17.0 E25 56 13.9	780 m	Sw	ot	300	11-15%	5	LL	-	1
				vp	1000	>35%				
516	S32 43 17.2 E25 56 30.9	821 m	Ms	ot	200	7-10%	1	LL	-	1
517	S32 43 24.7 E25 56 15.6	787 m	Va	ot	250	11-15%	4	LL	-	1
				vp	790	35-55%				
518	S32 43 21.9 E25 56 16.9	778 m	Va	ot	250	11-15%	4	LL	-	1
				vp	730	35-55%				
519	S32 43 54.4 E25 56 36.4	802 m	Du	ot	300	11-15%	5	LC	-	1

GPS No.	Location	Elevation	Soil form	Horizon	Depth (mm)	Clay	TMU	SS	Lime	Rocks
				al	1000					
520	S32 43 55.6 E25 56 36.9	803 m					Termite Mound (Grey)			
521	S32 43 56.2 E25 56 36.4	800 m					Termite Mound (Brown)			
522	S32 43 56.0 E25 56 40.7	803 m					Termite Mound (Yellow Brown)			
523			Ms	ot	130	7-10%	1	VC	-	4
524	S32 44 24.1 E25 56 48.6	825 m	Ms	ot	110	7-10%	1	VC	-	4
525			Ms	ot	190	7-10%	2	LL	-	4
526	S32 44 22.9 E25 56 49.7	805 m	Gs	ot	200	11-15%	2	LL	-	4
				so	480					
527	S32 44 26.6 E25 56 45.6	833 m	Ms	ot	180	7-10%	3	LL	-	2
528	S32 44 25.1 E25 56 46.9	832 m	Gs	ot	150	11-15%	3	LL	-	1
				so	410					
529	S32 44 19.9 E25 56 52.8	786 m	Ms	ot	110	7-10%	3	LL	-	4
530	S32 44 21.5 E25 56 51.1	798 m	Sw	ot	250	16-20%	3	LV	-	2
				vp	890					

GPS No.	Location	Elevation	Soil form	Horizon	Depth (mm)	Clay	TMU	SS	Lime	Rocks
531	S32 44 16.7 E25 56 54.1	770 m	Sw	ot	100	16-20%	3	LV	-	1
				vp	480					
532	S32 44 14.2 E25 56 55.4	764 m	Du	ot	400	7-10%	4	LL	-	1
				al	2000					
533	S32 44 11.1 E25 56 57.9	757 m	Du	ot	400	11-15%	5	LL	-	1
				al	2500	31-35%				
534	S32 44 20.2 E25 57 16.6	752 m	Va	ot	250	11-15%	3	LL	-	2
				vp	850	35-55%				
535	S32 43 58.3 E25 56 58.9	812 m	Ms	ot	180	7-10%	1	LV	-	2
536	S32 44 00.0 E25 57 01.2	801 m	Ms	ot	160	7-10%	1	VV	-	3
537	S32 43 59.5 E25 57 05.0	793 m	Ms	ot	180	7-10%	1^1	VV	-	3
538	S32 43 59.5 E25 57 05.0	793 m	Ms	ot	190	7-10%	1^1	VV	-	3
539	S32 43 59.4 E25 57 08.7	784 m	Gs	ot	100	11-15%	1^2	LV	-	1
				so	240					
540	S32 44 00.0 E25 57 13.1	782 m	Ms	ot	190	7-10%	2	LV	-	1
541	S32 44 00.4 E25 57 15.1	777 m	Gs	ot	100	11-15%	2^1	LV	-	2

GPS No.	Location	Elevation	Soil form	Horizon	Depth (mm)	Clay	TMU	SS	Lime	Rocks
				so	280					
542	S32 44 00.6 E25 57 17.0	765 m	Gs	ot	100	11-15%	2	LV	-	2
				so	310				-	
543	S32 44 00.5 E25 57 21.9	760 m	Gs	ot	100	11-15%	3	LV	-	2
				so	110				-	
544	S32 44 01.6 E25 57 24.9	755 m	Ms	ot	110	7-10%	3	LV	-	2
545	S32 44 01.6 E25 57 27.8	750 m	Gs	ot	100	11-15%	3^1	LL	-	2
				so	180				-	
546	S32 44 04.3 E25 57 27.8	745 m	Ms	ot	150	7-10%	3^2	LL	-	2
547	S32 44 04.9 E25 57 27.9	736 m	Pn	ot	340	7-10%	1^3	LV	-	4
				ye	700	11-15%			-	
548	S32 44 06.7 E25 57 28.2	735 m	Va	ot	280	11-15%	4	LL	-	1
				vp	840	20-25%			-	
549	S32 44 10.9 E25 57 28.4	735 m	Va	ot	400	11-15%	4	LL	-	1
				vp	1100	20-25%			-	
550	S32 44 12.3 E25 57 29.0	736 m	Sw	ot	250	11-15%	5	LL	-	1

GPS No.	Location	Elevation	Soil form	Horizon	Depth (mm)	Clay	TMU	SS	Lime	Rocks
				vp	600	15-20%			-	
551	S32 44 13.4 E25 57 29.4	735 m	Du	ot	300	3-7%	5	LL	-	4
				al	1000					
700	S32 53 18.7 E26 07 55.6	786 m	Ms	ot	400	10%	1	VV	-	3
701	S32 44 35.6 E25 56 46.2	853 m	Ms	ot	400	15%	1	VV		2
702	S32 44 34.7 E25 56 50.3	846 m	Cf	ot	250	15%	2\3	VV		3
				E	350	15%				
				so	450					
703	S32 44 35.2 E25 56 54.4	839 m	Ms	ot	100	10%	1	CL	-	3
704	S32 44 35.9 E25 56 55.6	838 m	Ms	ot	100	10%	3	VV	-	3
705	S32 44 31.8 E25 56 59.4	819 m	Gs	ot	100	15%	3\4	CV	-	2
				so	300					
706	S32 44 29.3 E25 57 00.1	811 m	Gs	ot	100	15%	3	CV	-	1
				so	300					
707	S32 44 25.8 E25 57 02.3	798 m	Oa	ot	100	15%	2\1	CV	-	1
				ne	300	20%				
708	S32 43 54.2 E25 56 16.9	805 m	Sw	ot	100		3	VV		

GPS No.	Location	Elevation	Soil form	Horizon	Depth (mm)	Clay	TMU	SS	Lime	Rocks
				vp	300					
709	S32 43 56.3 E25 56 15.6	803 m	Du	ot	150		3	LV		
				al	400					
710	S32 43 59.3 E25 56 14.3	795 m	Sw	ot			4	LV		
				pd						
711	S32 44 00.8 E25 56 13.8	790 m					4	CV		
712	S32 44 02.9 E25 56 12.5	800 m					4	LV		
713	S32 44 03.1 E25 56 12.6	796 m	Ag	ot		15%	4	VV		
				nc		25%				
714	S32 44 04.3 E25 56 09.8	805 m	Gs	ot	100	10%	3	LV		
				so	180					
715	S32 44 05.0 E25 56 07.2	812 m	Ms	ot	100	10%	3	LV		
716	S32 44 06.6 E25 56 05.0	817 m	Ag	ot	200	10%	3	Lv		
				nc	400	25%				
717	S32 44 08.1 E25 56 03.5	822 m	Gs	ot	100	10%	3	LL		
				so	300					
718	S32 44 13.3 E25 56 01.2	838 m	Ms	ot	150	15%	1	VV		

GPS No.	Location	Elevation	Soil form	Horizon	Depth (mm)	Clay	TMU	SS	Lime	Rocks
719	S32 44 09.5 E25 55 58.7	828 m	Se	ot	150	15%	3	CL		
				vp	450	25%				
720	S32 44 06.3 E25 55 58.4	822 m	Gs	ot	100	15%	3	LC		
				so	250					
721	S32 44 03.6 E25 55 57.9	813 m	Sw	ot	150	15%	3	LC		
				vp	400	20%				
722	S32 44 01.6 E25 55 57.5	807 m	Se	ot	150	15%	4	LC		
				vp	450	20%				
723	S32 43 59.4 E25 55 58.0	802 m	Sw	ot	150	15%	5	CC		
				vp	400	25%				
724	S32 42 02.1 E25 55 16.2	1020 m	Ms	ot	200	15%	1	VV	-	1
725	S32 42 06.0 E25 55 16.6	999 m	Rock				2	VV	-	4
726	S32 42 15.3 E25 55 17.0	950 m	Se	ot	200	15%	4	CC	-	1
				vp	500	25%				
				uw		30%				
727	S32 42 24.4 E25 55 17.0	934 m	Gs	ot	100	15%	1	LV	-	1
				so	250					

GPS No.	Location	Elevation	Soil form	Horizon	Depth (mm)	Clay	TMU	SS	Lime	Rocks
728	S32 42 32.1 E25 55 20.9	927 m	Gs	ot	100	15%	1	VV	-	2
				so	150					
729	S32 42 40.7 E25 55 21.5	911 m	Gs	ot	100	15%	1	LL	-	1
				so	250					
730	S32 42 48.1 E25 55 20.3	903 m	Gs	ot	100	15%	1	LC	-	1
				so	300					
731	S32 42 55.0 E25 55 23.5	898 m	Gs	Ot	100	15%	1	LC	-	2
				so	110					
732	S32 43 00.3 E25 55 28.1	887 m	Gs	ot	100	15%	3	VV	-	2
				so	400					
733	S32 43 05.8 E25 55 31.8	871 m	Gs	ot	100	15%	3	VV	-	2
				so	200					
734	S32 43 11.9 E25 55 35.7	850 m	Gs	ot	100	10%	4	LV	-	3
				so	150					
735	S32 43 17.3 E25 55 41.8	823 m	Du	ot	100	15%	5	LC	-	
				al	150	15%				

GPS No.	Location	Elevation	Soil form	Horizon	Depth (mm)	Clay	TMU	SS	Lime	Rocks
736	S32 43 16.8 E25 55 44.3	818 m	Sw	ot	200	11%	5	LC	-	1
				vp	600	20%				
737	S32 43 12.3 E25 55 45.5	825 m	Sw	ot	200	11%	4	CL	-	1
				vp	500	20%				
738	S32 43 11.0 E25 55 44.2	828 m	Sw	ot	100	15%	3	LL	-	1
				vp	300	20%				
739	S32 43 09.9 E25 55 41.6	837 m	Sw	ot	100	15%	3	VV	-	2
				vp	200					
740	S32 43 09.2 E25 55 39.8	845 m	Ms	ot	100	15%	3	VV	-	1
741	S32 43 03.9 E25 55 48.0	830 m					5	LL	Y	2
742	S32 43 04.3 E25 55 46.2	832 m							Y	1
743	S32 43 04.0 E25 55 45.7	836 m	Gs	ot	100	10%	3	VV	-	1
				so	150					
744	S32 43 03.9 E25 55 45.3	835 m	Ms	ot	100	10%	3	VV	-	1
745	S32 42 58.3 E25 55 48.5	833 m	Sw	ot	200	15%	4	CL	-	2
				vp	600	20%				
746	S32 42 58.7 E25 55 45.6	839 m	Sw	ot	200	15%	3	LV	-	1

GPS No.	Location	Elevation	Soil form	Horizon	Depth (mm)	Clay	TMU	SS	Lime	Rocks
				vp	500	20%				
747	S32 42 58.6 E25 55 43.2	847 m	Ms	ot	80	10%	3	CV	-	3
748	S32 42 50.7 E25 55 46.3	847 m	Gs	ot	100	10%	3	VV	-	3
				so	100					
749	S32 42 47.3 E25 55 46.1	860 m	Ms	ot	50	10%	3	VV	-	2
750	S32 42 47.7 E25 55 48.5	853 m	Ms	ot	100	10%	3	VV	-	3
751	S32 42 47.4 E25 55 49.4	849 m	Rock				3	VV		4
752	S32 42 48.0 E25 55 50.3	842 m	Sw	ot	200	10%	5	CC	-	2
				vp	400	20%				
754	S32 44 26.4 E25 59 11.9	728 m	Ms	ot	400	10%	1	LV	Y	2
755	S32 44 21.2 E25 59 12.0	721 m	Gs	ot	150	10%	3	LV	Y	2
				so	400					
756	S32 44 16.2 E25 59 12.7	715 m	Sw	ot	400	10-15%	3	LV	Y	
				vp	700	25%			Y	1
				C	700+					
757	S32 44 12.4 E25 59 12.0	712 m	Sw	ot	400	10-15%	5	LV	Y	1
				vp	650	25%			Y	

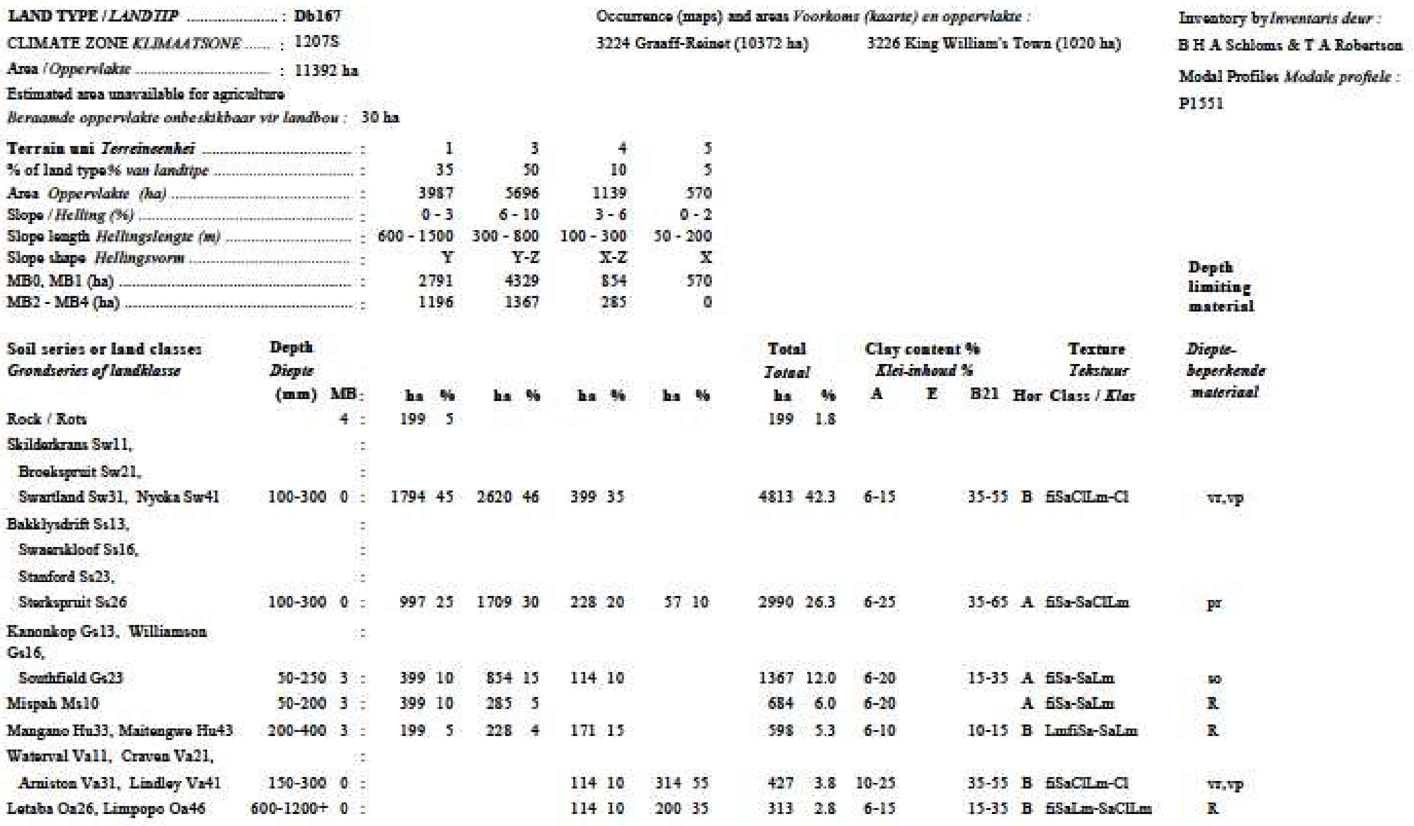
GPS No.	Location	Elevation	Soil form	Horizon	Depth (mm)	Clay	TMU	SS	Lime	Rocks
				C	650+					
758	S32 44 13.1 E25 59 09.3	717 m	Sw	ot	250	10%	5	LV	Y	1
				vp	600	25%			Y	
				C	600+					
759	S32 44 05.9 E25 59 07.1	715 m	Ag	ot	200	10%	4	LV	Y	1
				nc	500	25%			Y	
				C	500+					
760	S32 44 00.0 E25 59 03.9	723 m	Gs	ot	100	10%	3	L/CC	Y	1
				so	300					
761	S32 43 57.7 E25 59 01.7	732 m	Sw	ot	300	10%	3	CV	Y	
				vp	600	20%			Y	
				C	600+					
762	S32 43 53.9 E25 58 56.0	749 m	Gs	ot	100	10%	1	CV	Y	2
				so	200					
763	S32 43 54.5 E25 58 53.8	748 m	Gs	ot	100	10%	1	CV	Y	2
				so	300					

GPS No.	Location	Elevation	Soil form	Horizon	Depth (mm)	Clay	TMU	SS	Lime	Rocks
764	S32 43 57.7 E25 58 51.6	733 m	Ag	ot	200	10%	3	LV	Y	1
				nc	600	20%			Y	
				so	600+					
765	S32 44 00.7 E25 58 49.8	727 m	Sw	ot	300	15%	4	LV	Y	NONE
				vp	600	25%			Y	
				C	600+					
766	S32 44 03.4 E25 58 48.2	719 m	Sw	Ot	200	15%	5	CC	Y	NONE
				vp	450	25%			Y	
				C	450+					
767	S32 44 09.5 E25 58 43.6	719 m	Sw	ot	200	15%	5	LV	X	NONE
				vp	400	25%			X	
				C	400+					

APPEDIX C

LAND TYPE DATA OF THE BEDFORD CATCHMENTS

Table 1 Land Type Db167



LAND TYPE / *LANDTIP* .... : **Db167**
CLIMATE ZONE *KLIMAATSONE* ...... : 1207S
Area / *Oppervlakte* .... : 11392 ha
Estimated area unavailable for agriculture
Beraamde oppervlakte onbeskikbaar vir landbou : 30 ha

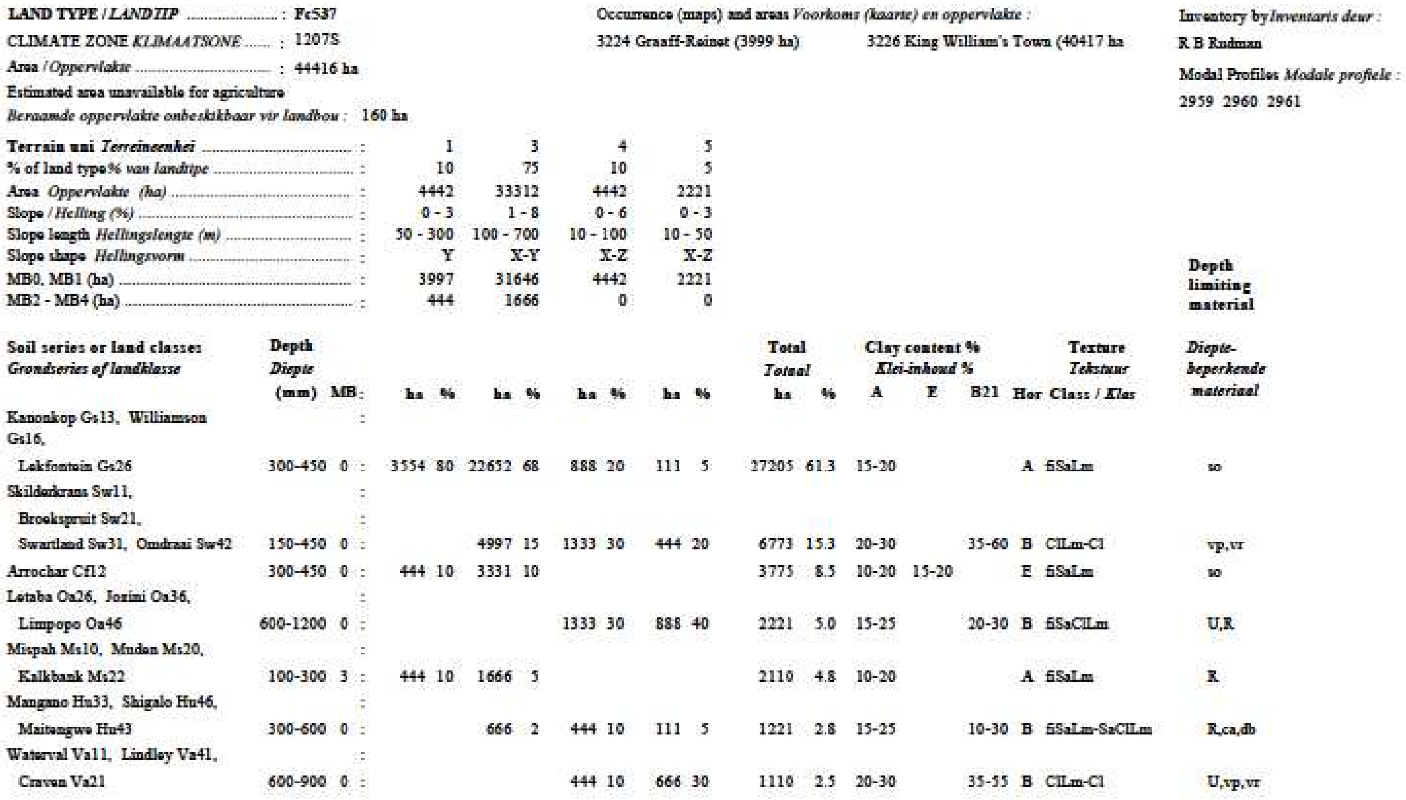
Occurrence (maps) and areas *Voorkoms (kaarte) en oppervlakte* :
3224 Graaff-Reinet (10372 ha) 3226 King William's Town (1020 ha)

Inventory by *Inventaris deur* :
B H A Schloms & T A Robertson
Modal Profiles *Modale profiele* :
P1551

Terrain uni *Terreineenhei* .... :	1	3	4	5
% of land type% *van landtipe* .... :	35	50	10	5
Area *Oppervlakte (ha)* .... :	3987	5696	1139	570
Slope / *Helling (%)* .... :	0 - 3	6 - 10	3 - 6	0 - 2
Slope length *Hellingslengte (m)* .... :	600 - 1500	300 - 800	100 - 300	50 - 200
Slope shape *Hellingsvorm* .... :	Y	Y-Z	X-Z	X
MB0, MB1 (ha) .... :	2791	4329	854	570
MB2 - MB4 (ha) .... :	1196	1367	285	0

Soil series or land classes *Grondseries of landklasse*	**Depth** *Diepte* (mm)	MB	ha	%	ha	%	ha	%	ha	%	**Total** *Totaal* ha	%	**Clay content %** *Klei-inhoud %* A	E	B21	Hor	**Texture** *Tekstuur* Class / *Klas*	**Depth limiting material** *Diepte-beperkende materiaal*
Rock / Rots		4	199	5							199	1.8						
Skilderkrans Sw11,																		
Brookspruit Sw21,																		
Swartland Sw31, Nyoka Sw41	100-300	0	1794	45	2620	46	399	35			4813	42.3	6-15		35-55	B	fiSaClLm-Cl	vr,vp
Bakklysdrift Ss13,																		
Swaarskloof Ss16,																		
Stanford Ss23,																		
Sterkspruit Ss26	100-300	0	997	25	1709	30	228	20	57	10	2990	26.3	6-25		35-65	A	fiSa-SaClLm	pr
Kanonkop Gs13, Williamson Gs16,																		
Southfield Gs23	50-250	3	399	10	854	15	114	10			1367	12.0	6-20		15-35	A	fiSa-SaLm	so
Mispah Ms10	50-200	3	399	10	285	5					684	6.0	6-20			A	fiSa-SaLm	R
Mangano Hu33, Maitengwe Hu43	200-400	3	199	5	228	4	171	15			598	5.3	6-10		10-15	B	LmfiSa-SaLm	R
Waterval Va11, Craven Va21,																		
Arniston Va31, Lindley Va41	150-300	0					114	10	314	55	427	3.8	10-25		35-55	B	fiSaClLm-Cl	vr,vp
Letaba Oa26, Limpopo Oa46	600-1200+	0					114	10	200	35	313	2.8	6-15		15-35	B	fiSaLm-SaClLm	R

Table 2 Land Type Fc537



LAND TYPE / *LANDTIP* .... : **Fc537**
CLIMATE ZONE *KLIMAATSONE* ...... : 1207S
Area / *Oppervlakte* .... : **44416 ha**
Estimated area unavailable for agriculture
Beraamde oppervlakte onbeskikbaar vir landbou : 160 ha

Occurrence (maps) and areas *Voorkoms (kaarte) en oppervlakte :*
3224 Graaff-Reinet (3999 ha) 3226 King William's Town (40417 ha

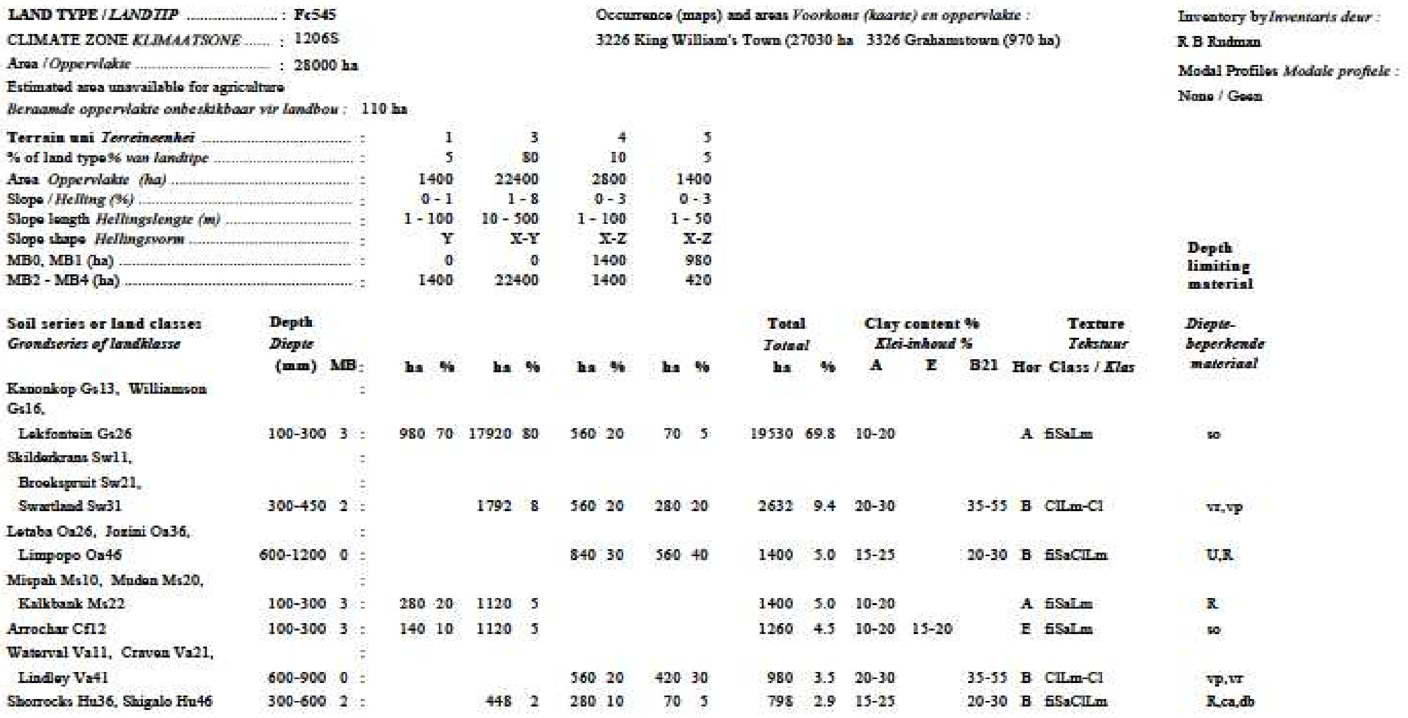
Inventory by *Inventaris deur :*
R B Rudman

Modal Profiles *Modale profiele :*
2959 2960 2961

Terrain uni *Terreineenhei*	:	1	3	4	5
% of land type% *van landtipe*	:	10	75	10	5
Area *Oppervlakte (ha)*	:	4442	33312	4442	2221
Slope / *Helling (%)*	:	0 - 3	1 - 8	0 - 6	0 - 3
Slope length *Hellingslengte (m)*	:	50 - 300	100 - 700	10 - 100	10 - 50
Slope shape *Hellingsvorm*	:	Y	X-Y	X-Z	X-Z
MB0, MB1 (ha)	:	3997	31646	4442	2221
MB2 - MB4 (ha)	:	444	1666	0	0

Soil series or land classes *Grondseries of landklasse*	**Depth** *Diepte* (mm)	MB	ha	%	ha	%	ha	%	ha	%	**Total** *Totaal* ha	%	**Clay content %** *Klei-inhoud %* A	E	B21	Hor	**Texture** *Tekstuur* Class / *Klas*	**Depth limiting material** *Diepte-beperkende materiaal*
Kanonkop Gs13, Williamson Gs16, Lekfontein Gs26	300-450	0	3554	80	22652	68	888	20	111	5	27205	61.3	15-20			A	fiSaLm	so
Skilderkrans Sw11, Broekspruit Sw21, Swartland Sw31, Omdraai Sw42	150-450	0			4997	15	1333	30	444	20	6773	15.3	20-30		35-60	B	ClLm-Cl	vp,vr
Arrochar Cf12	300-450	0	444	10	3331	10					3775	8.5	10-20	15-20		E	fiSaLm	so
Letaba Oa26, Josini Oa36, Limpopo Oa46	600-1200	0					1333	30	888	40	2221	5.0	15-25		20-30	B	fiSaClLm	U,R
Mispah Ms10, Mudan Ms20, Kalkbank Ms22	100-300	3	444	10	1666	5					2110	4.8	10-20			A	fiSaLm	R
Mangano Hu33, Shigalo Hu46, Maitengwe Hu43	300-600	0			666	2	444	10	111	5	1221	2.8	15-25		10-30	B	fiSaLm-SaClLm	R,ca,db
Waterval Va11, Lindley Va41, Craven Va21	600-900	0					444	10	666	30	1110	2.5	20-30		35-55	B	ClLm-Cl	U,vp,vr

Table 3 Land Type Fc545



LAND TYPE / ***LANDTIP*** .... : Fc545
CLIMATE ZONE *KLIMAATSONE* ...... : 1206S
Area / *Oppervlakte* .... : 28000 ha
Estimated area unavailable for agriculture
Beraamde oppervlakte onbeskikbaar vir landbou : 110 ha

Occurrence (maps) and areas *Voorkoms (kaarte) en oppervlakte :*
3226 King William's Town (27030 ha 3326 Grahamstown (970 ha)

Inventory by *Inventaris deur :*
R B Rudman

Modal Profiles *Modale profiele :*
None / Geen

	1	3	4	5
Terrain uni ***Terreineenhei***	1	3	4	5
% of land type% *van landtipe*	5	80	10	5
Area *Oppervlakte (ha)*	1400	22400	2800	1400
Slope / *Helling (%)*	0 - 1	1 - 8	0 - 3	0 - 3
Slope length *Hellingslengte (m)*	1 - 100	10 - 500	1 - 100	1 - 50
Slope shape *Hellingsvorm*	Y	X-Y	X-Z	X-Z
MB0, MB1 (ha)	0	0	1400	980
MB2 - MB4 (ha)	1400	22400	1400	420

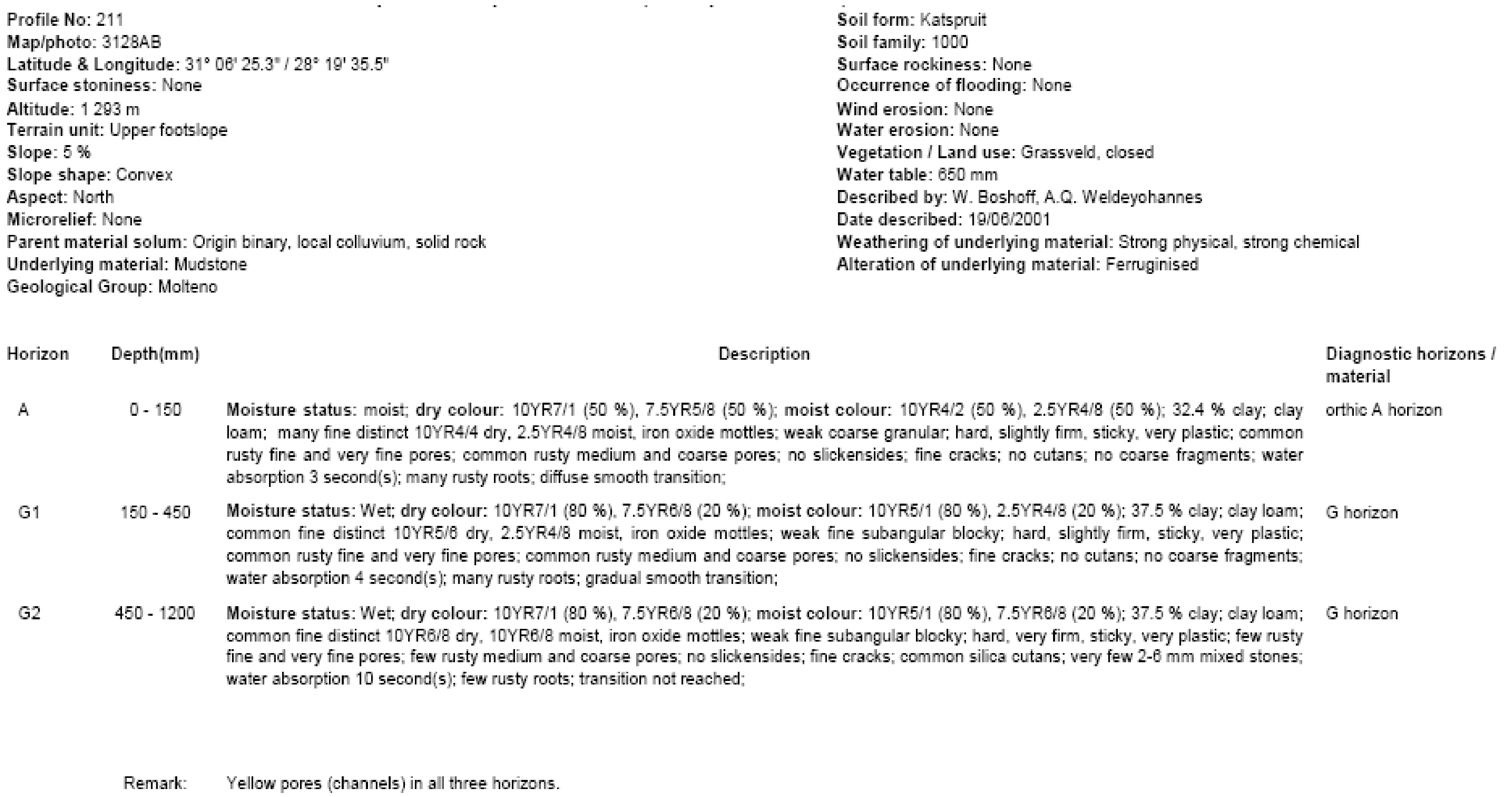
Soil series or land classes *Grondseries of landklasse*	**Depth** *Diepte* **(mm)**	**MB**	**ha**	**%**	**ha**	**%**	**ha**	**%**	**ha**	**%**	**Total** *Totaal* **ha**	**%**	**Clay content %** *Klei-inhoud %* **A**	**E**	**B21**	**Hor**	**Texture** *Tekstuur* **Class /** ***Klas***	**Depth limiting material** *Diepte-beperkende materiaal*
Kanonkop Gs13, Williamson Gs16, Lekfontein Gs26	100-300	3	980	70	17920	80	560	20	70	5	19530	69.8	10-20			A	fiSaLm	so
Skilderkrans Sw11, Brookspruit Sw21, Swartland Sw31	300-450	2			1792	8	560	20	280	20	2632	9.4	20-30		35-55	B	ClLm-Cl	vr,vp
Letaba Oa26, Jozini Oa36, Limpopo Oa46	600-1200	0					840	30	560	40	1400	5.0	15-25		20-30	B	fiSaClLm	U,R
Mispah Ms10, Muden Ms20, Kalkbank Ms22	100-300	3	280	20	1120	5					1400	5.0	10-20			A	fiSaLm	R
Arrochar Cf12	100-300	3	140	10	1120	5					1260	4.5	10-20	15-20		E	fiSaLm	so
Waterval Va11, Craven Va21, Lindley Va41	600-900	0					560	20	420	30	980	3.5	20-30		35-55	B	ClLm-Cl	vp,vr
Shorrocks Hu36, Shigalo Hu46	300-600	2			448	2	280	10	70	5	798	2.9	15-25		20-30	B	fiSaClLm	R,ca,db

APPENDIX D

PHOTOS, PROFILE DESCRIPTIONS AND ANALYTICAL DATA FOR THE UPPER CATCHMENT, WEATHERLEY

Figure 1 Photo of P211 in the upper catchment, Weatherley (Van Huyssteen *et al*., 2005).

Table 1 Profile description of P211 (Van Huyssteen *et al*., 2005).



Profile No: 211
Map/photo: 3128AB
Latitude & Longitude: 31° 06' 25.3" / 28° 19' 35.5"
Surface stoniness: None
Altitude: 1 293 m
Terrain unit: Upper footslope
Slope: 5 %
Slope shape: Convex
Aspect: North
Microrelief: None
Parent material solum: Origin binary, local colluvium, solid rock
Underlying material: Mudstone
Geological Group: Molteno

Soil form: Katspruit
Soil family: 1000
Surface rockiness: None
Occurrence of flooding: None
Wind erosion: None
Water erosion: None
Vegetation / Land use: Grassveld, closed
Water table: 650 mm
Described by: W. Boshoff, A.Q. Weldeyohannes
Date described: 19/06/2001
Weathering of underlying material: Strong physical, strong chemical
Alteration of underlying material: Ferruginised

Horizon	Depth(mm)	Description	Diagnostic horizons / material
A	0 - 150	**Moisture status:** moist; **dry colour:** 10YR7/1 (50 %), 7.5YR5/8 (50 %); **moist colour:** 10YR4/2 (50 %), 2.5YR4/8 (50 %); 32.4 % clay; clay loam; many fine distinct 10YR4/4 dry, 2.5YR4/8 moist, iron oxide mottles; weak coarse granular; hard, slightly firm, sticky, very plastic; common rusty fine and very fine pores; common rusty medium and coarse pores; no slickensides; fine cracks; no cutans; no coarse fragments; water absorption 3 second(s); many rusty roots; diffuse smooth transition;	orthic A horizon
G1	150 - 450	**Moisture status:** Wet; **dry colour:** 10YR7/1 (80 %), 7.5YR6/8 (20 %); **moist colour:** 10YR5/1 (80 %), 2.5YR4/8 (20 %); 37.5 % clay; clay loam; common fine distinct 10YR5/6 dry, 2.5YR4/8 moist, iron oxide mottles; weak fine subangular blocky; hard, slightly firm, sticky, very plastic; common rusty fine and very fine pores; common rusty medium and coarse pores; no slickensides; fine cracks; no cutans; no coarse fragments; water absorption 4 second(s); many rusty roots; gradual smooth transition;	G horizon
G2	450 - 1200	**Moisture status:** Wet; **dry colour:** 10YR7/1 (80 %), 7.5YR6/8 (20 %); **moist colour:** 10YR5/1 (80 %), 7.5YR6/8 (20 %); 37.5 % clay; clay loam; common fine distinct 10YR6/8 dry, 10YR6/8 moist, iron oxide mottles; weak fine subangular blocky; hard, very firm, sticky, very plastic; few rusty fine and very fine pores; few rusty medium and coarse pores; no slickensides; fine cracks; common silica cutans; very few 2-6 mm mixed stones; water absorption 10 second(s); few rusty roots; transition not reached;	G horizon

Remark: Yellow pores (channels) in all three horizons.

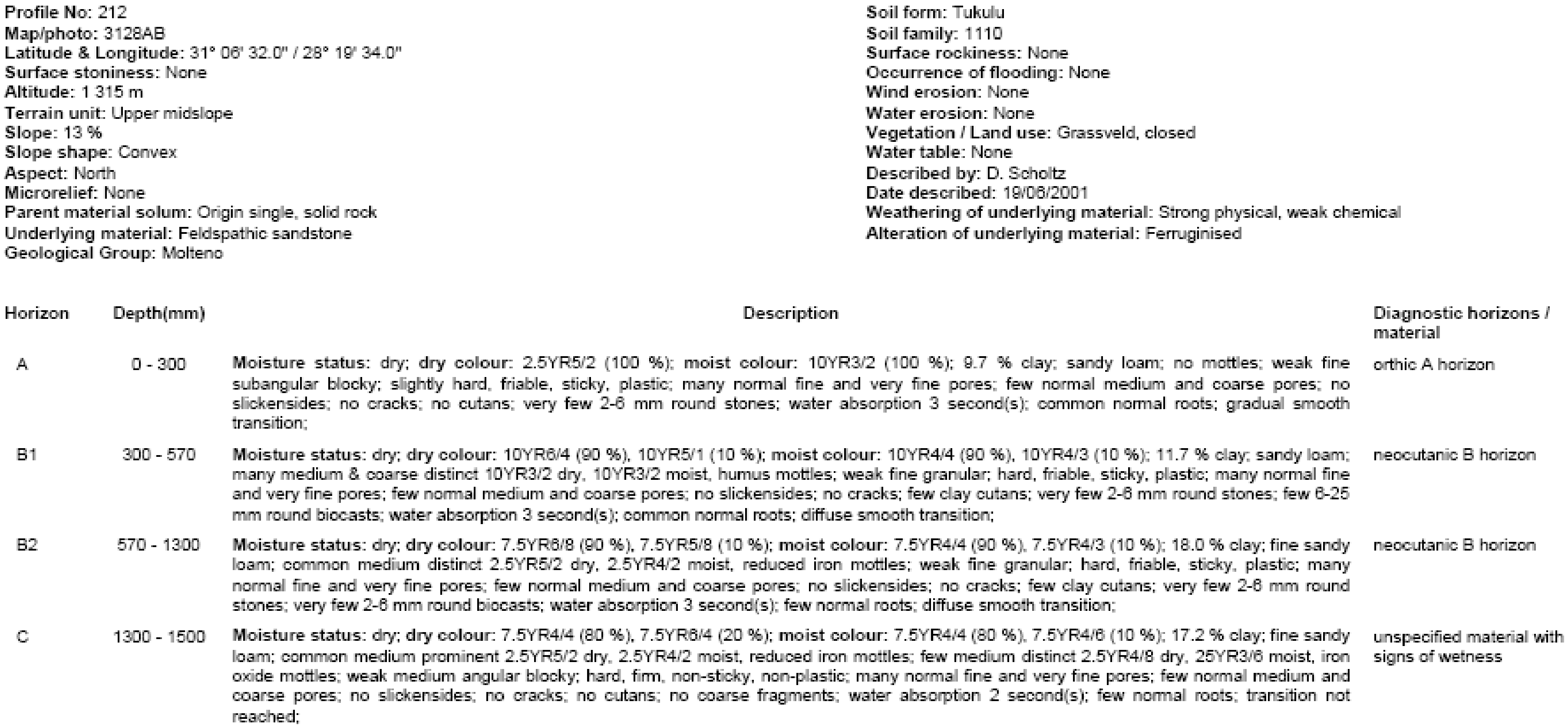
Table 2 Analytical data for P211 (Van Huyssteen *et al*., 2005).

Horizon	Depth	Diagnostic horizon	Gravel	Texture of the fine earth							Exchangeable cations					CEC soil	CEC clay	Base sat
				coSa	meSa	fiSa	vfSa	Si	fiSi	Cl	Ca	Mg	K	Na	S			
	mm		%	%							$cmol_c\ kg^{-1}$							%
A	0-100	ot	5.5	5.7	6.0	4.2	9.3	13.9	24.9	32.6	11.83	1.95	0.33	0.23	14.34	9.68	29.7	148.2
	100-200		11.4	5.4	5.4	3.4	8.3	15.4	27.8	32.1	9.35	1.91	0.25	0.19	11.71	9.52	29.6	123.1
G1	200-300	gh	13.9	4.2	5.0	3.5	8.1	12.3	24.6	38.9	17.35	3.10	0.27	0.22	20.93	13.65	35.1	153.4
	300-400		5.2	4.4	4.9	3.5	7.8	13.0	20.8	40.9	3.06	3.67	0.27	0.23	7.24	13.43	32.8	53.9
G2	400-500	gh	2.4	4.4	4.9	3.4	7.3	12.3	33.5	32.7	4.43	4.96	0.30	0.34	10.03	13.81	42.2	72.6
	500-600		7.1	5.8	5.7	4.4	9.0	10.5	20.9	41.9	4.48	4.80	0.19	0.29	9.75	15.66	37.4	62.3

Horizon	Depth	Bulk density	pH		Org C	N	C:N	Fe			Mn			
								CBD			CBD			
	mm	$Mg\ m^{-3}$	H_2O	KCl	%	$mg\ kg^{-1}$		$mg\ kg^{-1}$						
A	0-100	1.39	5.07	3.99	1.39	1070	13.0	9250			191.0			
	100-200		5.51	4.01	1.04	995	10.5	9850			243.0			
G1	200-300		5.72	4.43	0.95	891	10.6	9600			158.0			
	300-400	1.66	6.19	4.36	0.56	802	7.0	10250			181.5			
G2	400-500		5.95	4.27	0.45	650	7.0	10900			14.0			
	500-600		5.81	4.50	0.26	488	5.4	4985			13.5			

Figure 2 Photo of P212 (Van Huyssteen *et al*., 2005)..

Table 3 Profile description of P212 (Van Huyssteen *et al*., 2005)



Profile No: 212
Map/photo: 3128AB
Latitude & Longitude: 31° 06' 32.0" / 28° 19' 34.0"
Surface stoniness: None
Altitude: 1 315 m
Terrain unit: Upper midslope
Slope: 13 %
Slope shape: Convex
Aspect: North
Microrelief: None
Parent material solum: Origin single, solid rock
Underlying material: Feldspathic sandstone
Geological Group: Molteno

Soil form: Tukulu
Soil family: 1110
Surface rockiness: None
Occurrence of flooding: None
Wind erosion: None
Water erosion: None
Vegetation / Land use: Grassveld, closed
Water table: None
Described by: D. Scholtz
Date described: 19/06/2001
Weathering of underlying material: Strong physical, weak chemical
Alteration of underlying material: Ferruginised

Horizon	**Depth(mm)**	**Description**	**Diagnostic horizons / material**
A	0 - 300	**Moisture status:** dry; **dry colour:** 2.5YR5/2 (100 %); **moist colour:** 10YR3/2 (100 %); 9.7 % clay; sandy loam; no mottles; weak fine subangular blocky; slightly hard, friable, sticky, plastic; many normal fine and very fine pores; few normal medium and coarse pores; no slickensides; no cracks; no cutans; very few 2-6 mm round stones; water absorption 3 second(s); common normal roots; gradual smooth transition;	orthic A horizon
B1	300 - 570	**Moisture status:** dry; **dry colour:** 10YR6/4 (90 %), 10YR5/1 (10 %); **moist colour:** 10YR4/4 (90 %), 10YR4/3 (10 %); 11.7 % clay; sandy loam; many medium & coarse distinct 10YR3/2 dry, 10YR3/2 moist, humus mottles; weak fine granular; hard, friable, sticky, plastic; many normal fine and very fine pores; few normal medium and coarse pores; no slickensides; no cracks; few clay cutans; very few 2-6 mm round stones; few 6-25 mm round biocasts; water absorption 3 second(s); common normal roots; diffuse smooth transition;	neocutanic B horizon
B2	570 - 1300	**Moisture status:** dry; **dry colour:** 7.5YR6/8 (90 %), 7.5YR5/8 (10 %); **moist colour:** 7.5YR4/4 (90 %), 7.5YR4/3 (10 %); 18.0 % clay; fine sandy loam; common medium distinct 2.5YR5/2 dry, 2.5YR4/2 moist, reduced iron mottles; weak fine granular; hard, friable, sticky, plastic; many normal fine and very fine pores; few normal medium and coarse pores; no slickensides; no cracks; few clay cutans; very few 2-6 mm round stones; very few 2-6 mm round biocasts; water absorption 3 second(s); few normal roots; diffuse smooth transition;	neocutanic B horizon
C	1300 - 1500	**Moisture status:** dry; **dry colour:** 7.5YR4/4 (80 %), 7.5YR6/4 (20 %); **moist colour:** 7.5YR4/4 (80 %), 7.5YR4/6 (10 %); 17.2 % clay; fine sandy loam; common medium prominent 2.5YR5/2 dry, 2.5YR4/2 moist, reduced iron mottles; few medium distinct 2.5YR4/8 dry, 25YR3/6 moist, iron oxide mottles; weak medium angular blocky; hard, firm, non-sticky, non-plastic; many normal fine and very fine pores; few normal medium and coarse pores; no slickensides; no cracks; no cutans; no coarse fragments; water absorption 2 second(s); few normal roots; transition not reached;	unspecified material with signs of wetness

Table 4 Analytical data of P212 (Van Huyssteen *et al*., 2005)

Horizon	Depth	Diagnostic horizon	Gravel	Texture of the fine earth							Exchangeable cations					CEC soil	CEC clay	Base sat
				coSa	meSa	fiSa	vfSa	Si	fiSi	Cl	Ca	Mg	K	Na	S			
	mm		%	%							$\text{cmol}_c\ \text{kg}^{-1}$							%
A	0-100	ot	10.0	20.7	15.6	17.9	17.9	11.2	10.0	9.0	1.04	0.56	0.19	0.13	1.92	3.64	40.5	52.8
	100-200		10.1	20.6	17.6	17.2	17.2	8.0	11.4	10.0	0.94	0.50	0.11	0.12	1.68	2.99	29.9	56.2
	200-300		15.9	20.4	16.7	17.5	17.5	8.9	10.4	10.0	0.92	0.54	0.12	0.11	1.69	3.04	30.4	55.4
B1	300-400	ne	19.9	26.3	17.1	17.6	17.6	6.4	9.0	9.0	0.83	0.56	0.11	0.12	1.61	3.21	35.6	50.3
	400-500		13.7	23.9	16.8	16.5	16.5	8.3	10.4	10.4	0.88	0.65	0.12	0.12	1.78	2.12	20.4	83.9
	500-600		10.4	23.0	14.2	14.8	14.8	6.4	10.5	15.6	0.73	0.59	0.10	0.12	1.55	2.83	18.1	54.7
B2	600-700	ne	9.2	33.6	11.7	13.3	13.3	7.7	7.1	15.1	0.64	0.60	0.09	0.12	1.46	3.04	20.2	47.8
	700-800		15.1	19.9	9.9	12.4	12.4	12.1	17.4	17.6	0.62	0.71	0.07	0.13	1.53	3.04	17.3	50.3
	800-900		25.5	14.9	10.2	14.0	14.0	11.7	17.2	17.2	0.61	0.65	0.07	0.13	1.47	3.10	18.0	47.5
	900-1000		17.5	12.5	11.0	13.2	13.2	11.5	18.5	20.5	0.63	0.79	0.08	0.14	1.65	3.48	17.0	47.3
	1000-1100		13.4	14.4	9.3	12.0	12.0	14.3	17.5	18.8	0.60	0.82	0.08	0.14	1.63	3.64	19.4	44.8
	1100-1200		-	-	-	-	-	-	-	-	0.61	0.47	0.06	0.13	1.27	3.15	-	40.3
	1200-1300		20.6	18.1	13.4	13.0	13.0	10.7	15.5	18.5	0.45	0.71	0.07	0.11	1.34	3.97	21.5	33.8
C1	1300-1400	so	26.4	15.4	9.4	12.0	12.0	12.3	21.2	18.2	0.62	0.56	0.08	0.13	1.39	3.59	19.7	38.9
	1400-1500		22.9	7.0	14.5	14.1	14.1	12.4	18.1	18.1	0.54	0.76	0.07	0.13	1.50	3.26	18.0	46.0
C2	1500-1600	so	19.3	21.8	10.3	11.3	11.3	9.7	16.3	16.3	0.46	0.63	0.05	0.15	1.30	2.34	14.3	55.5
	1600+		17.2	24.0	11.4	13.9	13.9	8.7	15.0	16.0	0.40	0.66	0.07	0.13	1.25	2.45	15.3	51.1

Horizon	Depth	Bulk density	pH		Org C	N	C:N	Fe			Mn		
								CBD			CBD		
	mm	Mg m^{-3}	H_2O	KCl	%	mg kg^{-1}		mg kg^{-1}					
A	0-100	1.52	5.32	4.44	0.79	369	21.5	4505			14.5		
	100-200		5.22	4.26	0.70	406	17.3	3910			37.0		
	200-300		5.31	4.29	0.66	332	19.8	5325			12.5		
B1	300-400	1.64	5.37	4.27	0.38	385	10.0	4055			12.0		
	400-500		5.40	4.41	0.37	270	13.6	4860			15.0		
	500-600		5.55	4.14	0.25	226	10.9	6065			25.0		
B2	600-700	1.64	5.44	4.06	0.15	195	7.9	7400			54.5		
	700-800		5.43	4.05	0.18	178	10.4	12600			50.5		
	800-900		5.40	4.22	0.15	187	8.0	7970			96.0		
	900-1000	1.60	5.43	4.22	0.27	202	13.1	8015			112.5		
	1000-1100		5.59	4.10	0.11	181	5.9	8080			133.5		
	1100-1200		-	-	-	-	-	10700			101.0		
	1200-1300	1.68	5.71	4.17	0.11	160	6.6	8050			79.0		
C1	1300-1400		5.70	4.12	0.05	173	2.8	6955			82.0		
	1400-1500		5.68	4.33	0.12	118	9.8	6970			62.5		
C2	1500-1600	-	5.74	4.24	0.05	104	4.9	12600			60.0		
	1600+		5.69	4.16	0.04	90	4.7	4505			14.5		

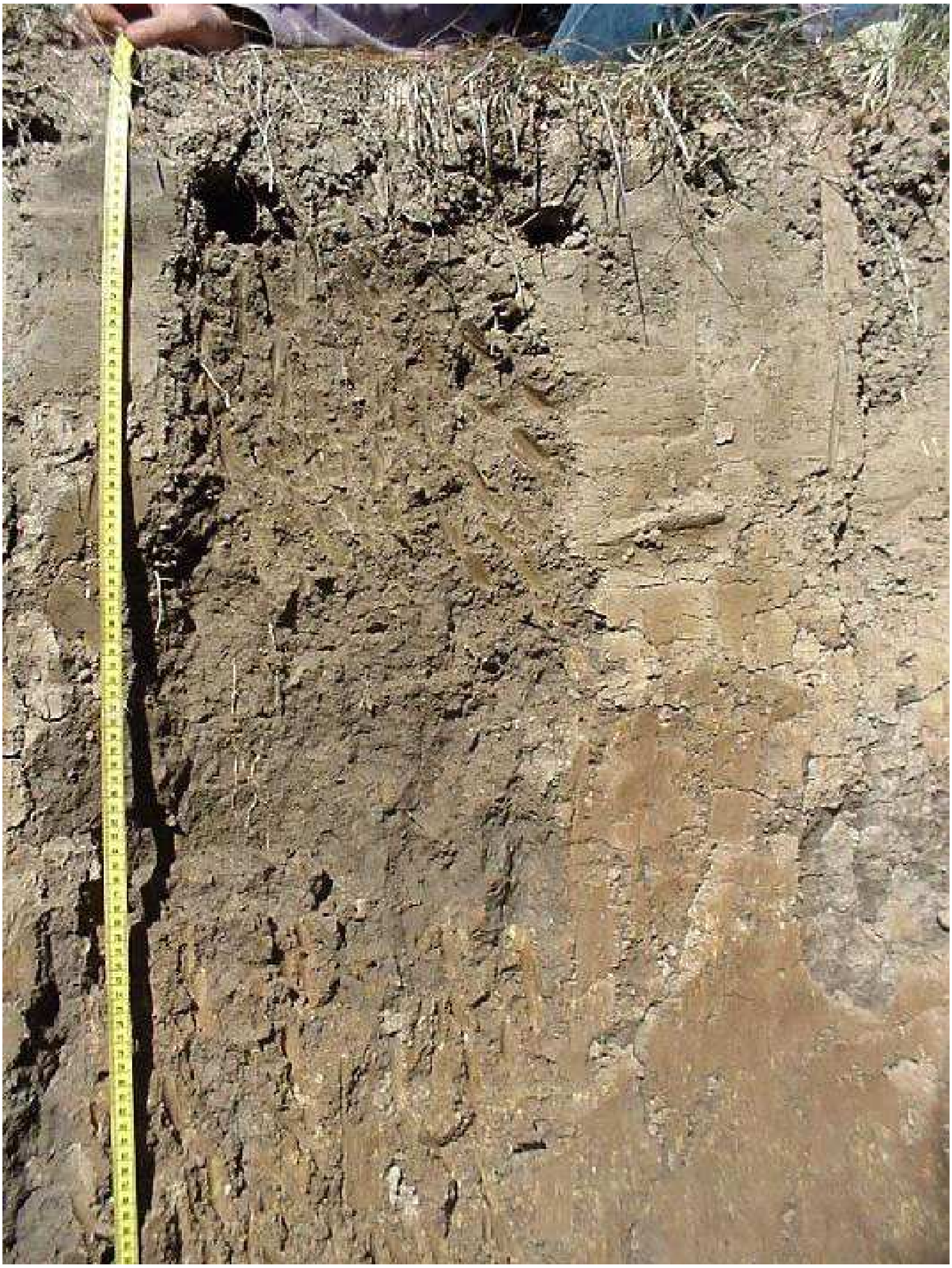
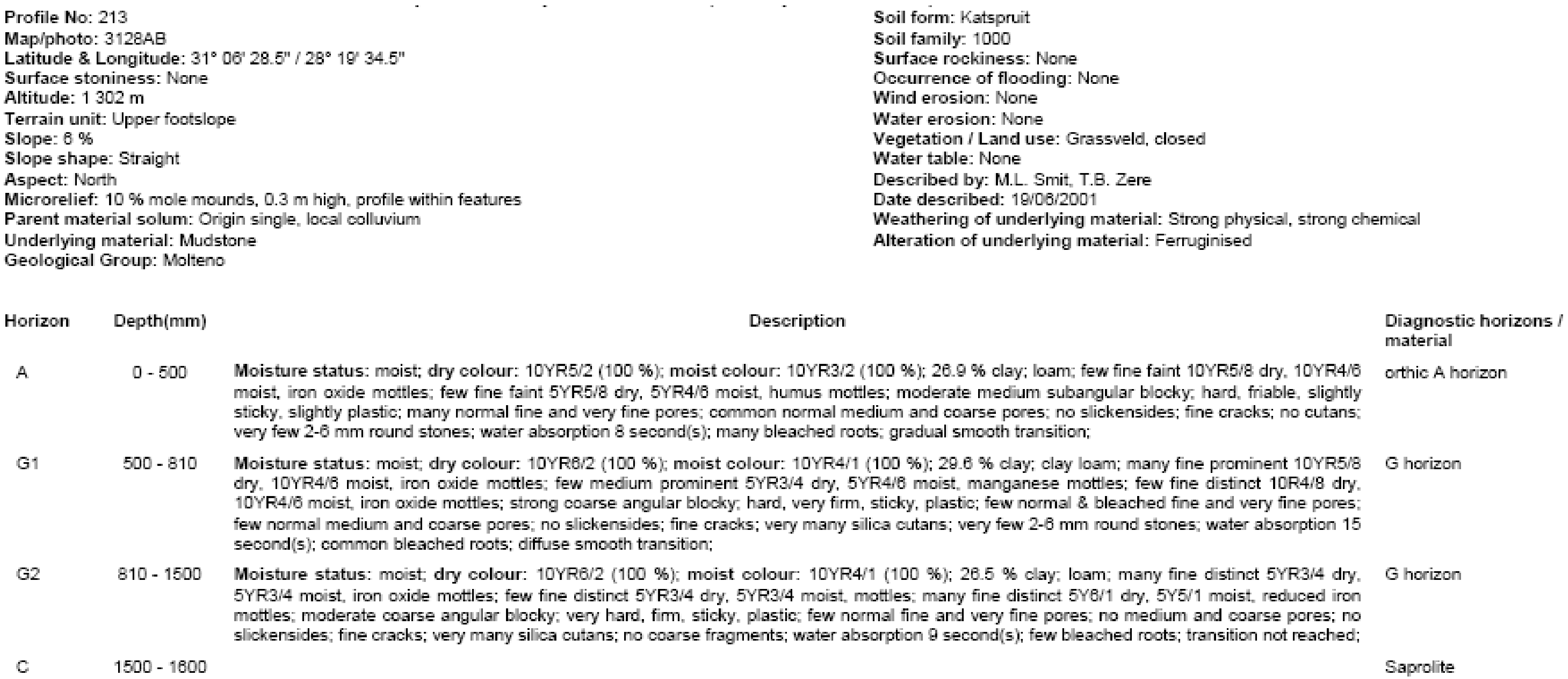


Figure 3 Photo of P213 (Van Huyssteen *et al*., 2005).

Table 5 Profile description of P213 (Van Huyssteen *et al*., 2005)



Profile No: 213
Map/photo: 3128AB
Latitude & Longitude: 31° 06' 28.5" / 28° 19' 34.5"
Surface stoniness: None
Altitude: 1 302 m
Terrain unit: Upper footslope
Slope: 6 %
Slope shape: Straight
Aspect: North
Microrelief: 10 % mole mounds, 0.3 m high, profile within features
Parent material solum: Origin single, local colluvium
Underlying material: Mudstone
Geological Group: Molteno

Soil form: Katspruit
Soil family: 1000
Surface rockiness: None
Occurrence of flooding: None
Wind erosion: None
Water erosion: None
Vegetation / Land use: Grassveld, closed
Water table: None
Described by: M.L. Smit, T.B. Zere
Date described: 19/06/2001
Weathering of underlying material: Strong physical, strong chemical
Alteration of underlying material: Ferruginised

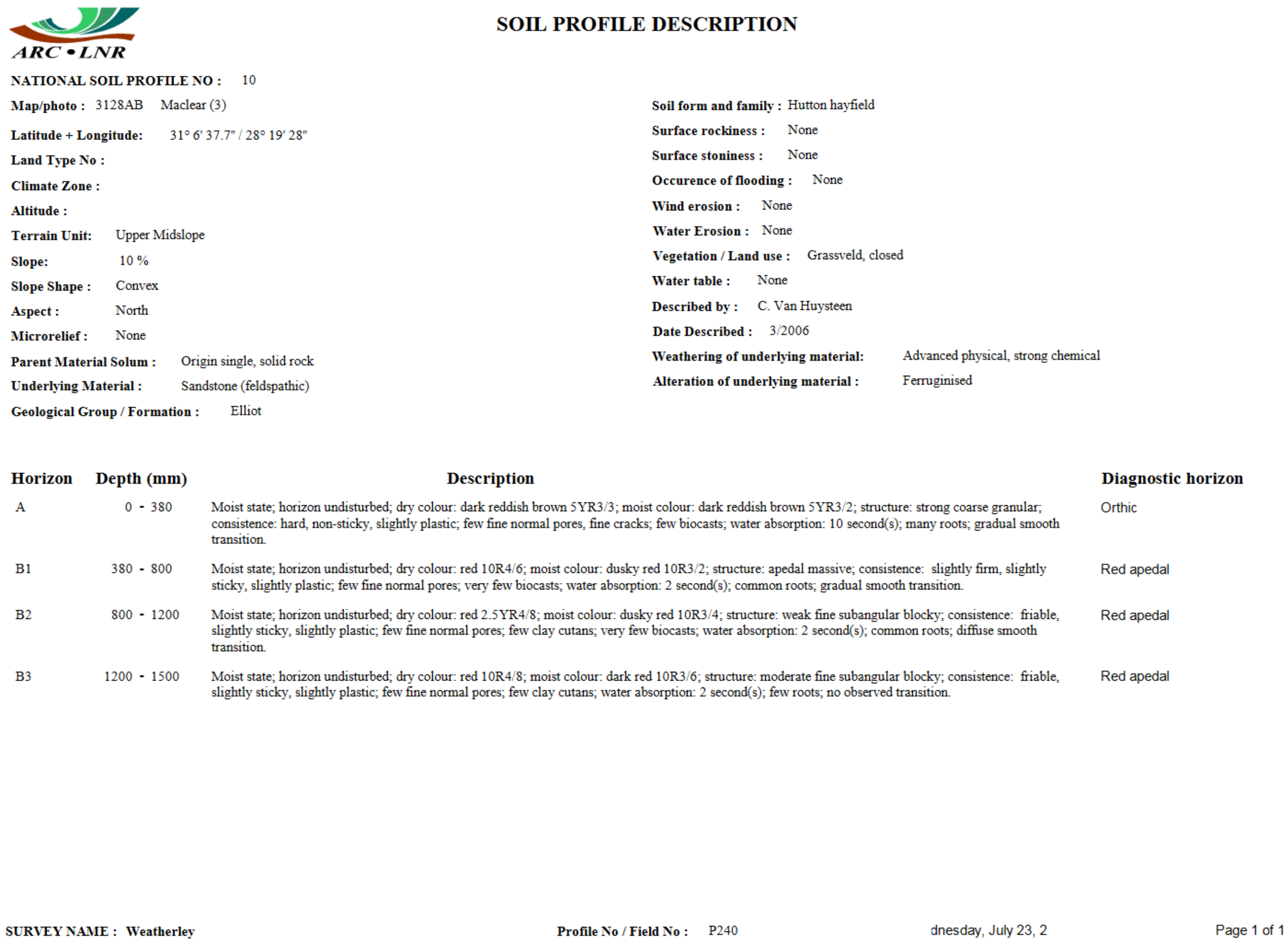
Horizon	Depth(mm)	Description	Diagnostic horizons / material
A	0 - 500	**Moisture status:** moist; **dry colour:** 10YR5/2 (100 %); **moist colour:** 10YR3/2 (100 %); 26.9 % clay; loam; few fine faint 10YR5/8 dry, 10YR4/6 moist, iron oxide mottles; few fine faint 5YR5/8 dry, 5YR4/6 moist, humus mottles; moderate medium subangular blocky; hard, friable, slightly sticky, slightly plastic; many normal fine and very fine pores; common normal medium and coarse pores; no slickensides; fine cracks; no cutans; very few 2-6 mm round stones; water absorption 8 second(s); many bleached roots; gradual smooth transition;	orthic A horizon
G1	500 - 810	**Moisture status:** moist; **dry colour:** 10YR6/2 (100 %); **moist colour:** 10YR4/1 (100 %); 29.6 % clay; clay loam; many fine prominent 10YR5/8 dry, 10YR4/6 moist, iron oxide mottles; few medium prominent 5YR3/4 dry, 5YR4/6 moist, manganese mottles; few fine distinct 10R4/8 dry, 10YR4/6 moist, iron oxide mottles; strong coarse angular blocky; hard, very firm, sticky, plastic; few normal & bleached fine and very fine pores; few normal medium and coarse pores; no slickensides; fine cracks; very many silica cutans; very few 2-6 mm round stones; water absorption 15 second(s); common bleached roots; diffuse smooth transition;	G horizon
G2	810 - 1500	**Moisture status:** moist; **dry colour:** 10YR6/2 (100 %); **moist colour:** 10YR4/1 (100 %); 26.5 % clay; loam; many fine distinct 5YR3/4 dry, 5YR3/4 moist, iron oxide mottles; few fine distinct 5YR3/4 dry, 5YR3/4 moist, mottles; many fine distinct 5Y6/1 dry, 5Y5/1 moist, reduced iron mottles; moderate coarse angular blocky; very hard, firm, sticky, plastic; few normal fine and very fine pores; no medium and coarse pores; no slickensides; fine cracks; very many silica cutans; no coarse fragments; water absorption 9 second(s); few bleached roots; transition not reached;	G horizon
C	1500 - 1600		Saprolite

Table 6 Analysis data for 213 (Van Huyssteen *et al*., 2005)

Horizon	Depth	Diagnostic horizon	Gravel	Texture of the fine earth							Exchangeable cations					CEC soil	CEC clay	Base sat
				coSa	meSa	fiSa	vfSa	Si	fiSi	Cl	Ca	Mg	K	Na	S			
	mm		%	%							cmol$_c$ kg^{-1}							%
A	0-100	ot	17.2	8.4	8.6	7.3	13.0	12.2	23.9	24.0	5.51	3.33	0.33	0.17	9.34	9.30	38.7	100.4
	100-200		17.6	8.3	6.8	5.5	13.9	15.9	19.8	27.8	3.85	2.44	0.43	0.17	6.89	9.90	35.6	69.6
	200-300		4.5	5.7	7.1	6.5	14.8	14.7	25.1	25.0	3.59	2.46	0.43	0.17	6.64	8.70	34.8	76.4
	300-400		25.4	6.8	6.6	5.7	12.4	14.1	25.4	26.2	3.29	2.50	0.35	0.19	6.33	9.90	37.8	64.0
	400-500		33.0	7.6	5.9	4.9	11.5	11.6	24.6	31.3	4.69	3.10	0.33	0.23	8.34	12.18	38.9	68.5
G1	500-550	gh	44.7	7.1	6.8	5.8	11.5	10.3	22.0	34.1	4.86	4.37	0.25	0.24	9.72	10.11	29.7	96.1
	550-600		44.5	7.9	7.5	7.8	11.3	26.9	14.0	21.1	4.25	3.21	0.21	0.27	7.95	11.96	56.7	66.4
	600-700		39.7	6.2	6.8	7.4	13.3	12.2	20.9	31.9	5.08	3.55	0.24	0.22	9.10	13.38	41.9	68.0
	700-800		37.6	7.1	8.3	7.3	13.6	13.5	17.3	31.4	5.04	4.46	0.21	0.22	9.94	10.77	34.3	92.3
G2	800-900	gh	43.6	9.9	12.7	6.9	9.3	10.9	17.2	30.0	4.99	4.27	0.18	0.24	9.67	10.55	35.2	91.7
	900-1000		34.9	7.9	11.8	8.7	12.7	12.0	15.0	30.8	5.58	4.46	0.19	0.24	10.48	10.87	35.3	96.3
	1000-1100		37.2	9.6	10.2	7.4	12.7	11.9	21.4	24.8	5.44	3.12	0.20	0.26	9.02	11.53	46.5	78.2
	1100-1200		38.9	7.7	9.9	7.2	13.2	13.4	19.2	25.6	5.34	3.77	0.19	0.31	9.61	11.69	45.7	82.2
	1200-1300		49.2	7.5	8.9	7.3	13.0	13.4	22.6	25.3	4.93	3.57	0.19	0.26	8.95	10.28	40.6	87.1
	1300-1400		45.7	8.3	9.0	7.0	12.5	12.7	23.8	24.6	5.94	4.05	0.20	0.24	10.43	11.64	47.3	89.6
	1400-1500		39.3	6.7	9.2	8.2	14.4	12.9	22.7	24.7	5.59	4.29	0.21	0.22	10.31	11.04	44.7	93.4
C	1500-1600	so	42.9	6.4	9.0	7.6	13.8	15.6	22.4	22.7	5.54	3.97	0.20	0.20	9.91	10.33	45.5	95.9

Horizon	Depth	Bulk density	pH		Org C	N	C:N	Fe			Mn			
								CBD			CBD			
	mm	Mg m^{-3}	H$_2$O	KCl	%	mg kg^{-1}		mg kg^{-1}						
A	0-100	1.61	5.60	4.78	1.41	530	26.5	6015			160.5			
	100-200		5.46	4.35	1.46	951	15.3	6705			181.5			
	200-300		5.45	4.18	1.07	867	12.3	7825			127.5			
	300-400	1.64	5.49	4.41	0.85	747	11.4	7705			90.5			
	400-500		4.89	4.32	0.61	657	9.3	7770			53.0			
G1	500-550		5.66	4.40	0.42	572	7.4	10150			35.5			
	550-600		5.85	4.28	0.38	503	7.6	9600			55.5			
	600-700	1.71	6.12	4.32	0.24	414	5.8	2000			73.0			
	700-800		6.13	4.52	0.18	362	5.1	7910			64.0			
G2	800-900		6.22	4.43	0.17	363	4.7	6245			28.0			
	900-1000	1.73	6.30	4.61	0.13	311	4.1	2795			108.0			
	1000-1100		6.41	4.73	0.10	296	3.5	7210			113.5			
	1100-1200		6.41	4.47	0.11	310	3.4	7775			85.5			
	1200-1300	1.76	6.42	4.59	0.15	311	4.8	5765			75.0			
	1300-1400		6.45	4.74	0.09	285	3.1	5375			79.0			
	1400-1500		6.42	4.59	0.08	271	3.1	5540			88.5			
C	1500-1600	-	6.37	4.54	0.13	271	4.9	5385			92.5			

Table 7 Profile description of P240



ARC • LNR

SOIL PROFILE DESCRIPTION

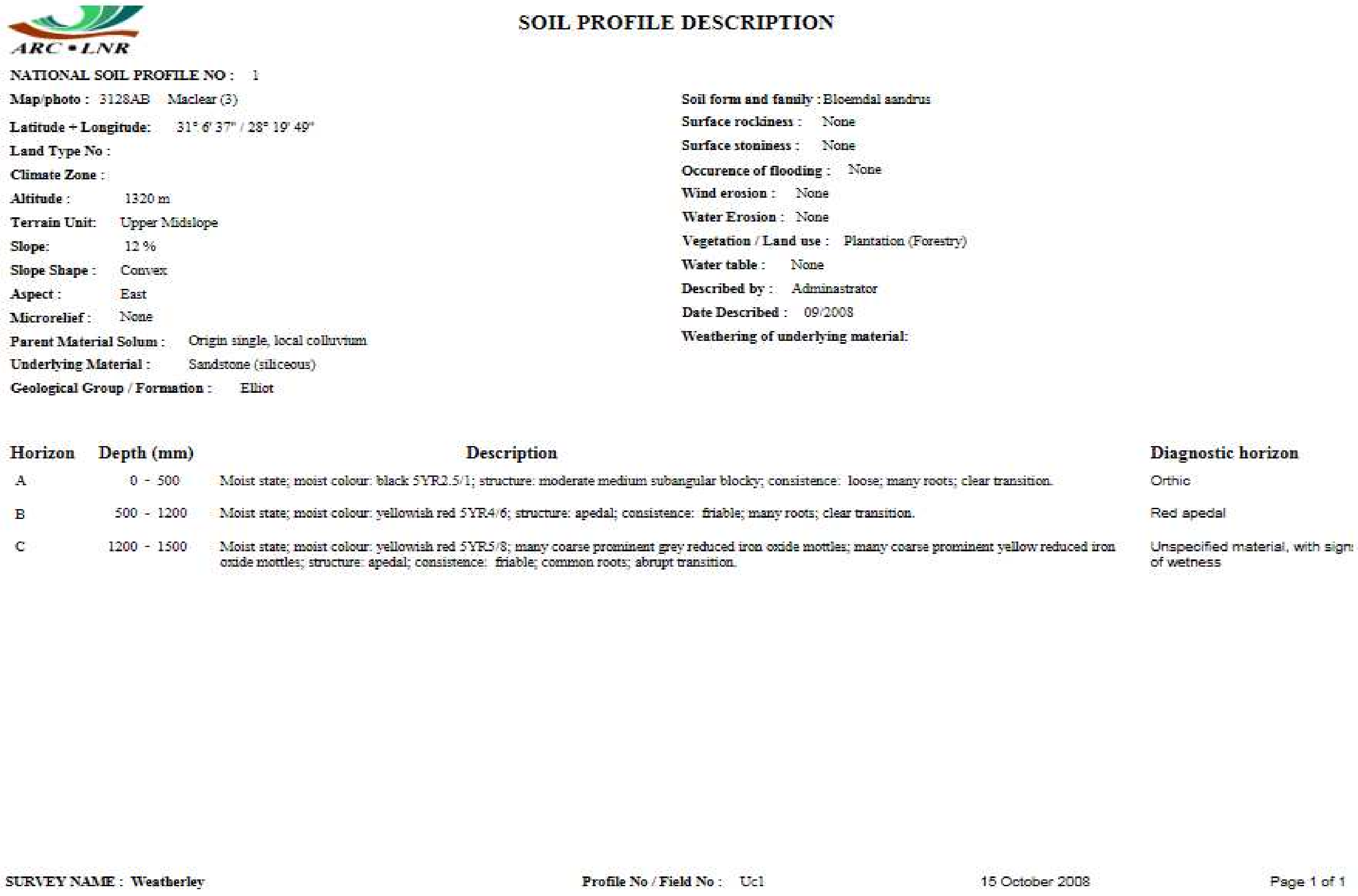
NATIONAL SOIL PROFILE NO :	10
Map/photo :	3128AB Maclear (3)
Latitude + Longitude:	31° 6' 37.7" / 28° 19' 28"
Land Type No :	
Climate Zone :	
Altitude :	
Terrain Unit:	Upper Midslope
Slope:	10 %
Slope Shape :	Convex
Aspect :	North
Microrelief :	None
Parent Material Solum :	Origin single, solid rock
Underlying Material :	Sandstone (feldspathic)
Geological Group / Formation :	Elliot

Soil form and family :	Hutton hayfield
Surface rockiness :	None
Surface stoniness :	None
Occurence of flooding :	None
Wind erosion :	None
Water Erosion :	None
Vegetation / Land use :	Grassveld, closed
Water table :	None
Described by :	C. Van Huysteen
Date Described :	3/2006
Weathering of underlying material:	Advanced physical, strong chemical
Alteration of underlying material :	Ferruginised

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 380	Moist state; horizon undisturbed; dry colour: dark reddish brown 5YR3/3; moist colour: dark reddish brown 5YR3/2; structure: strong coarse granular; consistence: hard, non-sticky, slightly plastic; few fine normal pores, fine cracks; few biocasts; water absorption: 10 second(s); many roots; gradual smooth transition.	Orthic
B1	380 - 800	Moist state; horizon undisturbed; dry colour: red 10R4/6; moist colour: dusky red 10R3/2; structure: apedal massive; consistence: slightly firm, slightly sticky, slightly plastic; few fine normal pores; very few biocasts; water absorption: 2 second(s); common roots; gradual smooth transition.	Red apedal
B2	800 - 1200	Moist state; horizon undisturbed; dry colour: red 2.5YR4/8; moist colour: dusky red 10R3/4; structure: weak fine subangular blocky; consistence: friable, slightly sticky, slightly plastic; few fine normal pores; few clay cutans; very few biocasts; water absorption: 2 second(s); common roots; diffuse smooth transition.	Red apedal
B3	1200 - 1500	Moist state; horizon undisturbed; dry colour: red 10R4/8; moist colour: dark red 10R3/6; structure: moderate fine subangular blocky; consistence: friable, slightly sticky, slightly plastic; few fine normal pores; few clay cutans; water absorption: 2 second(s); few roots; no observed transition.	Red apedal

SURVEY NAME : Weatherley **Profile No / Field No :** P240 dnesday, July 23, 2 Page 1 of 1

Table 8 Profile description of profile Uc1



ARC • LNR

SOIL PROFILE DESCRIPTION

NATIONAL SOIL PROFILE NO : 1

Map/photo : 3128AB Maclear (3)

Latitude + Longitude: 31° 6' 37" / 28° 19' 49"

Land Type No :

Climate Zone :

Altitude : 1320 m

Terrain Unit: Upper Midslope

Slope: 12 %

Slope Shape : Convex

Aspect : East

Microrelief : None

Parent Material Solum : Origin single, local colluvium

Underlying Material : Sandstone (siliceous)

Geological Group / Formation : Elliot

Soil form and family : Bloemdal aandrus

Surface rockiness : None

Surface stoniness : None

Occurence of flooding : None

Wind erosion : None

Water Erosion : None

Vegetation / Land use : Plantation (Forestry)

Water table : None

Described by : Adminastrator

Date Described : 09/2008

Weathering of underlying material:

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 500	Moist state; moist colour: black 5YR2.5/1; structure: moderate medium subangular blocky; consistence: loose; many roots; clear transition.	Orthic
B	500 - 1200	Moist state; moist colour: yellowish red 5YR4/6; structure: apedal; consistence: friable; many roots; clear transition.	Red apedal
C	1200 - 1500	Moist state; moist colour: yellowish red 5YR5/8; many coarse prominent grey reduced iron oxide mottles; many coarse prominent yellow reduced iron oxide mottles; structure: apedal; consistence: friable; common roots; abrupt transition.	Unspecified material, with sign of wetness

SURVEY NAME : **Weatherley**

Profile No / Field No : Uc1

15 October 2008

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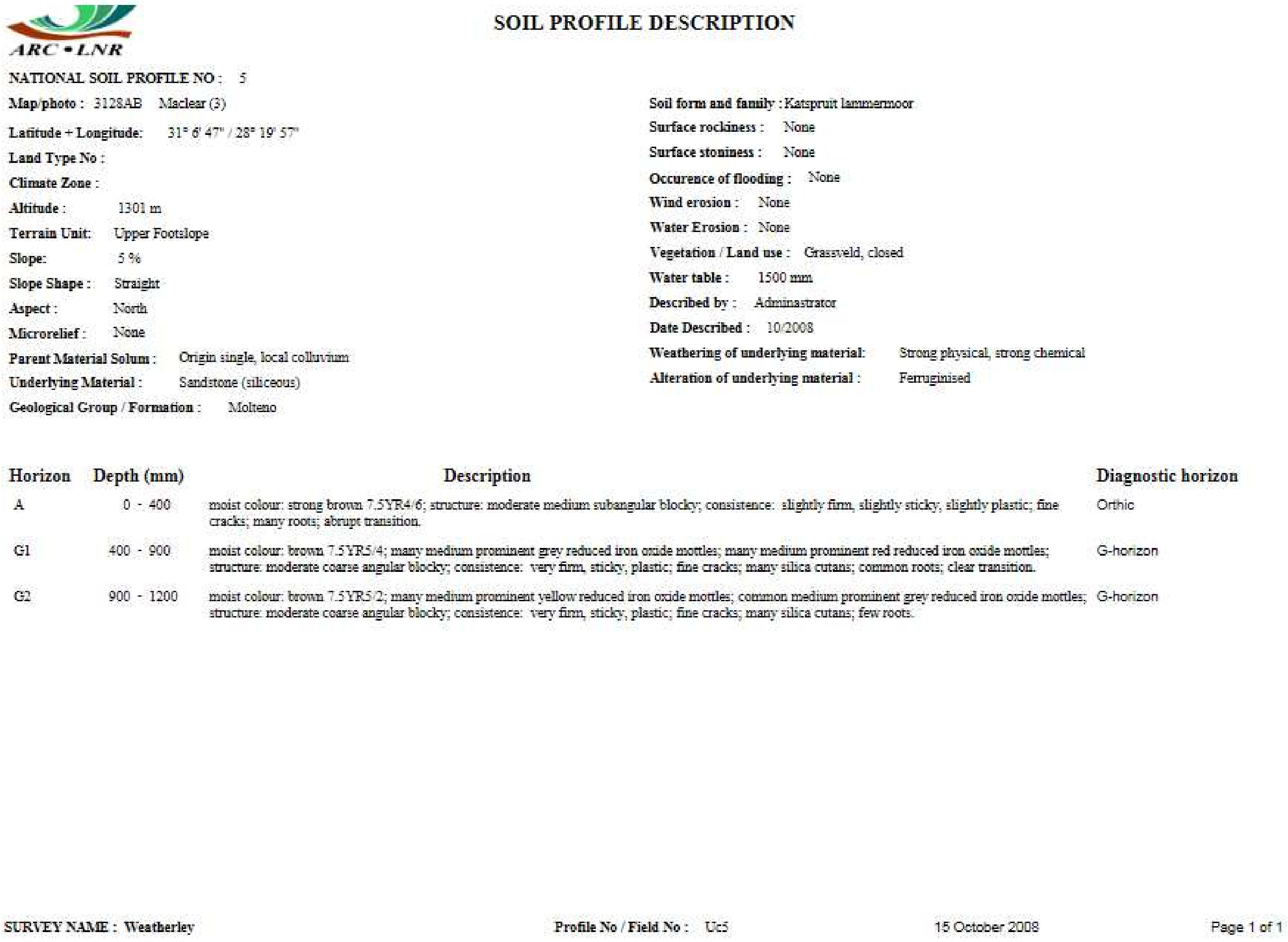
Table 9 Profile description of profile Uc5



ARC • LNR

SOIL PROFILE DESCRIPTION

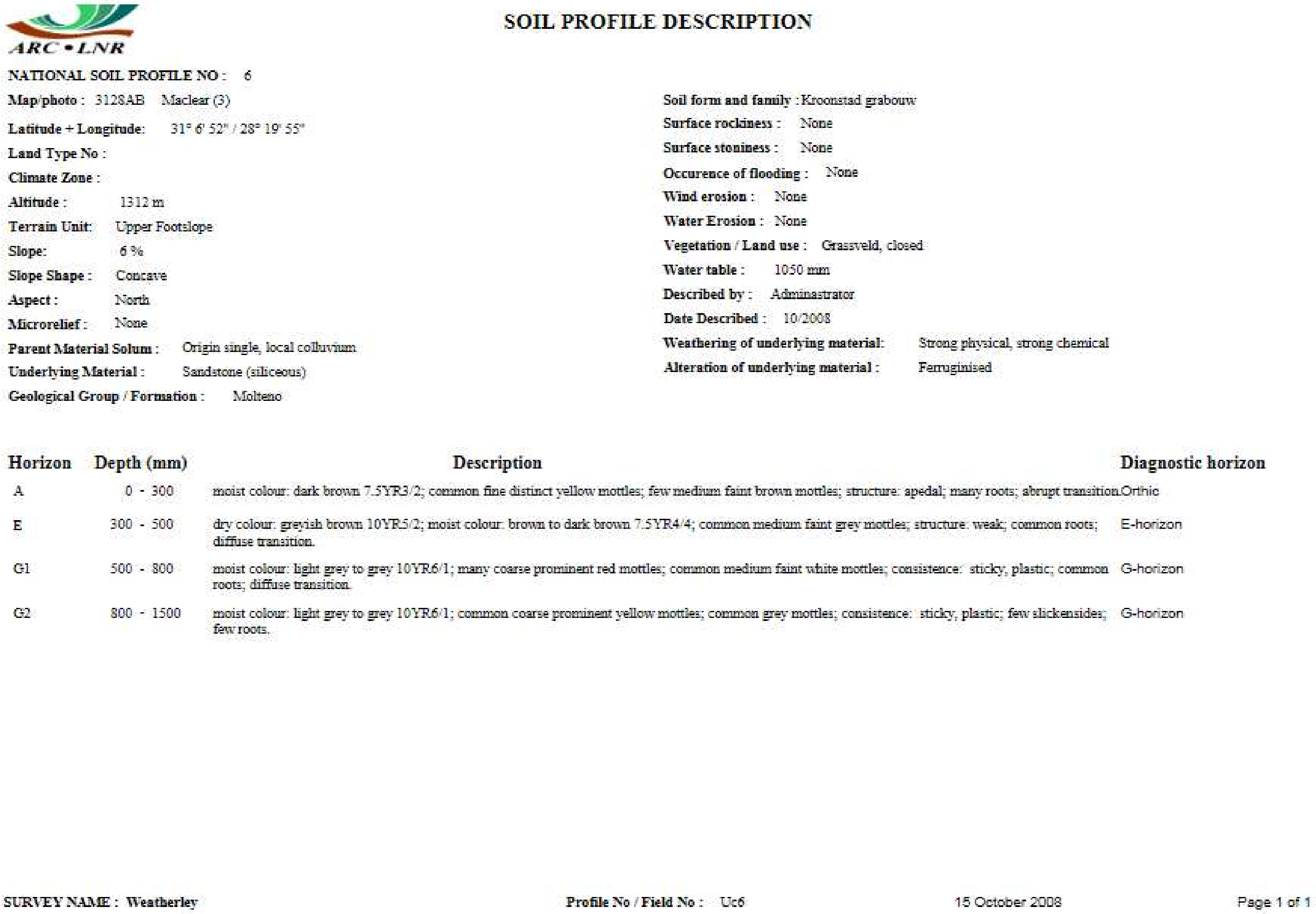
NATIONAL SOIL PROFILE NO : 5
Map/photo : 3128AB Maclear (3)
Latitude + Longitude: 31° 6' 47" / 28° 19' 57"
Land Type No :
Climate Zone :
Altitude : 1301 m
Terrain Unit: Upper Footslope
Slope: 5 %
Slope Shape : Straight
Aspect : North
Microrelief : None
Parent Material Solum : Origin single, local colluvium
Underlying Material : Sandstone (siliceous)
Geological Group / Formation : Molteno

Soil form and family : Katspruit lammermoor
Surface rockiness : None
Surface stoniness : None
Occurence of flooding : None
Wind erosion : None
Water Erosion : None
Vegetation / Land use : Grassveld, closed
Water table : 1500 mm
Described by : Adminastrator
Date Described : 10/2008
Weathering of underlying material: Strong physical, strong chemical
Alteration of underlying material : Ferruginised

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 400	moist colour: strong brown 7.5YR4/6; structure: moderate medium subangular blocky; consistence: slightly firm, slightly sticky, slightly plastic; fine cracks; many roots; abrupt transition.	Orthic
G1	400 - 900	moist colour: brown 7.5YR5/4; many medium prominent grey reduced iron oxide mottles; many medium prominent red reduced iron oxide mottles; structure: moderate coarse angular blocky; consistence: very firm, sticky, plastic; fine cracks; many silica cutans; common roots; clear transition.	G-horizon
G2	900 - 1200	moist colour: brown 7.5YR5/2; many medium prominent yellow reduced iron oxide mottles; common medium prominent grey reduced iron oxide mottles; structure: moderate coarse angular blocky; consistence: very firm, sticky, plastic; fine cracks; many silica cutans; few roots.	G-horizon

SURVEY NAME : Weatherley **Profile No / Field No :** Uc5 15 October 2008 Page 1 of 1

Table 10 Profile description of profile Uc6



ARC • LNR

SOIL PROFILE DESCRIPTION

NATIONAL SOIL PROFILE NO : 6

Map/photo : 3128AB Maclear (3)

Latitude + Longitude: 31° 6' 52" / 28° 19' 55"

Land Type No :

Climate Zone :

Altitude : 1312 m

Terrain Unit: Upper Footslope

Slope: 6 %

Slope Shape : Concave

Aspect : North

Microrelief : None

Parent Material Solum : Origin single, local colluvium

Underlying Material : Sandstone (siliceous)

Geological Group / Formation : Molteno

Soil form and family : Kroonstad grabouw

Surface rockiness : None

Surface stoniness : None

Occurence of flooding : None

Wind erosion : None

Water Erosion : None

Vegetation / Land use : Grassveld, closed

Water table : 1050 mm

Described by : Adminastrator

Date Described : 10/2008

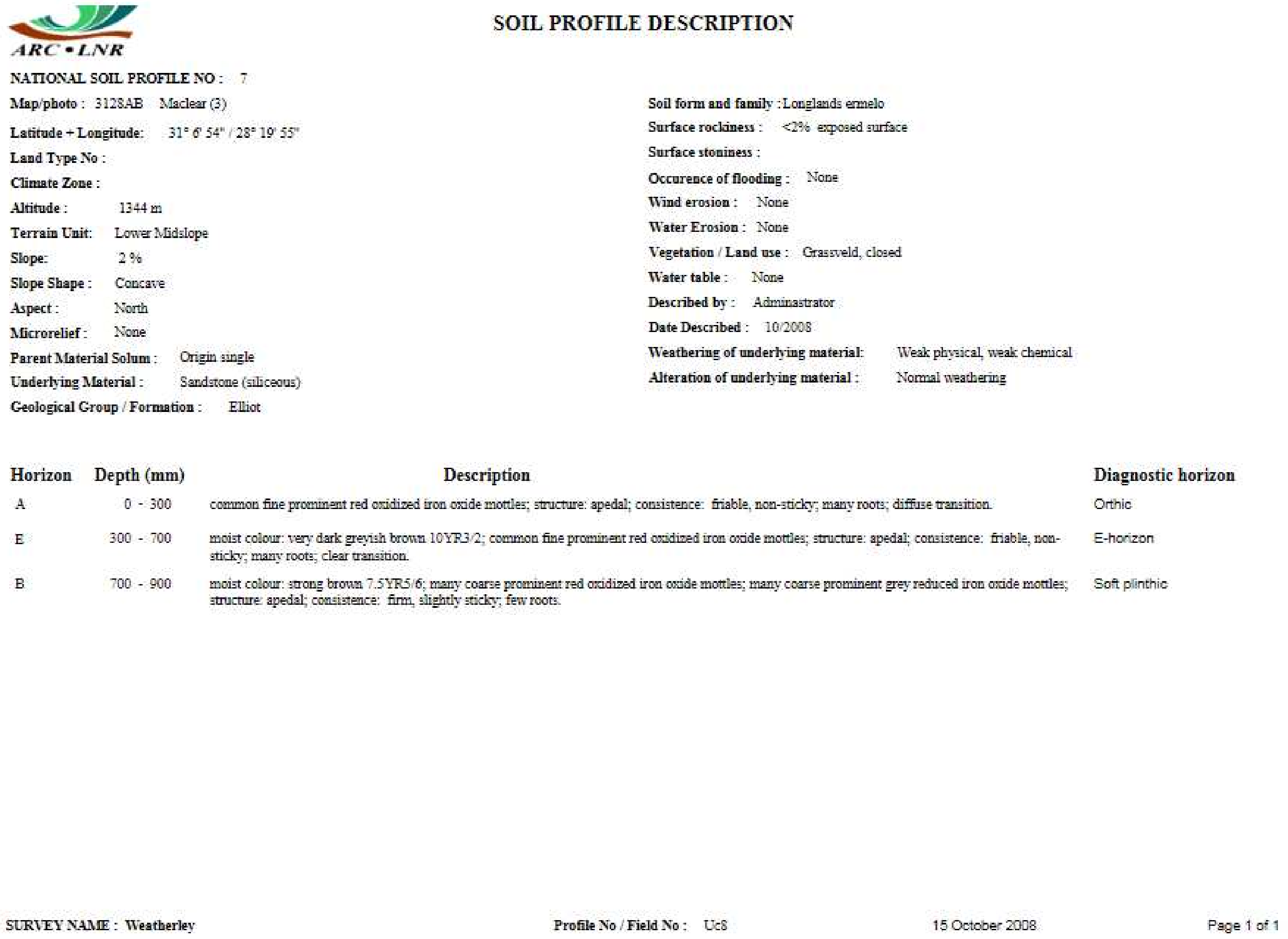
Weathering of underlying material: Strong physical, strong chemical

Alteration of underlying material : Ferruginised

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 300	moist colour: dark brown 7.5YR3/2; common fine distinct yellow mottles; few medium faint brown mottles; structure: apedal; many roots; abrupt transition.	Orthic
E	300 - 500	dry colour: greyish brown 10YR5/2; moist colour: brown to dark brown 7.5YR4/4; common medium faint grey mottles; structure: weak; common roots; diffuse transition.	E-horizon
G1	500 - 800	moist colour: light grey to grey 10YR6/1; many coarse prominent red mottles; common medium faint white mottles; consistence: sticky, plastic; common roots; diffuse transition.	G-horizon
G2	800 - 1500	moist colour: light grey to grey 10YR6/1; common coarse prominent yellow mottles; common grey mottles; consistence: sticky, plastic; few slickensides; few roots.	G-horizon

SURVEY NAME : Weatherley **Profile No / Field No :** Uc6 15 October 2008 Page 1 of 1

Profile 11 Profile description of profile Uc8



SOIL PROFILE DESCRIPTION

ARC • LNR

NATIONAL SOIL PROFILE NO : 7

Map/photo : 3128AB Maclear (3)

Latitude + Longitude: 31° 6' 54" / 28° 19' 55"

Land Type No :

Climate Zone :

Altitude : 1344 m

Terrain Unit: Lower Midslope

Slope: 2 %

Slope Shape : Concave

Aspect : North

Microrelief : None

Parent Material Solum : Origin single

Underlying Material : Sandstone (siliceous)

Geological Group / Formation : Elliot

Soil form and family : Longlands ermelo

Surface rockiness : <2% exposed surface

Surface stoniness :

Occurence of flooding : None

Wind erosion : None

Water Erosion : None

Vegetation / Land use : Grassveld, closed

Water table : None

Described by : Adminastrator

Date Described : 10/2008

Weathering of underlying material: Weak physical, weak chemical

Alteration of underlying material : Normal weathering

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 300	common fine prominent red oxidized iron oxide mottles; structure: apedal; consistence: friable, non-sticky; many roots; diffuse transition.	Orthic
E	300 - 700	moist colour: very dark greyish brown 10YR3/2; common fine prominent red oxidized iron oxide mottles; structure: apedal; consistence: friable, non-sticky; many roots; clear transition.	E-horizon
B	700 - 900	moist colour: strong brown 7.5YR5/6; many coarse prominent red oxidized iron oxide mottles; many coarse prominent grey reduced iron oxide mottles; structure: apedal; consistence: firm, slightly sticky; few roots.	Soft plinthic

SURVEY NAME : Weatherley

Profile No / Field No : Uc8

15 October 2008

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