

HYDROPEDOLOGICAL INTERPRETATIONS OF THE SOILS OF SELECTED CATCHMENTS WITH THE AIM OF IMPROVING THE EFFICIENCY OF HYDROLOGICAL MODELS

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

The interaction between soil and hydrology, i.e. hydropedology, is an important field of research that has been neglected for a long time. Partly because of the prevailing ever increasing stress on the natural environment, it has recently become increasingly important to elucidate and quantify the interaction between water and soil, not only directly with regard to hydrological studies but also with regard to wetland ecosystems; non-wetland ecosystems; the agro-ecosystem (crop production and food security); carbon sequestration; forestry; catchment management; efficient water use; environmental degradation involving soil hydrology, i.e. pollution studies.

Achieving the aims of this study will provide information that will be useful in all these natural resource problem areas that are currently becoming increasingly important.

The aims of the project were:

- 1 To develop advanced soil survey techniques, with which soil survey information suitable for hydrological research and modelling can be generated at reasonable cost.
- 2 To optimise the intensity of soil survey information that contributes effectively to hydrological modelling.
- 3 To improve the interpretation of soil information in ACRU (a hydrological model using detail soil information).
- 4 To improve the contribution of hydropedology to the hydrology of catchments by quantifying the soil water regime of selected hydrologically important soils of South Africa.
- 5 To improve the understanding of the impact of land-use change on the soil water regime and therefore on the hydrology of the Weatherley catchment.

A detailed literature review on three aspects of hydropedology is presented. The subjects covered are: international advances in hydropedology; application of hydropedology in hydrological research; knowledge contributions. The procedure adopted to achieve the first four aims was carried out on five catchments, viz. Weatherley, Cathedral Peak VI, Two Streams, Craigieburn and Bedford. The soil survey techniques used aimed at identifying modal hillslopes and the main soils in each of the hillslopes. For Weatherley the previously completed soil survey results (Roberts *et al.*, 1996) were used. Preliminary office studies of each catchment were conducted using land type data (1:250 000), 1:50 000 maps, Google images, application of 3D Mapper technology and study of relevant literature. Field work consisted of making effective soil survey transects along which the main soils were identified and samples taken for analysis. The results obtained enabled the description of the modal hillslopes in each catchment and their component pedosequences.

For the main hillslopes in each catchment conceptual flowpath models were formulated, depending on the soil distribution patterns, and presented in diagrammatic form. The relevant hydrological characteristics of the main soils were described and were quantified where possible. Important hydrological characteristics of the soils of Weatherleyey are described in detail in van Huyssteen *et al.* (2005). In the study described here, soils of the following forms were identified during the soil surveys: Champagne, Tukulu, Longlands, Kroonstad, Katspruit, Mispah, Augrabies, Swartland, Valsrivier, Oakleaf, Glenrosa, Dundee, Nomanci, Kranskop, Cartef. Based on their hydrological characteristics these soils were subdivided into three hydrological soil groups named recharge, interflow and saturation excess soils. The predicted roles that the important soils played in the hillslope hydrological processes in each catchment were identified and described by means of conceptual hillslope hydrological response models. As far as possible the hydrological properties of individual soils and their diagnostic horizons were also quantified.

The following procedure was adopted to specifically address aim (2), i.e. to test the influence of improved soil data on the performance of hydrological models. For the catchments Weatherleyey, Two Streams, Craigieburn and Bedford soil information at two levels was presented, i.e. firstly, land type data, and secondly the current soil survey results. The models tested were ACRU on Weatherleyey and Craigieburn, Pitman on Bedford and ACRU, SWAT and WAVES on Two Streams. The exercise produced mixed results. A logical hypothesis is that better soil data should produce better simulations by the hydrological models. It needs to be kept in mind however, that this hypothesis can only prove to be correct if the hydrological models used can use any soil data, and particularly the improved soil data, effectively. The results indicate that both SWAT and WAVES are unable to do this. ACRU gave mixed results and the reasons for this are unclear. As measured runoff data is not available for Bedford, it is not possible to evaluate the response of the Pitman model to improved soil data in a reliable way. An important result of this exercise is that all the models responded to differences in soil data inputs, i.e. they recognise that the soils that occur in a catchment influence the hydrograph.

The influence of land used change from grassland to afforestation at selected sites in the Weatherleyey catchment has been quantified. Soil water regime measurements show that as expected, the trees dry the soil out to a greater extent than the grassland did, i.e. the trees use more water; that most of this additional extraction is from the deep soil layers; that the surface soil under the trees is generally wetter than under grassland, presumably due to the influence of decreased evaporation loss promoted by the layer of litter and increased shading; that the soil water regime in a profile monitored in the marsh has become wetter after afforestation in the adjacent hillslope, presumably because of a decrease in overland flow due to denser hillslope vegetation promoting increased deep percolation of water into the lower vadose zone feeding the marsh.

It is considered that the aims of the project have been satisfactorily achieved; that all members of the research team have experienced major intellectual capacity growth; and furthermore, that a useful

preliminary contribution has been made to the hydropedology of South African soils and hillslopes, an important subject still in its infancy and therefore calling for continued intensive study.

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LIST OF SYMBOLS USED

(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
Ah	Humic A horizon
AN	Arrow number
AN – 1a, etc.	Refers to arrow numbers used in conceptual model of the upper catchment of Weatherleyey
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
BS	Base saturation
CEC	Cation exchange capacity
Cf	Cartref soil form
Cl	Clay
COFRU	Coefficient of runoff
CoSa	Coarse sand
CoSi	Coarse Silt
CR	Count ratio
Cv	Clovelly soil form
D_b	Bulk density
$D_{s>0.7}$	Mean duration of $s>0.7$ events (days.event^{-1})
DEM	Digital elevation model
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
FISl	Fine silt
f_{Sat}	Soil water content at field saturation
$F_{s>0.7}$	Frequency of events where $s>0.7$ (events.year^{-1})
Gf	Griffin soil form
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
K	Hydraulic conductivity
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
NWM	Neutron water meter
Nc	Neocarconate horizon
Ne	Neocutanic B horizon
Oa	Oakleaf soil form
OC	Organic carbon
On	Unspecified material with signs of wetness
ot	Orthic A horizon
P	Precipitation
P221, etc.	Refers to profiles in the Weatherleyey 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
S value	Sum of exchangeable Na, K, Mg, and Ca ions
SaCl	Sand clay
SaClLm	Sand clay loam
Sa	Sand fraction
SaLm	Sand loam
Se	Effective degree of saturation
Se	Sepane soil form
Si	Silt content
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 Weatherleyey catchment
Uc8, etc.	Refers to tensiometer nests in the upper catchment of the Weatherleyey catchment
Va	Valsrivier soil form
vfiSa	Very fine sand
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)

ABREVIATIONS

ABRESP	Fraction of the saturated soil water to be distributed daily from the topsoil into the subsoil when the topsoil is above its drained upper limit
BFRESP	Fraction of the saturated water to be distributed daily from the subsoil into the intermediate/groundwater store when the subsoil is above its drained upper limit.
DEPAHO, DEPBHO, DEPINTZ	Depth of the A-, B- and Intermediate soil horizons respectively (m)
FC1, FC2, FCINTZ	Field capacity of the A-, B- and Intermediate soil horizons respectively
INTZRESP	Intermediate zone response factor
MPRESP	Macropore response factor
NDAYSMAXGW	Max duration of unit response for the groundwater response function (days)
NDAYSMAXI	Max duration of unit response for the lateral response function (days)
NDAYSMAXMP	Max duration of unit response for the macropore response function (days)
PO1, PO2, POINTZ	Porosity of the A-, B- and Intermediate soil horizons respectively
QFRESP	Stormflow response fraction for the catchment (daily)
RESDIMEMP	Mean response time for the macropore response function (days)
RESDISPGW	Response dispersion for the groundwater response function
RESDISPL	Response dispersion for the lateral response function
RESDISPMP	Response dispersion for the macropore response function
RESTIMEGW	Mean response time for the groundwater response function (days)
RESTIMEL	Mean response time for the lateral response function (days)
SMAINI, SMBINI, SMIINI	Soil water content of the A-, B- and Intermediate soil horizons at the start of the simulation respectively as a percentage of plant available water (m)
WP1, WP2, WPINTZ	Wilting point of the A-, B- and Intermediate soil horizons respectively

Chapter 1 INTRODUCTION

1.1 PROBLEM STATEMENT

Water is increasingly referred to as 'blue gold'; this is because water is one of the most important resources that our planet has to offer. The demand for water doubles every 20 years which is more than twice the rate of the world's population growth. New water resources are becoming scarcer, and to treat and remediate existing sources, more expensive (Clothier *et al.*, 2008). The protection and management of surface and groundwater resources requires the accurate analysis of hydrological processes. These processes define how precipitation reaches the catchment outlets (flowpaths) and how long the water is stored as surface water, soil water and groundwater (residence time and storage) (Uhlenbrook *et al.*, 2005). In the highly variable hydrological regime of southern Africa the management of water resources is critically dependent on a clear understanding of these hydrological processes (Wenninger *et al.*, 2008). 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 resource predictions, estimating the hydrologic sensitivity of the land for cultivation, contamination and development, and for quantifying low flow mechanisms (Lorentz *et al.*, 2007a).

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

The need for predictions of these hydrological processes is becoming increasingly important. This need led to 'The International Association of Hydrological Sciences' (IAHS) decade (2003-2012) on 'Predictions in Ungauged Basins' or PUB. The aim of this initiative is to formulate and implement appropriate science programmes to facilitate and energize predictions of hydrological processes in ungauged basins (Sivapalan 2003a; Sivapalan *et al.*, 2003). An 'ungauged basin' is defined as a basin or catchment with inadequate hydrological observations to enable calculation of hydrological variables (water quality and quantity) for spatial and temporal scales at an accuracy acceptable for practical

applications (Sivapalan *et al.*, 2003). All of the catchments on earth are therefore ungauged to a certain extent!

The answer to the challenge for predictions in ungauged basins might lie in the conclusions drawn by leading hillslope hydrologists in the paper 'Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology' (McDonnell *et al.*, 2007). In this paper it is argued that any mapping and characterization should be driven by the desire to generalize and extrapolate from one place to another over multiple scales using an interdisciplinary approach, or in their own words: *"New approaches should not rely on calibration but rather a systematic learning from observed data and on increased understanding and search for new hydrologic theories through embracing new organizing principles behind watershed behaviour that are derived from our **sister disciplines**"*

Soil science is a sister discipline which can make a valuable contribution to hydrology. 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; Soulsby *et al.*, 2006). 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). Soils play a major role in catchment hydrology by facilitating infiltration, and thereby largely controlling stormflow generation. Soil acts as a water store which provides water for evapotranspiration. Soil is also responsible for redistributing water, both within and without the soil profile, and by drainage below the root zone and eventually into the groundwater zone (Schulze, 1995; Sivapalan, 2003). Hydrologists agree that the spatial variation of soil properties significantly influences hydrological processes but they lack the skill to gather and interpret soil information (Lilly, Boorman & Hollis, 1998; Chirico, Medina & Romano, 2006).

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. This interactive relationship serves as a basis for a new interdisciplinary research field, hydopedology, which promotes *"...synergistic integration of pedology with hydrology to enhance the holistic study of soil-water interactions and landscape-soil-hydrology relationships across space and time, aiming to understand pedologic controls on hydrologic processes and properties, and hydrologic impacts on soil formation, variability, and functions"* (Lin *et al.*, 2008). This field aims to bridge gaps between pedology, soil physics, hydrology and geomorphology and also between micro and macroscopic scales of water interactions. Issues covered by hydopedology include: i) hydrology as factor of soil formation, ii) soil as essential component of hydrological cycle and filter of water, iii) soil morphology as signatures of soil hydrology and iv) landscape – soil – water relationships across scales.

Almost every hydrological process (for example evapotranspiration, infiltration and subsurface flow) is difficult to observe and measure, because these processes are dynamic in nature with strong temporal variation (Sivapalan, 2003a). Soil properties are in the short term not dynamic in nature, and their

spatial variation is not random (Webster, 2000). The correct interpretation of spatially varying soil properties associated with the interactive relationship between soil and hydrology can serve as indicators of the dominant hydrological processes, and improve the understanding of hillslope hydrology (Lin *et al.*, 2006).

Relatively little soil data (soil maps, analytical data and profile descriptions) are however currently used in hydrological modelling. Soil survey data are often not available or unsuitable for hydrological modelling purposes. Soil survey data, including the soil classification systems applied in the surveys, are biased towards agricultural requirements. The result is that understanding of the behaviour of soils in hillslopes is poorly supported by soil maps.

The tendency in the past to neglect soil science in natural science research, especially multidisciplinary environmental science, has been unwise. Soil science has traditionally been dedicated to serving agriculture. Soil is a major crop production factor. It plays a major role in the food security of all countries. This traditional primary focus is the reason why research regarding the role of soil in natural ecosystems has therefore largely been neglected. Knowledge of the role of soils in natural ecosystems, both biotic and abiotic systems, is still therefore relatively limited.

Soil science research was first recorded in the late 19th century (Joffe, 1949). The focus was on the formation of soils and explanations for the soil distribution patterns in a discipline called pedology. Fundamentally pedology focussed on the association between soil forming factors and soil properties. The interpretation and application of soil properties to understand these relationships needs now to be revisited.

Priorities changed after the First World War. Food security was a high priority and the knowledge of soils was organised in soil classification systems serving the agricultural industry, more specific crop production. Soil science expanded to include organised research in soil fertility, soil chemistry, soil physics and later also soil biology. This focus on food security was enhanced by the Second World War and the Cold War.

The standard equation of soil formation shows its relationship with the environment (Jenny, 1941):

$$S = f(cl, o, r, p, t, \dots)$$

Where: S = Soil

cl = Climate

o = Organisms

r = Relief

p = Parent material

t = Time

... = smaller influences

The first reverse change came in the 1980s. Overproduction of food in the First World resulted in soil science inputs becoming less important. In addition increased worldwide environmental awareness

emphasised the shortage of soil science knowledge, creating opportunities for soil research in natural systems. This was helped along by pollution with agricultural chemicals in the intensive production systems of the developed countries.

Soil has a unique role in the environment. The lithosphere, atmosphere, hydrosphere, biosphere and pedosphere share common elements like water, biology, minerals, etc. Soil has a special mixture of these elements. Soil makes its largest contribution to environmental systems as a buffer. Soil not only buffers water regimes, for example by providing a medium whereby instantaneous rainfall events become a water supply to plants that lasts for months, and providing water for base flow in rivers; it also has a huge ability to buffer pH, plant nutrients, redox conditions, temperature and organic carbon recycling. Compared to the roles of water, rock, air and the biological sphere, these are important benefits which soil contributes to the health of our environment.

The common ground between soil and hydrology is the water that drains through the soil profile. Because this water is moved by gravity and redistributed by the permeability of the soil horizons and rock layers, it reacts differently in different hydrological soil types in the hillslope. The interaction between the soil and fractured rock regarding the drainable water is controlled by the distribution of soils in the hillslope. Soils of the Katspruit and Kroonstad forms occur typically in the valley bottoms and deliver peak flow after rain events. Soils of the Hutton and Glenrosa forms are typical of the crests and they recharge the lower vadose zone. Soils of the Avalon and Longlands forms occur on midslopes and footslopes where interflow occurs.

The close relationship between soil and hydrology is reflected in the soil water regime of specific horizons and the quality and quantity of water they provide. The soil classification system of South Africa and the interpretation of the soils for different land-uses make use of these relationships. This interactive relationship is the core of the service that soil science can provide to hydrology. There are two aspects. Firstly, appropriate soil survey procedures and the interpretation of the soil survey data to make this information suitable for use by hydrologists at all scales, intensive and extensive, is of immediate importance. Secondly, the quantitative characterisation of the annual and seasonal soil water regimes of hydrologically important soils of South Africa is important. The annual duration of different degrees of wetness provides a useful way of describing soil water regimes.

The hydrological characteristics of a soil can either be determined quantitatively (by frequent, regular long-term measurements), or qualitatively by inference from the soil colour, exchangeable bases, occurrence of mottles, concretions, etc. Soil colour is the most important morphological soil property used to predict the water regime of soil. The major soil classification systems of the world apply soil colours as distinguishing criteria. In the South African soil classification system the definitions used for horizons defined by colour were compiled to differentiate between horizons with differing soil water regimes. During the development phase of soil classification in South Africa very limited data was available to quantify the hypopedological properties. Many of the hypotheses behind the South

African soil classification system were confirmed, and some questioned, in a previous WRC report (Van Huyssteen *et al.*, 2005).

A distinction needs to be made between the following three categories of soil science knowledge of use to hydrologists: advanced soil survey techniques to improve the acquisition of more accurate, more intensive, quality, spatial soil information relevant to hydrology; interpretation of currently available so called soft knowledge and user unfriendly knowledge; generation and verification of soil water regime data.

A valuable source of small scale soil survey information is available in the form of the land type survey of South Africa recently completed by the ARC-ISCW. The soil component of the land type survey is based on the toposequence, a characteristic distribution of soils in the landscape. The land type inventory makes it possible to distinguish between regions of South Africa with different toposequences on a reconnaissance scale. Land type data has, however, severe limitations for application on detail-reconnaissance, detail and intensive scales.

Application of soil survey information in hydrological studies is complicated by scale. Soil properties have a dominating influence on hydrological behaviour at any point in a catchment hence their relative importance in small catchment hydrological studies. This is in contrast to large catchments (small scale hydrology) where soil influences tend to balance out against each other (Schulze, 2004). Research is therefore needed on the variation in impact of soil information on hydrological behaviour at different scales (Van Huyssteen *et al.*, 2006).

Different levels of soil survey information useful for hydrological research can be defined as follows:

1. Land type data, reconnaissance scale 1:250 000: Reconnaissance surveys are suitable for regional planning and hydrology research on primary and secondary catchments. Several land types usually cover primary catchments and secondary catchments may be covered by mainly one land type. To make land type data applicable to hydrological research it needs to be interpreted (soil and terrain data) to characterise hillslopes and predict hillslope behaviour.
2. Soilscape survey, detail-reconnaissance scale 1:50 000: The subdivision of land types into soilscales reduces variation in the soil distribution in map units (Hensley *et al.*, 2007). This scale may assist in identifying and characterising typical hillslopes. The extent to which it can assist hydrological research has to be tested.
3. Hillslope survey, detail and intensive survey scale, 1:10 000 and larger: A hillslope survey delineates characteristic hillslopes and should assist in the interpretation of hillslope behaviour.

The processes involved in the throbbing pulsating soil water in the landscape have in the past received relatively little attention from soil scientists in a way that may be of use to hydrologists. There is a good relationship between topography and the hydrosequence, a special type of toposequence related to

hydrological behaviour. The hydrosequence concept or, in other words, the hydropedological characteristics of soils in a hillslope, is however not new to soil scientists.

It has become increasingly evident that topographic controls of water accumulation and discharge, upon which many hydrological models are based, are not as influential in these mechanisms as previously thought (Rodgers *et al.*, 2005; McGuire *et al.*, 2006). In addition, the links between subsurface response zones are imperative to define if accurate simulations are to be made (Siebert *et al.*, 2003). Subsurface response mechanisms have also been found to respond to threshold criteria, rather than continuous fluxes. Lateral hillslope discharges are also subject to control by bedrock topography rather than ground surface topography (Howe & Lorentz, 1995; Lorentz & Esprey, 1998).

Catchment scale hydrological models are designed to mimic the dominant response mechanisms averaged over typical zones of response. These are referred to as hydrological response units, which typically integrate hydrological influences, such as soil, topography, land use and climate zones. More than this, however, is the importance of identifying typical patterns and laws which govern general hydrological response behaviour. Sivapalan (2003) states: "Prediction in Ungauged Basins (PUB), calls for a new holistic theory of how water reacts with the entire earth system. Observation is the foundation of all learning yet almost every process of interest in hydrology is difficult to observe. Soils tend to develop in response to state controls such as topography, with different parts of a basin being formed by different processes and having different functions. The resulting soil patterns (soil catena) exhibit a common form of organization and symmetry, with water movement clearly being an active agent in their formation. The interactions between climate, soils, vegetation and topography thus contribute to the most amazing patterns that we see in natural basins, which must contain valuable information about the way they function. A fundamental aim of theoretical hydrology must be to identify such patterns, decipher the underlying order or symmetry occurring over a wide range of scales and the rules that govern them, and explore the mechanisms that generate them. Theory development advance if we 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."

The soil classification system of South Africa effectively accommodates hydrologically different soils. Properties that relates closely to the hydrological characteristics of soils, e.g. soil colour and mottles, are prominent distinguishing criteria. Observations like this are probably the result of studies concerned with the influence of soils on dryland crop production in a water poor county. Understanding of hydropedology in the past was limited to the role of soils as water reservoirs. This included the processes of infiltration, runoff by overland flow and evapotranspiration (ET). The role of the lower vadose zone and interaction between the lower vadose zone and the overlying soils has been somewhat neglected until fairly recently. The hydrological approach of dividing soils into

recharge, saturation excess responsive, and interflow soils is a refreshing advance in thinking about the role of soils in hydrology.

1.2 HYPOTHESIS

The hypothesis is that soil properties, presented in the form of hydropedological soil maps together with the relevant soil hydrology data, can serve as indicators of the hydrological behaviour of soils in a hillslope, and therefore facilitate prediction of the hydrological behaviour of hillslopes, particularly those in ungauged catchments.

1.3 AIMS

The aims of the project are:

- 1 To develop advanced soil survey techniques, with which soil survey information suitable for hydrological research and modelling, can be generated at reasonable cost.
- 2 To optimise the intensity of soil survey information that contributes effectively to hydrological modelling.
- 3 To improve the interpretation of soil information in ACRU (a hydrological model using detail soil information).
- 4 To improve the contribution of hydropedology to the hydrology of catchments by quantifying the soil water regime of selected hydrologically important soils of South Africa.
- 5 To improve the understanding of the impact of land-use change on the soil water regime and therefore on the hydrology of the Weatherleyey catchment.

1.4 PRODUCTS

In the research process towards achieving the aims, advanced soil survey procedures aimed at providing soil information currently too expensive and generally not available to hydrologists will have been developed. These should be of benefit to the forestry industry, hydrologists, catchment management authorities and agriculture. The procedure is discussed in Chapter 3. Another product covered in several chapters is the improved understanding of the hydrology of South African soils. This new knowledge should benefit hydrological decisions in general and specifically on the impact of land-use on soil and water resources. More important can be the progress made towards predicting the behaviour of ungauged catchments using soil data. The third product from the research is a contribution to improved hydrological modelling in general, and particularly to ACRU.

This should benefit hydrological modelling activities in general and catchment management authorities specifically, by providing improved hydrological predictions.

Chapter 2 **LITERATURE REVIEW AND KNOWLEDGE CONTRIBUTIONS**

2.1 INTERNATIONAL ADVANCES IN HYDROPEDOLOGY

The interdisciplinary science of hydropedology was defined some 40 years ago (Kutilek, 1966 as cited by Kutilek, 2004). It was, however, not until 2003 that the science of hydropedology gained international recognition, after the publication of “Hydropedology: bridging disciplines, scales, and data” (Lin, 2003). A vision paper entitled “Hydropedology: synergistic integration of pedology and hydrology” followed Lin *et al.* (2006), setting the stage for a myriad of papers to follow.

Schoeneberger and Wysocki (2005) argued that soil hydrology and hydropedology are similar. Miyazaki (1993) also suggested that soil hydrology could be considered to be a bridge between soil physics and hydrology. This notion was shared by Kutilek and Nielsen (1994), who defined soil hydrology as the physical interpretation of phenomena which govern hydrological events related to soil or the uppermost mantle of the earth’s crust. Hydropedology is, however, defined very specifically as an intertwined branch of soil science and hydrology that encompasses multi-scale basic and applied research of interactive pedological and hydrological processes and their properties in the unsaturated zone (Lin *et al.*, 2005).

In spite of the obvious overlap in the disciplines of hydrology and soil science, relatively little hydropedology research has been done in Africa and South Africa (Donkin & Fey, 1991; Van Huyssteen, 1995; Le Roux, 1996; Blavet *et al.*, 2000; Blavet *et al.*, 2002; Van Huyssteen *et al.*, 2005), with some valuable pioneering collateral applications by Schulze (1989).

The aim of this chapter was to discuss the initiation and advances in the interdisciplinary science of hydropedology.

2.1.1 Hydropedology

Hydropedology draws on the synergy generated by bridging the gap between traditional pedology, soil physics, and hydrology, to integrate the study of the soil-water relationships across spatial and temporal scales (Lin, 2003; Lin *et al.*, 2005). He further suggests that hydropedology can: (a) address knowledge gaps between pedology, soil physics and hydrology; (b) bridge scales – being applied at microscopic, mesoscopic, and macroscopic levels; and (c) transform soil survey data into soil hydraulic information.

Lin *et al.* (2005) proposed the development of “quantitative physical measurements and model descriptions of soils to predict and verify flow and transport pathways of solutes, liquids and gases, mechanisms of mass movement and energy fluxes within the system, and movement of microbes in the environment”. Soil profile descriptions, and hence soil classification, is a major source of *in situ* soil morphological information, which are signatures of hydrology in the unsaturated zone (Wilding & Lin, 2006). Hydropedology also has an important role to play in formulating environmental policies both “up to global” and “down to local” (Bouma, 2006). Soil survey databases provide a wealth of information that can be utilized to predict the fate of water and contaminants in the landscape (Wilding & Lin, 2006). Wilding and Lin (2006) further state that the emphasis of pedology is shifting from classification and inventory to understanding and quantifying spatially and temporal processes upon which the water cycle and ecosystems depend. The quantification of soil hydromorphology and modelling, predictions of soil and hydrologic properties and processes and data-bridging through pedotransfer functions are identified as current knowledge gaps (Lin, 2003; Lin *et al.*, 2006; Wilding & Lin, 2006).

It is envisaged that hydropedology will contribute to the understanding of environmental, ecological, agricultural, and natural resource issues (Lin, 2003). These include water quality and soil quality, landscape processes and management, nutrient cycling, contaminant movement, waste disposal, precision agriculture, climate change and ecosystem functions.

Integrating pedology, soil physics and hydrology could close many knowledge gaps related to (Lin *et al.*, 2005):

- quantifying soil hydromorphology and its relations to soil hydrology;
- quantifying soil structure and modelling its impact on flow and transport processes;
- predicting preferential flow at different scales and determination of its mechanisms and patterns;
- relating water movement over the landscape with soil cover;
- performing soil-water mapping and soil-landscape modelling across scales;
- describing soil spatio-temporal variability and the underlying causes, identifying patterns, and predicting various soil and hydrological properties and processes;
- bridging scales from laboratory to field, landscape, region, and globe; and
- bridging data through approaches such as pedotransfer functions, including the understanding of the fundamental mechanisms and practical enhancements.

2.1.1.1 Knowledge gaps

Lin (2003) describes the knowledge gaps in hydropedology as follows: *Soil structure* needs to be quantified (to enable application thereof in models) and the impact thereof on water flow remains unresolved. *Preferential flow* dynamics, velocity, and pathways differ between soils. Quantitative relationships need to be determined between soil structure, texture, and layering could provide a means of estimating preferential flow paths in soils. Soil micro and macro *hydromorphology* have long been used to infer qualitative relationships with soil water regime. Quantitative relationships, to determine soil water table behaviour, drainage classes, and soil hydraulic properties, have, however, been lacking. The impact of *water flow patterns over the landscape* and the impact thereof on soil processes and soil formation need to be better understood. Quantification of soil spatial and temporal variation is essential for the effective modelling of hydraulic processes in the landscape.

2.1.1.2 Bridging scales

Soil process need to be scaled from laboratory core studies to field pedons, mapping units, watershed, regional, and global scales (up scaling). There also need to be a similar downscaling from catchment to pedon, and soil horizon, scale (Lin, 2003). Another example is the proposal of Schulze (2004), who stated that different natural and anthropogenic influences impact differently at different scales (Figure 2.1).

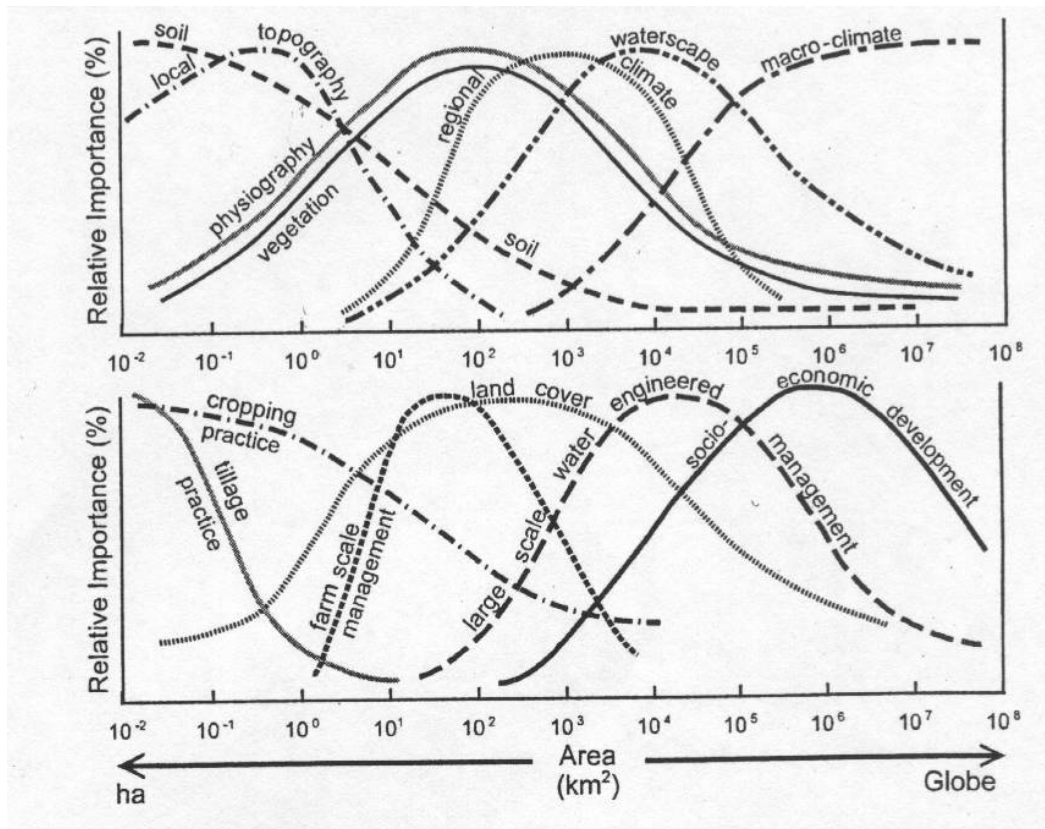


Figure 2.1 Natural heterogeneities (top) and anthropogenic influences (bottom) occur across a range of spatial scales, but dominate hydrological responses over a narrower spectrum (Schulze, 2004).

Royappen *et al.* (2002) make the following relevant statement: “Many past ACUR simulations on both large and small catchments have highlighted a general problem of correctly simulating flows from small catchments. Over large catchments, spatial variations in geological and soil characteristics tend to average out, allowing easier simulations of the combined flows from the many smaller sub-catchments. At the larger scale, however, individual characteristics express themselves strongly through the hydrograph, and highlight our incomplete understanding in the link between rainfall and stream flow”. The phrase “easier simulations” in the second sentence probably means “more accurate simulations”. Schulze (2004) also presents his views on the relative importance of different catchment features and anthropogenic influences on hydrological responses in the form of the diagram reproduced here as Figure 2.1. Only the top portion of the diagram is relevant here, where soil and local topography are considered to dominate the “hydrological response” on catchments with areas less than about 500 ha.

Soil texture, depth and drainage are important soil characteristics; and slope, aspect, and altitude gradient influences microclimate as important topographic characteristics (Schulze, 2004). The relative importance of soil and local topography is shown to be small on catchments larger than about

10 000 ha (Figure 2.1). This can be misleading and it should be remembered that the diagram deals with “hydrological responses”, and not with “hydrological processes”. The diagram is in agreement with the statement of Royappen *et al.* (2002) quoted above. Simulations measure the hydrological responses of catchments where shortcomings, due to incomplete understanding of the complex processes involved, result in inaccuracies for particular sub-catchments. In larger catchments, with many sub-catchments, it seems that these inaccuracies tend to balance out, resulting in satisfactory results – referred to by Royappen *et al.* (2002) as “easier simulations”. It should not, however, be concluded from Figure 2.1 that soil and topography become relatively unimportant with regard to hydrological process in large catchments. Soil and local topography must inevitably be of dominating importance in all catchments since all the water that reaches the stream must either pass over or through the soil at some stage.

The identification, definition and quantification of the sources, pathways and travel times of components of flow making up stream discharge are important to capture in hydrological models. This is essential for accurate water resources prediction, for estimating impacts of climate and land use change, for predicting water quality impacts and for quantifying low flow mechanisms (Lorentz *et al.*, 2007).

It has become increasingly evident that topographic controls of water accumulation and discharge, upon which many hydrological models are based, are not as influential in these mechanisms as previously thought. For example Rodgers *et al.* (2005) state that “It appears that landscape organization and the combination of soil/topographic units in different sub catchments, rather than scale alone has the strongest influence on the hydrological characteristics of flow path partitioning and mean residence times... In particular, the results indicate that the hydrological responsiveness of headwater peat soils exerts the dominant influence on the overall seasonal patterns and residence times observed at the larger catchment scale, despite the significant downstream groundwater inputs and mixing with more constant signal groundwater dominated sub-basin drainage.” This was confirmed by McGuire *et al.* (2005), who state that “Landscape organization, rather than basin area controls catchment scale dynamics. Simple topographic attributes such as median flow path length and gradient were strongly correlated to response times at the catchment scale. This relationship allows for the regionalization of residence time and insight into process understanding at the meso-scale.”

In addition, the links between subsurface response zones are imperative to define if accurate simulations are to be made, as pointed out by Siebert *et al.* (2003) “Total storage is divided into two compartments, saturated and unsaturated, with the boundary moving up and down in response to the water budget of the compartments. Hillslopes are also divided into riparian and upslope reservoirs with characteristic response mechanisms. Groundwater response is not proportional to storage.” and

Asano *et al.* (2002) "Soil water response time (0-27 days) and transient groundwater response (23-67 days) depend more on vertical infiltration length than slope."

Subsurface response mechanisms have also been found to respond to threshold criteria, rather than continuous fluxes. Lateral hillslope discharges are also subject to control by bedrock topology rather than ground surface topography. Howe and Lorentz (1995) "Threshold response of soil/bedrock interface where positive pressures build up before discharge occurs into fractured bedrock or saprolite." Lorentz and Esprey (1998) "Bedrock controlled response in Weatherley research catchment hillslopes."

These observations and many like them have led to the development, in *ACRU2000*, of linked land units in which subsurface stores interact via unit response functions (Figure 2.2). It is envisaged that the soil survey observations of this project will inform further development of this model structure as well as provide rules for linking subsurface response zones and the response functions which control the discharges between the zones.

Catchment scale hydrological models are not designed to simulate detailed mechanisms and aggregate these into a catchment response, but are rather designed to mimic the dominant response mechanisms averaged over typical zones of response. These are referred to as hydrological response units, which typically integrate hydrological influences, such as soil, topography, land use, and climate zones. It is, however, the importance of identifying typical patterns and laws which govern general hydrological response behaviour, as stated by Sivapalan (2003): "Prediction in Ungauged Basins (PUB), calls for a new holistic theory of how water reacts with the entire earth system. Observation is the foundation of all learning yet almost every process of interest in hydrology is difficult to observe. Heterogeneity of landscapes and climatic inputs require a search for patterns and laws: Rivers carve the landscape into beautiful shapes called river networks, which seem to embody a deep sense of symmetry, and some general principles such as minimum energy are said to be at work. Geological faces tend to be discrete units associated with specific formational processes, sometimes organized in certain sequences. Soils tend to develop in response to state controls such as topography, with different parts of a basin being formed by different processes and having different functions. The resulting soil patterns (soil catena) exhibit a common form of organization and symmetry, with water movement clearly being an active agent in their formation. The interactions between climate, soils, vegetation and topography thus contribute to the most amazing patterns that we see in natural basins, which must contain valuable information about the way they function. A fundamental aim of theoretical hydrology must be to identify such patterns, decipher the underlying order or symmetry occurring over a wide range of scales and the rules that govern them, and explore the mechanisms that generate them. 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.” And Woods (2004): “Distribution of soil moisture is not entirely dependent on terrain, but rather on soils and vegetation distribution. Where soil driven patterns are thought to be important for modelling, the use of surrogate patterns for soil properties is not necessarily helpful.”

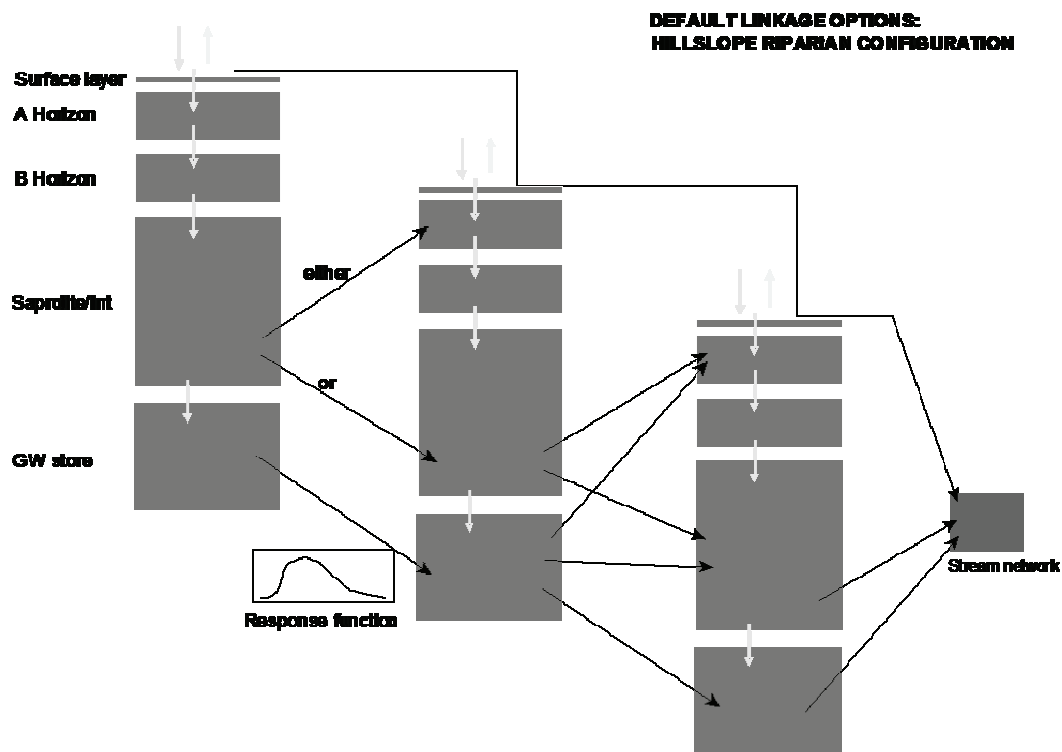


Figure 2.2 Schematic layout of lateral land segments in which subsurface stores are linked by unit response functions (Lorentz *et al.*, 2007).

The importance of hillslope behaviour is emphasised by McGuire *et al.* (2005), who conclude that the median flow path length ($R^2 = 0.72$) and median flow path gradient ($R^2 = 0.64$) have poor correlations with mean residence time and that the correlation is increased to $R^2 = 0.91$ for median flow path length ÷ median flow path gradient (Figure 2.3).

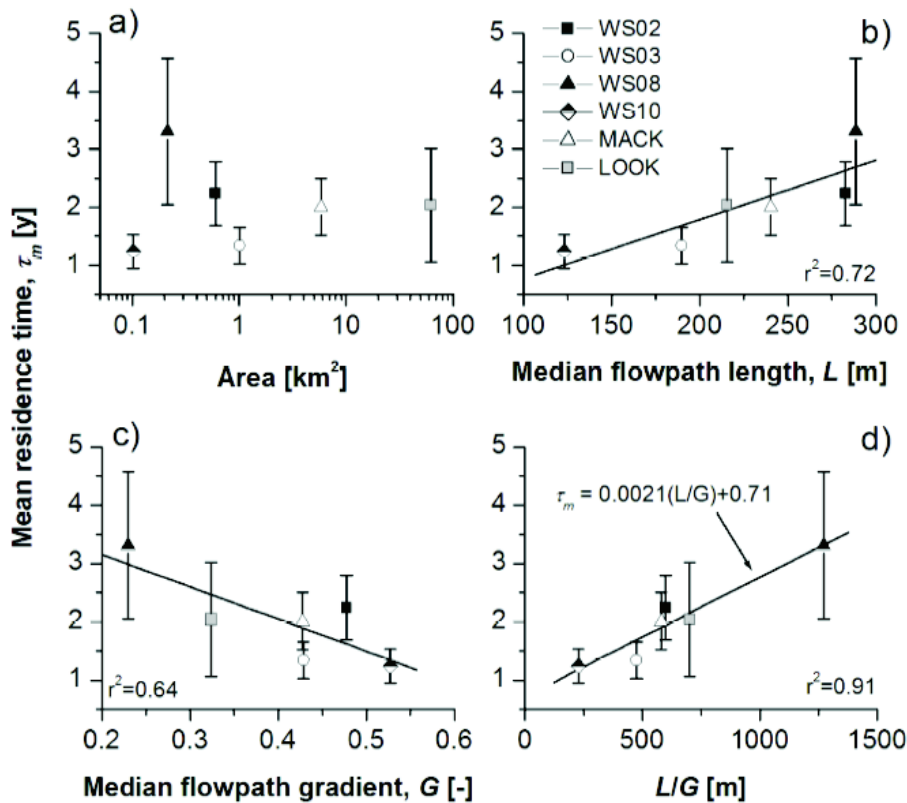


Figure 2.3 The correlation of catchment area, median flow path length (L), median flow path gradient (G) and L/G with mean residence time (McGuire *et al.*, 2005).

2.1.1.3 Transformation of survey data

Most disciplines suffer from a data rich, but information poor syndrome (Lin, 2003). Data exist in South Africa, for example in the land type data base (Land Type Survey Staff, 2000), but procedures to extract useful information from these are lacking. The costly nature of field measurement of soil hydrological properties often resulted in the estimation thereof, using soil texture, bulk density, organic matter content, etc., through pedotransfer functions.

2.1.2 Pedotransfer functions

The concept of pedotransfer functions was introduced by Bouma (1989) to relate simple soil characteristics often found in soil surveys to more complex parameters that are relatively difficult to measure. McBratney *et al.* (2002) proposed soil inference systems as a concept to properly and logically conjoin pedotransfer functions that serve as the knowledge rules for inference engines.

Pedotransfer functions in essence aim to predict difficultly (and therefore infrequently) measured soil properties from easier (and therefore frequently) measured soil properties. Examples include the

estimation (Lin *et al.*, 1999; Pachepsky *et al.*, 2006) of soil hydraulic properties (hydraulic conductivity at zero potential and water flow rates in macro, meso, and micro pores) from soil morphological features (e.g. texture, initial moisture state, pedality, macro porosity, and root density), usually available from soil surveys (Pachepsky *et al.*, 2006). Various authors (Marnique & Jones, 1991; Bernoux *et al.*, 1998; Tomasella & Hodnett, 1998; Benites *et al.*, 2007) also describe methods to determine bulk density from soil survey data. Most of these pedotransfer function algorithms are, however, specific to the area for which it was developed (De Vos *et al.*, 2005). Extreme caution should therefore be used, when applying these algorithms and they should be verified in the study area.

2.1.3 Hydrology of soil types

Hydrology of soil types (HOST) was published by the Institute of Hydrology in the United Kingdom during November 1995 (Boorman, Hollist & Lilly, 1995), with the explicit aim of classifying soils, based on the existing soil maps, to aid hydrological studies and analyses. HOST classification is based on three conceptual models of water flow processes taking place within the soil (Figure 4.2): (a) soil on a permeable substrate with a deep aquifer (>2 m); (b) soil on permeable substrate with a shallow water table (<2 m); and (c) soil (or soil and substrate) with an impermeable or semi permeable layer within 1 m of the surface. The three conceptual models are further subdivided, based on different soil properties, into 11 models. The 11 models are, in turn, subdivided into 29 HOST classes, based on geology and other properties (Figure 2.5). The classification was calibrated by relating base flow index and standard percentage runoff to soil distribution at a 1:250 000 (catchment) scale.

Soil properties used to derive the HOST classification are: (a) depth to a gleyed layer; (b) depth to a slowly permeable layer; (c) integrated air capacity (macro pore volume > 60 μm); (d) presence of a peaty surface layer; and (e) a soil hydro geological classification (describing soil parent materials). The 32 hydro geological substrate classes are given in Table 2.1.

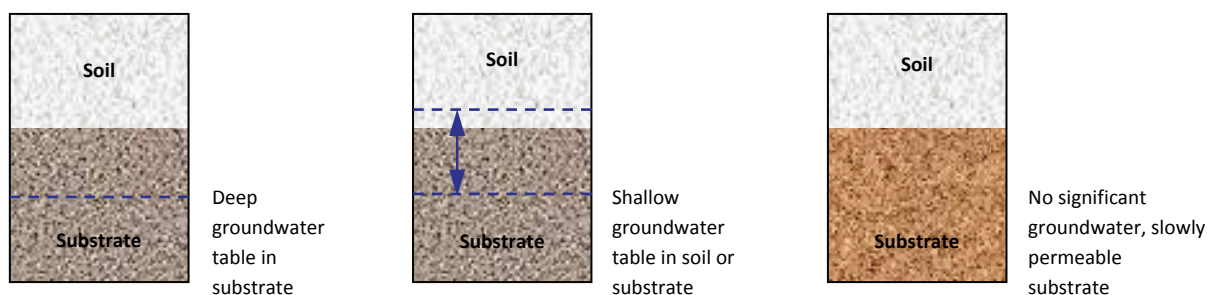


Figure 2.4 Physical settings underlying the HOST response models (Boorman, Hollist & Lilly, 1995)

2.1.4 Temporal stability of spatially measured soil water contents

Temporal stability of spatially measured soil water contents offers a valuable, new method to study the relationship between soil and water. Temporal stability of spatially measured soil water contents is defined as the time invariant average of spatially measured soil water contents (Vachaud *et al.*, 1985). Recent studies applying temporal stability of spatially measured soil water contents to study soil-water relationships are: Vachaud *et al.* (1985); Comegna and Basile (1994); Gómez-Plaza *et al.* (2000); Cosh *et al.* (2004); Martínez-Fernández and Ceballos (2005); Cosh *et al.* (2006); Lin (2006); and Starks *et al.* (2006).

Table 2.1 Soil-geology classes used the HOST classification

Class number	Class description
1	Soft sandstone, weakly consolidated sand
2	Weathered/fissured intrusive/metamorphic rock
3	Chalk, chalk rubble
4	Soft Magnesian, brashy or Oolitic limestone and ironstone
5	Hard fissured limestone
6	Hard coherent rocks
7	Hard but deeply shattered rocks
8	Soft shales with subordinate mudstones and siltstones
9	Very soft reddish blocky mudstones (marls)
10	Very soft massive clays
11	Very soft bedded loams, clays and sands
12	Very soft bedded loam/clay/sand with subordinate sandstone
13	Hard (fissured) sandstones
14	Earthy peat
15	River alluvium
16	Marne alluvium
17	Lake marl or tufa
18	Colluvium
19	Blown sand
20	Cover loam
21	Glaciacustrine clays and sifts
22	Till, compact head
23	Clay with flints or plateau drift
24	Gravel
25	Loamy drift
26	Chalky drift
27	Disturbed ground
34	Sand
35	Cryogenic'
36	Scree
43	Eroded Blanket Peat
44	Raw Peat
50	Unsurveyed
51	Lake
52	Sea

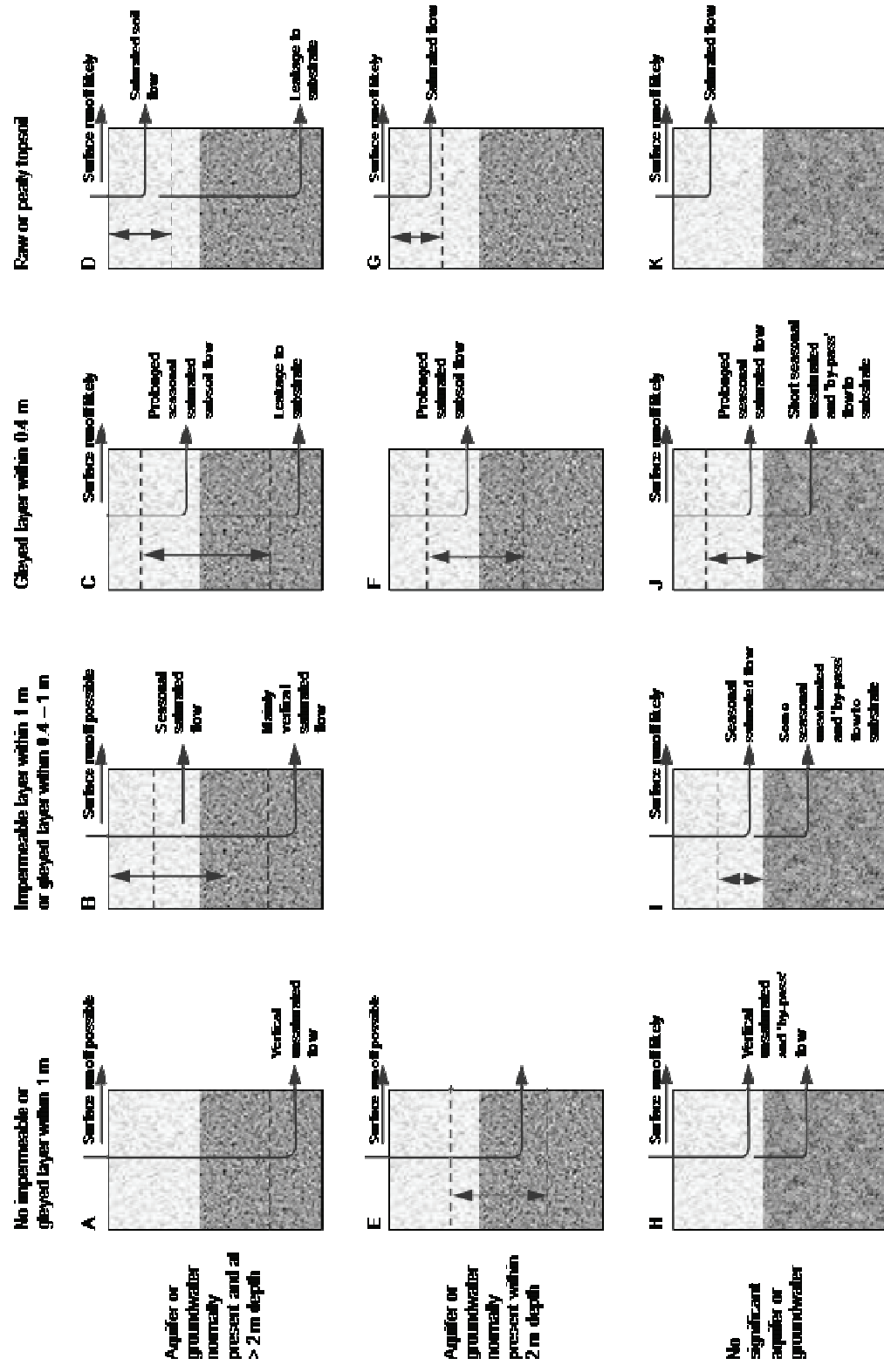


Figure 2.5 The 11 response models used in the HOST classification (Boorman, Hollist & Lilly, 1995).

Spatial stability of measured soil water contents, on the other hand, refers to the relationship between soil's water content and its location (Vachaud *et al.*, 1985) and is therefore typically represented as maps. The spatial stability relationship can to a large extent be explained by the soil's clay content, because clay will retain water longer, and would therefore have a higher probability of being wetter at any given time (Vachaud *et al.*, 1985; Grant *et al.*, 2004). Recent publications on the spatial relationship between soils and soil water are: Van Pelt and Wierenga, 2001; Ferreyra *et al.*, 2002; Cosh *et al.*, 2004; Grant *et al.*, 2004; Starr, 2005; and Cichota *et al.*, 2006.

Application of temporal stability has been used to reduce the number of measurements needed in catchment characterization (Vachaud *et al.*, 1985; Grant *et al.*, 2004; Lin, 2006). Temporal stability offers a valuable tool in monitoring site selection (Comegna and Basile, 1994; Ferreyra *et al.*, 2002; Grant *et al.*, 2004; Martínez-Fernández and Ceballos, 2005; Cosh *et al.*, 2006; Starks *et al.*, 2006). This is especially true as mechanistic hydrological models, necessary for solute and sediment transport models drive the need for increased understanding the direction and velocity of subsurface water flow (Lin, 2006).

Van Pelt and Wierenga (2001) studied the temporal stability of soil water matric potential measured at 60 locations in a 1 ha plot with the aim of finding a representative monitoring site for irrigation scheduling. They conclude that the concept of temporal stability of spatially measured soil water parameters is valid and that soil texture offers a convenient criterion for placing these sites. Spatial and temporal variability of soil water storage were similarly studied by Comegna and Basile (1994), on a 0.3 ha sandy soil cultivated with barley. They conclude that it is not possible to identify representative locations of average field water storage, due to the extreme homogeneity of the soil studied, and that the method would offer better possibilities in more heterogeneous soils. Starr (2005) mapped the temporally stable soil water pattern in an irrigated potato/barley field. He concludes that lower lying areas were consistently wetter and sandy soils consistently drier than the other areas. Gómez-Plaza *et al.* (2000) point out that temporal stability is scale dependent. At large (hillslope transect) scales, soil moisture patterns are temporally stable, with differences only apparent between dry and wet months. At medium scales soil moisture patterns are temporally unstable and depend on the scale considered. At small scales differences in local topography determine temporal stability.

Most temporal stability studies seem to have been made in very small (< 50 ha) areas (Comegna & Basile, 1994; Van Pelt & Wierenga, 2001; Lin, 2006), or in very large (> 100 km²) areas (Cosh *et al.*, 2004; Martínez-Fernández & Ceballos, 2005; Cosh *et al.*, 2006; Starks *et al.*, 2006), or by utilizing relatively short durations of water content measurements (Van Pelt & Wierenga, 2001; Cosh *et al.*, 2006; Lin 2006). Long term data from the mid-sized Weatherleyey catchment would therefore be a timely addition to the discussion on temporal stability.

The time-stable time average ($\bar{\delta}_i$) and relative soil water difference (δ_{ij}) of each measuring site was calculated per measuring depth using the procedure proposed by Vachaud *et al.* (1985):

$$\bar{\delta}_i = \frac{1}{M} \sum_{j=1}^M \delta_{ij} \quad (2.1)$$

Where M is the number of monitoring days, i is the monitoring site, j is the measurement day, and δ_{ij} is the difference in water content between the monitoring site and the catchment average:

$$\delta_{ij} = \frac{\theta_{ij} - \bar{\theta}_j}{\bar{\theta}_j} \quad (2.2)$$

Where θ_{ij} is the volumetric water content of monitoring site i on measurement day j, and $\bar{\theta}_j$ is the average volumetric soil water content of all monitoring sites on measurement day j:

$$\bar{\theta}_j = \frac{1}{N} \sum_{i=1}^N \theta_{ij} \quad (2.3)$$

Where N is the number of monitoring sites.

2.1.5 Redox reactions

The oxidation of organic matter (equation 4 and 5) in soils, by micro organisms that utilize the organic matter as food source, completes the carbon cycle, which was started during photosynthesis (equation 6 and 7). Both these processes are reduction-oxidation (redox) reactions, requiring an electron acceptor (oxidizing agent) and an electron donor (reducing agent).

Organic matter decomposition:



and



Photosynthesis:



and



Oxygen is used as electron acceptor by aerobic micro organisms in aerobic soils, because it releases the most energy (Table 2.2). When the soil is saturated with water all air, and therefore O_2 is excluded from the soil. Aerobic bacteria will die, due to lack of an electron acceptor, but facultative anaerobic and obligatory anaerobic bacteria can utilize other electron acceptors found in soils. These electron

acceptors release increasingly less energy to the micro organisms (Table 2.2). There is therefore a strict sequence in which these electron acceptors are reduced in soils.

Table 2.2 Order of utilization of electron acceptor half-reactions in soils and the associated electrode potentials (Bohn, McNeal & O'Connor, 1985; Vepraskas, 2001)

Reduction half reaction	Redox potential (mV)
$O_2 + 4e^- + 4H^+ \rightleftharpoons 2H_2O$	600 to 400
$2NO_3^- + 10e^- + 12H^+ \rightleftharpoons N_2 + 6H_2O$	500 to 200
$MnO_2 + 2e^- + 4H^+ \rightleftharpoons Mn^{2+} + 2H_2O$	400 to 200
$Fe(OH)_3 + e^- + 3H^+ \rightleftharpoons Fe^{2+} + 3H_2O$	
$FeOOH + e^- + 3H^+ \rightleftharpoons Fe^{2+} + 2H_2O$	300 to 100
$Fe_2O_3 + 2e^- + 6H^+ \rightleftharpoons 2Fe^{2+} + 3H_2O$	
$SO_4^{2-} + 8e^- + 10H^+ \rightleftharpoons H_2S + 4H_2O$	0 to -150
$2CO_2 + 8e^- + 8H^+ \rightleftharpoons CH_4 + 2H_2O$	-150 to -220
$2H^+ + 2e^- \rightleftharpoons H_2$	-150 to -220
Fe(OH) ₃ = ferrihydrite	
FeOOH = goethite	
Fe ₂ O ₃ = haematite	

The presence, absence and configuration of MnO, FeOOH, and organic matter can be used to infer the historical aeration (and therefore water saturation) status of soils, because these are also the dominant colorants in soils. These indicators are discussed in the following section.

2.1.6 Field indicators

The specific sequence of reactions, described above, results in unique soil morphological indicator developing in the soil, due to the prevalent water regime in the soil during soil formation. For example, a soil that never or seldom saturates with water will never be reduced. Iron and Mn can therefore not be reduced and mobilised. The result is a soil or horizon dominated by the colour associated with the Fe and/or Mn released from the parent material. Similarly, redox depletions (Figure 2.) will develop when reduced conditions predominate, while redox accumulations (Figure 2.7) develop in soils with alternating soil water saturation.

2.1.6.1 Redox depletions

Redox depletions are also known as reductimorphic colours (WRB, 2006). The term “redox depletions” is, however, more descriptive of the process and resulting morphology and is therefore preferred here.

Redox depletions are characterised by zones depleted of Fe and Mn (Figure 2.6). It therefore appears as grey (with chroma <2) mottles, cutans or matrices, because the soil granules have been stripped of the Fe colorants, revealing the grey quartz matrix. Redox depletions typically occur along root channels, on ped surfaces, or in the soil matrix. Redox depletions can also take the form of clay depletions, where the clay content is diminished as a result of Fe and Mn depletion. Clay depletions typically occur along ped surfaces or in large root channels and are therefore synonymous with silt

coatings, skeletans, and neoskeletans. Clay depletions form in the subsoil (> 0.3 m deep) and are less important indicators of reduced conditions in soils (Vepraskas, 2001). Examples of redox depletions in the form of mottles, cutans or matrices are given in Figure 2.8.

2.1.6.2 Redox accumulations

Redox accumulations are synonymous with oximorphic colours (WRB, 2006). Redox accumulations form when Fe and/or Mn accumulate at a point or in a plane like on the surface of a root channel (Figure 2.7). The accumulation forms when Fe and/or Mn move into an area, oxidizes and precipitates. The redox concentrations therefore contain more Fe than the surrounding soil matrix. Three kinds of redox concentrations have been defined based on hardness and occurrence in the soil: Fe masses, Fe pore linings, and Fe nodules and concretions.

Fe masses occur as soft accumulations of Fe^{3+} in the soil matrix, away from pores and cracks. The accumulations can have any shape and sizes vary from 1 to over 150 mm in diameter. The colour is variable, depending on the type of iron mineral present, with shades of red orange, yellow, or brown.

Fe pore linings are accumulations of Fe along root channels and/or ped surfaces. Fe pore linings form similar to Fe masses, differing only in occurrence: Fe masses occur in the soil matrix, while Fe pore linings occur along pores or ped surfaces. Pore linings are generally soft, similar to Fe masses, but may be cemented in extreme cases.

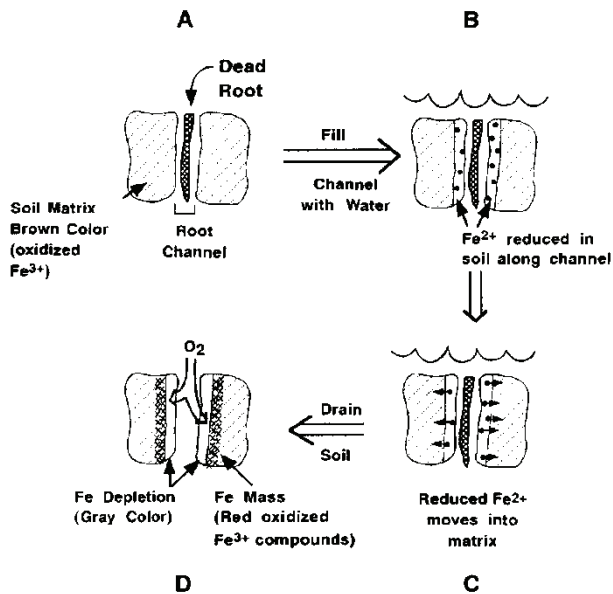


Figure 2.6 Formation of redox depletions around a root channel: (A) The soil is initially uniformly red throughout its matrix, with a channel containing a dead root, which is being decomposed by bacteria. (B) The channel is filled with water upon flooding and all dissolved O_2 in the water is reduced. When the water is anaerobic, the bacteria reduce Fe oxides and hydroxides in soil

surrounding the channel. (C) The Fe^{2+} dissolves and moves away from the channel, under a concentration gradient, leaving the soil particles around the channel stripped of the Fe oxide coatings. (D) If the stripped grains are largely composed of quartz and/or uncoated clay minerals, they will be grey in colour. The Fe^{2+} in the surrounding soil may subsequently oxidize to form a Fe mass (Vepraskas, 2001).

Fe nodules and concretions are hard, spherical bodies of soil particles cemented by Fe. Nodules and concretions range in size from 1 to 150 mm, similar to Fe masses. Concretions exhibit visible concentric layers, when broken, while nodules do not. There is no need to distinguish between the two terms, because the concentric layers may be visible under the microscope and are only indicative of formation over time and the two terms are therefore used interchangeably. Fe nodules and concretions can form *in situ*, or can be eroded, transported and deposited, due to its hardness. Fe nodules and concretions are therefore not reliable indicators of current soil redox conditions. Examples of redox accumulations in the form of Fe masses, Fe pore linings, and Fe concretions are given in Figure 2.7.

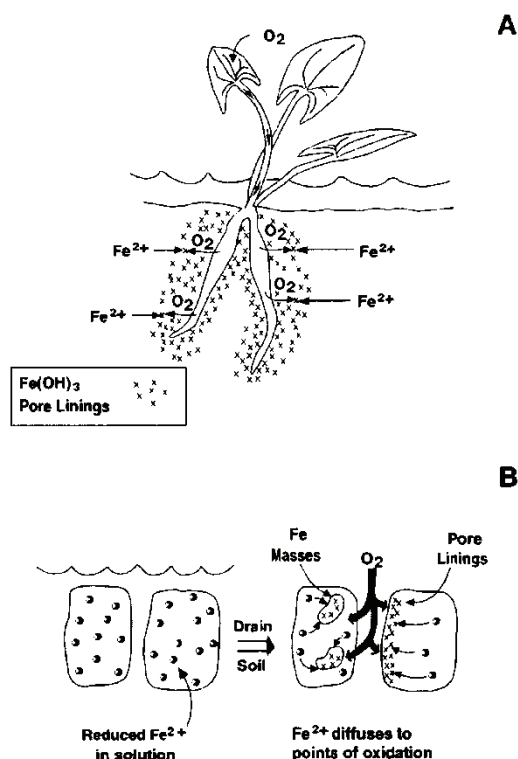


Figure 2.7 Formation of redox concentrations by two different processes: (A) Fe is oxidized around roots which are bringing O_2 into the flooded and reduced soil, forming redox concentration pore linings. (B) The Fe^{2+} is oxidized in the matrix after the soil has drained, and O_2 has been able to penetrate into reduced portions of the matrix. Iron masses are formed in this case. It is also possible for Fe masses to form where air has been trapped inside peds. (Vepraskas, 2001).

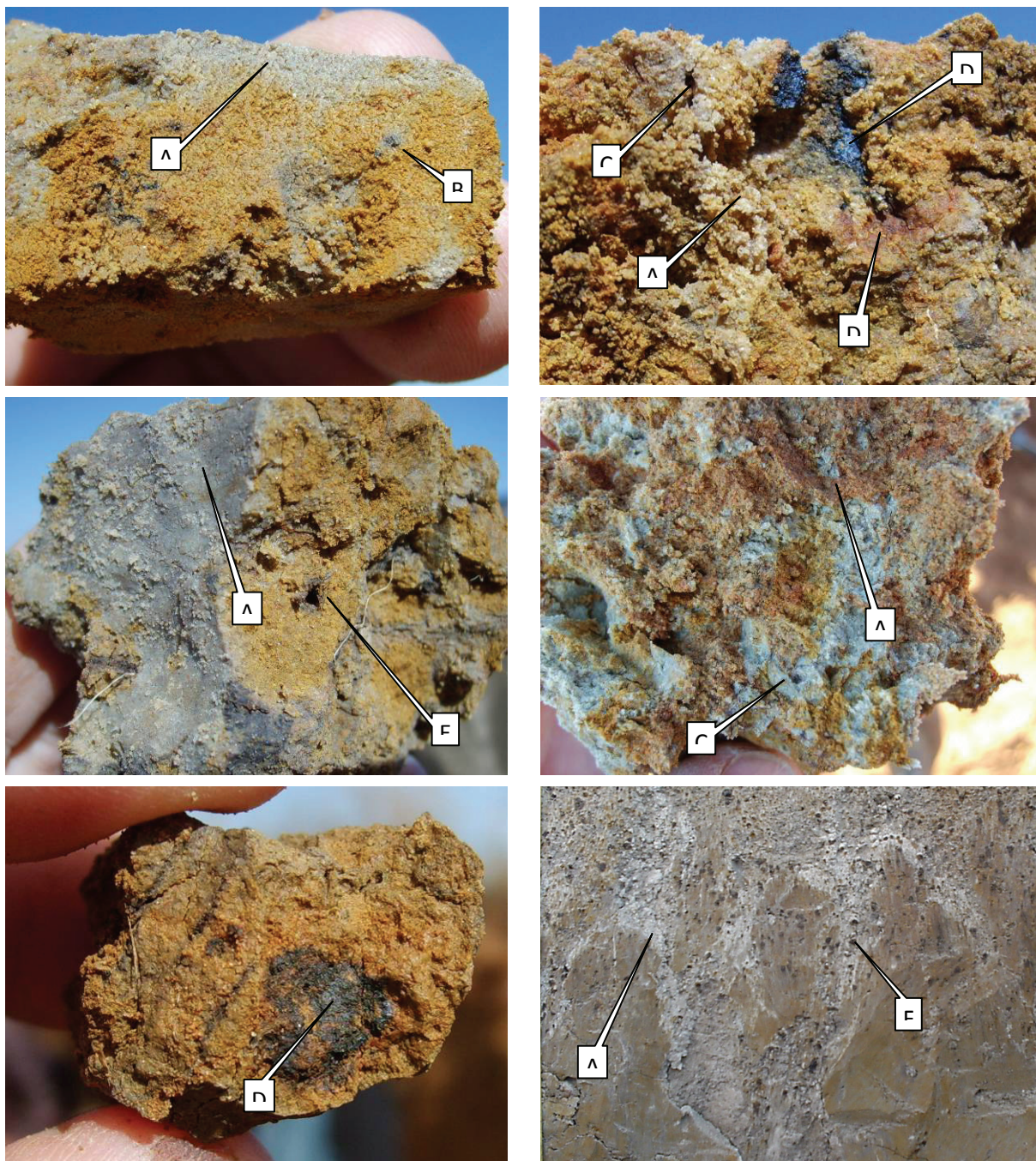


Figure 2.8 Redox depletions in the form of cutans [A], mottles [B], or along root channels [C] and redox accumulations in the form of Fe masses [D], Fe pore linings [E], and Fe nodules and concretions [F]

2.1.7 The critical zone

The earth's critical zone is defined. The United States National Research Council has identified integrated studies of the earth's critical zone as a compelling research area for the 21st century (NRC, 2001). It is in this critical zone, that the fate of water is decided (Figure 2.9). Hydropedology on the other hand is defined by Lin (2003) as "an interdisciplinary and multi-scale approach to study interactive pedological and hydrological processes in the earth's critical zone". As such soil forms an integral part of the critical zone (Lin *et al.*, 2005) of the earth, regulating the fate of water. A clear understanding of the fate of water in the soil layer of the critical zone is imperative, as the demand and competition for water increases amongst individuals, land uses, communities and nations.

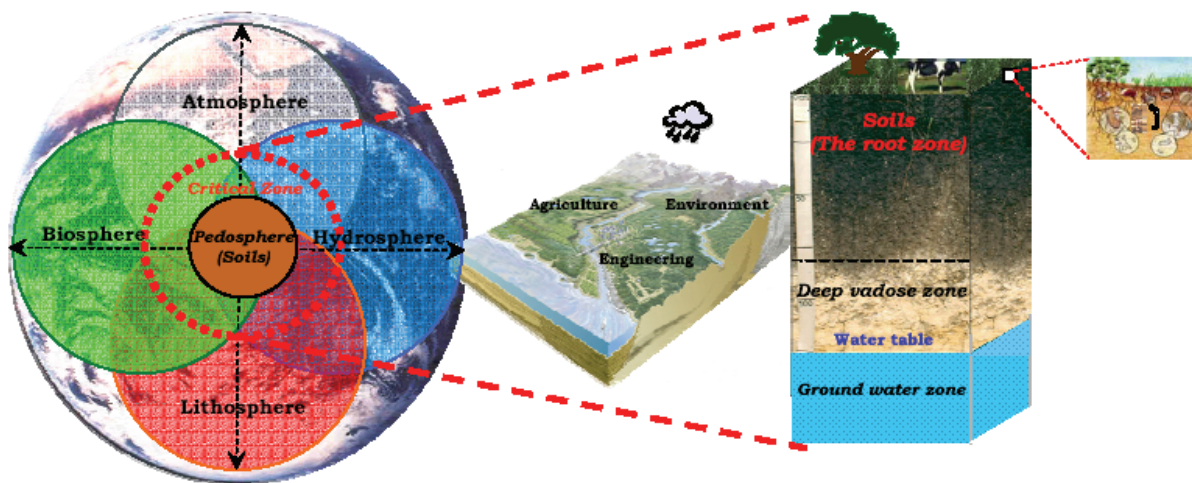


Figure 2.9 The pedosphere is the thin soil skin on the earth's surface. It is a geo membrane across which water and solutes, as well as energy, gases, solids, and living organisms are actively exchanged among the hydrosphere, atmosphere, biosphere, and lithosphere, thus creating a life-sustaining environment. Soil-water interaction is the fundamental interface between the biotic and abiotic and hence is a critical determinant of the state of the earth system and its critical zone (Lin *et al.*, 2006).

2.2 APPLICATION OF HYDROPEDOLOGY IN HYDROLOGICAL RESEARCH

Hydrological research can play a valuable role with regard to optimizing the development, conservation, and use of the relatively poor water resources in South Africa and large parts of Sub-Saharan Africa. This fact, and because studies in hydropedology can make a useful contribution to hydrological research (Lin *et al.*, 2005), provide the fundamental motivation for our research project. The project title "Hydropedological interpretation of the soils of selected catchments with the aim of improving the efficiency of hydrological models" expresses this. The focus is clearly on providing assistance to hydrologists and not on furthering the aims of soil science under the umbrella of hydropedology. Bias towards the latter aim seems to occur easily. For example in the paper "Advances in Hydropedology" by Lin, Bouma, Wilding, Richardson, Kutilek and Nielsen (2005) all the authors are

either soil scientists or their work is in closely related fields. There is no representative from leaders in the field of hydrological research. Notice also that Kutilek (2004a), referring to a definition which he formulated in 1966, defines hydropedology in the following way: "Combination of soil physical theories with theories of soil genesis and the related observations results in formation of the subject of hydropedology". In a wider and more appropriate definition Lin *et al.* (2004) describe the different aspects of hydropedology as follows: "Fundamental issues of hydropedology include:

- (1) Soil structure and layering as indicators of flow and transport characteristics in soils.
- (2) Soil morphology as signatures of soil hydrology.
- (3) Water movement over the landscape.
- (4) Hydrology as a factor of soil formation and driving force of soil dynamics."

Since the aim of this report is to provide guidelines for steering the course of our research wisely, we need to have clarity about the difference between hydropedology and soil hydrology.

Holistically the term hydropedology seems to be best described as the realm in which intimate, dynamic and continuous interaction occurs between the landscape, climate, water and soil as described in a lucid way by Bouma (2005): "... Water fluxes into and through soils in a landscape are the essence of life and resemble, in a way, the manner in which blood circulates in a human body. We could even compare blood pressure with the pressure potential of water in soil: when it is too high or too low soil functioning is clearly hampered. We could therefore speak of a *throbbing* landscape, in which water enters and leaves, on an hourly, weekly, monthly and yearly basis." Soil hydrology is clearly a subset of hydropedology, i.e. items one, two and maybe four in the list of four fundamental issues of hydropedology already presented. Soil hydrology is equally important in other subjects like irrigated and dryland crop production, forestry, pollution and engineering. Its focus is on water movement in soils, for example the detailed soil pore geometry studies described by Kutilek (2004b). The focus of soil hydrology is clearly not on water movement in the whole landscape.

It is also necessary to clarify the meaning of the term pedotransfer function or PTF. It is a much used term in hydropedology literature. It is important because it is the means by which hydropedological information can be extrapolated from catchments, hillslopes, or soils on which measurements have been made to others where similar measurements are needed but are not available. Bouma (2005) explains that, "Pedotransfer functions relate simple soil characteristics to be found in soil surveys to more complex parameters that are used in modelling and that are relatively difficult to measure."

Because of the acute shortage of relevant expertise in South Africa it is important that our research should focus on those aspects which will produce results that will be the most useful to hydrologists. There are some aspects of hydropedology that are attractive for a number of reasons, and which are receiving much attention elsewhere, but which do not offer optimum benefits in relation to the main objective of our project. We need to identify and avoid these. It is interesting to note that a leading

authority like Bouma (2005) advocates “more field work”. This is exactly the work that many scientists try to avoid! Our team has already clearly demonstrated that we do not intend to make this mistake.

An attempt will therefore be made here to identify the aspects of hydrogeology on which we need to focus. This will hopefully stimulate useful comments and guidance from our multidisciplinary Reference Group. We will also try to identify what we consider to be less fruitful avenues of research in relation to our objectives and resources.

2.2.1 Hydrological models

Drawing on much relevant experience Lorentz (2001) writes knowingly about hydrological models in the following way: “Whereas, in the past, we often had a plethora of environmental data without a holistic theory, nowadays we often suffer from a growing stockpile of models, many of which have not been adequately verified. Model development has become an increasingly attractive pursuit since funding is often limited, the cost of field studies is high, time and patience limited and cooperative research is often difficult and tedious. Nevertheless, modelling and process experimentation must be an ongoing endeavour that reciprocally enhances one another with sound, comprehensive experiments and observations serving as the building blocks of models. At the same time models must serve to economise experimental designs, direct objectives and test observed phenomena. The responsibility lies in the hands of environmental researchers to adhere to the modelling process and to seek out experimentalists that can assist in building and evaluating models.”

Members of our research team qualify as “environmental researchers” referred to in this passage. From our experience we can confirm the truth of the statement that difficulties in this work include the high cost of field studies, the need for patience, and the ability to conduct cooperative research in an effective way. These challenges face us in the present project.

There is indeed a stockpile of hydrological models available at present. Only a few selected ones will be considered here, and only those aspects that are directly relevant to our research. The structure of the models will not be discussed in detail – most of us have little expertise in this connection. Brief details of aspects relevant to our project for ACRU and the Pitman model will be presented.

The general structure of the ACRU model is presented in Figure 2.10 (Schulze & Smithers, 1995). The middle portion of the diagram represents the soil profile and the fourth box from the top describes the soil data required for the A and B horizons. Adequate data should include the following for the A and B horizons: thickness (m); texture class; permanent wilting point (m m^{-1}); porosity (m m^{-1}); “saturated” redistribution fraction from B horizon to intermediate/groundwater store. Although allowance is not specifically made for hydraulic conductivity values in the soil boxes this process is presumably partially dealt with via the last two parameters. The model uses daily time steps and thus daily climate data, thereby making optimal use of available data.

The Pitman model, a monthly time step rainfall-runoff model, is widely used in Southern Africa (Hughes *et al.*, 2006). Although the original version has undergone some alterations, the basic form has been preserved. The flow diagram of the recent SPATSIM version used by Hughes *et al.* (2006) is described in Figure 2.11 Soil information is needed mainly for the four central blocks in the diagram, i.e. soil moisture store; ground water recharge function; soil moisture runoff function; soil moisture runoff. Keeping in mind the difficulties involved in obtaining the necessary input data, the satisfactory results reported by Hughes *et al.* (2006) for each of the 17 sub-basins of the vast overall area of 228778 km² of the Okavango basin demonstrate the capability of this model for this kind of hydrological modelling. For our project Mr Kapangaziwiri will be conducting a study titled “Development of physically based parameter estimation procedures for the Pitman monthly rainfall-runoff model” under the guidance of Prof. D.A. Hughes. The soil information required for the parameter estimation procedures include: soil texture, structure, depth, hydraulic conductivity (if possible), infiltration rates and field capacity.

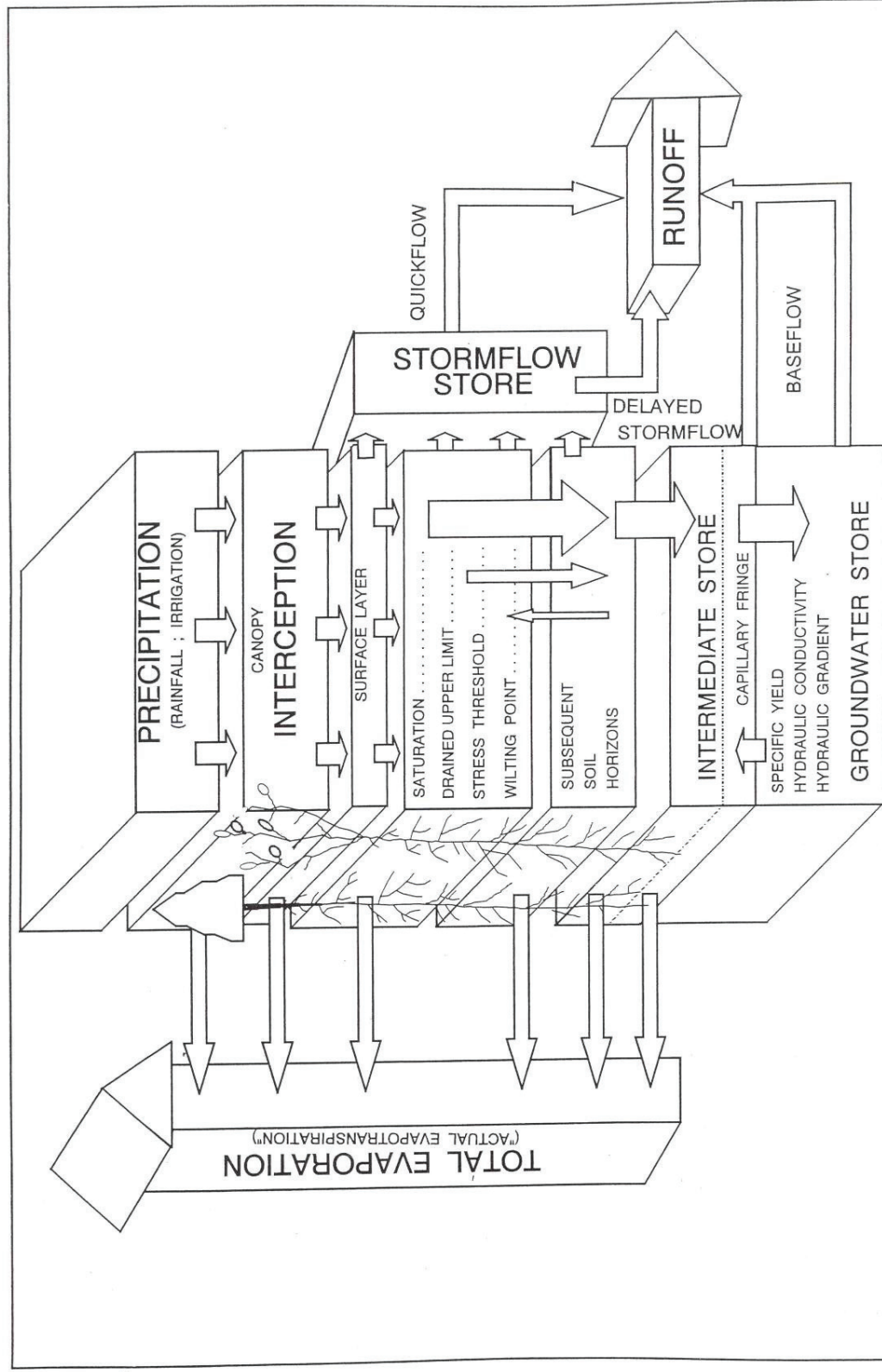


Figure 2.10 The ACRU agro hydrological modelling system: General structure (After Schulze & Smithers, 1995).

Table 2.3 Summary of simulation results to 13 South African catchments (After Royappen *et al.*, 2002)

Catchment	DWAF Weir No.	Figures	Page ref	Appendix ref	Lat (dm)	Long (dm)	MAP (mm)	Area (km ²)	R ²	Slope	Intercept	Accumulated flows as % of observed flows	Comments	Flow Parameters Acceptable
Lambrechtsbos B	G2H010	40-43	64-66	128-132	33 57	18 57	1472	0.66	0.733	1.989	-11.231	69.01		
Watervalsrivier	G1H012	44-47	67-69	128-132	33 21	19 06	664	36	0.859	1.068	1.860	88.44		✓
Dieprivier	K4H003	48-51	70-72	128-132	33 54	22 42	711	72	0.745	1.475	1.328	58.97		
Kruisrivier	H9H004	52-55	73-75	128-132	34 00	21 16	645	50					Irrigation, simulated only June – Sept each year	✓
Bloukransrivier	K7H001	56-59	76-78	128-132	33 57	23 37	1003	57	0.842	0.986	7.110	84.74		✓
Zululand	W1H016	60-63	79-81	133-138	28 50	31 46	1314	3.32	0.934	0.943	4.107	94.59		✓
Cathedral Peak IV	V1H005	64-67	82-84	133-138	29 00	29 25	1400	0.95	0.938	0.883	1.277	111.13		✓
DeHoek	V1H015	68-71	85-87	133-138	29 58	30 20	800	1.01	0.780	0.800	4.050	99.79		
Wilklip V	X2H038	72-75	88-90	133-138	25 14	30 53	1100	1.08	0.913	1.434	-6.638	89.25		✓
Treurrivier	B6H003	76-79	91-93	133-138	24 41	30 48	792	92	0.945	1.109	-1.556	94.32		✓
Beestekraalspruit	X2H026	80-83	94-96	139-142	25 17	30 34	977	14	0.757	0.578	10.523	121.82		
Westfalia B	B8H022	84-87	97-99	139-142	23 43	30 04	1253	0.33	0.844	0.895	0.421	110.58		✓
Groot-Nylrivier	A6H011	88-91	100-102	139-142	24 45	28 44	654	73	0.761	0.932	3.674	73.83		

Lat = latitude, °S

Long = longitude, °E

dm = degrees and minutes

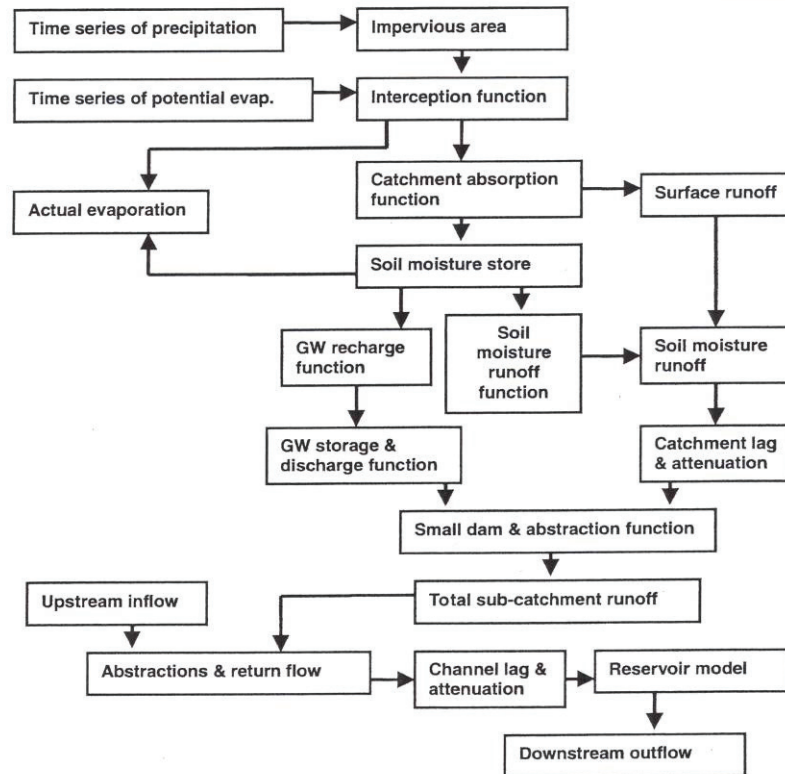


Figure 2.11 Flow diagram of the main components of the SPATSIM version of the Pitman model (After Hughes *et al.*, 2006).

This information will be supplied by our team for three catchments in the Bedford district.

In line with the old adage “the proof of the pudding is in the eating” only soil science related aspects of actual model performance will be considered in the form of three case studies. This exercise should reveal ways in which we can possibly contribute towards improving the models.

Case Study I “An Analysis of catchment attributes and hydrological response characteristics in a range of small catchments.” M. Royappen, P.J. Dye, R.E. Schulze & M.B. Gush, 2002.

A selection of 13 South African catchments was chosen to represent a broad range of climate, topography, vegetation and geology. “Daily rainfall and streamflow data were in every case considered to be of a high quality, spanning a continuous period of five years or longer. ACURU was configured for each catchment, and simulations assessed for realism, with particular emphasis on the relationship between simulated and observed flows.” No detailed soil survey data was available for any of the catchments. In the detailed assessment of results of the eight catchments attention was focussed on

the parameters termed QFRESP and COFRU “as these are the primary controls of the generation of streamflow in the ACUR model.” “The parameter QFRESP determines the fraction of the stormflow generated that will exit the catchment/subcatchment on the same day of a stormflow-producing rainfall event. In small catchments of the size range selected in this study, a high QFRESP (tending towards 1) is typical of catchments that are small, steep, and that contain areas that easily shed surface runoff. This parameter reduces towards zero as catchment size increases and the time for quickflow to exit the catchment lengthens.”

COFRU is the coefficient of baseflow response, i.e. “the fraction of water from the intermediate (groundwater) store that is released as the baseflow component of streamflow on a particular day.” For the sake of efficiency the results with regard to QFRESP and COFRU are presented verbatim from Royappen *et al.* (2002) in the following six paragraphs. The figure numbers are changed for this report. This information is being presented in this way because of its great significance with regard to hydrogeology and our project. The analysis of the results reflects the expertise of the authors which we need to capture as comprehensively as possible.

“Figure 2.12 shows no clear association between QFRESP and catchment area, but this is attributed to the relatively small size of catchments chosen for this study. There is a high degree of variation in QFRESP in the smaller catchments. The highest value is associated with the Zululand catchment, where coarse-textured soils permit very rapid movement of sub-surface water towards the stream channel (Hope and Mulder, 1979). Hydrographs from this region typically show very quick, “flashy” responses to rainfall: quickflow peaks are high and recede very rapidly. The lowest QFRESP is associated with Cathedral Peak IV. Catchments in this area are characterised by very thick subsoils that permit high water storage capacity (Everson *et al.*, 1998). Streamflow responses to the first spring rains are typically delayed until January, as infiltrating rainwater enters soil storage and is only released slowly towards the channel. Witklip V is similarly associated with a low QFRESP, which may reflect the very deep granite-derived soils of the area. In a similar area on Frankfort State Forest, bedrock was estimated to lie approximately 40 m beneath the surface (Dye *et al.*, 1997). The relatively high QFRESP estimated for Westfalia B is unexpected, since it is likewise associated with deep, granite-derived soils. The possibility of leaks across the catchment boundary has long been suspected, and may be responsible for the high QFRESP. Figure 2.13 illustrates the relationship between average soil depth and QFRESP. There is a convincing relationship between these two variables, with only the suspect Westfalia B not conforming to the overall trend.

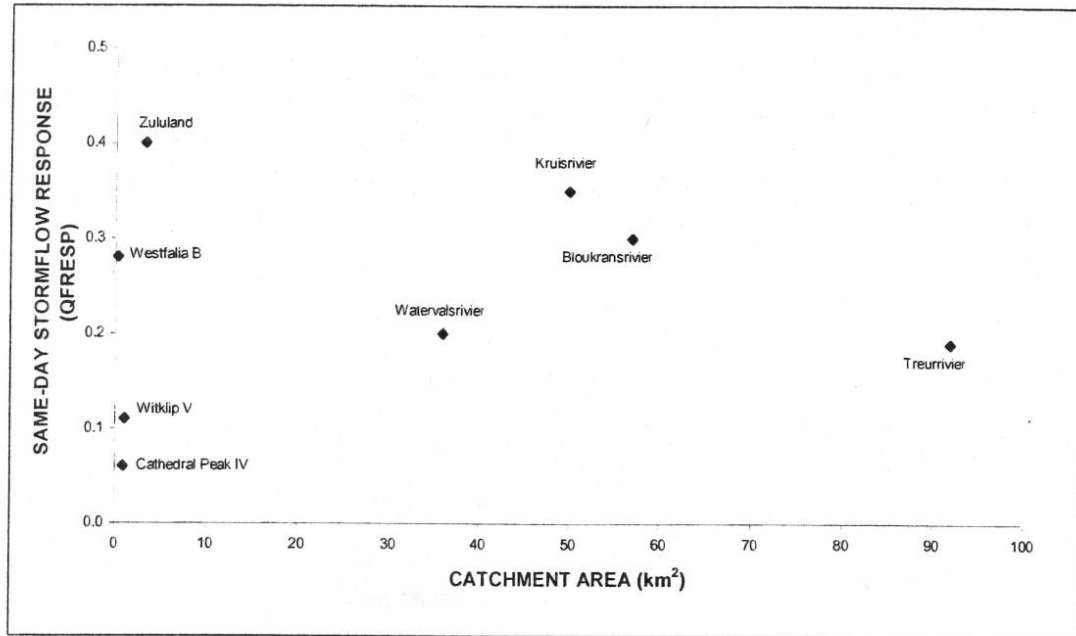


Figure 2.12 The association between the same-day stormflow response fraction (QFRESP) and catchment area.

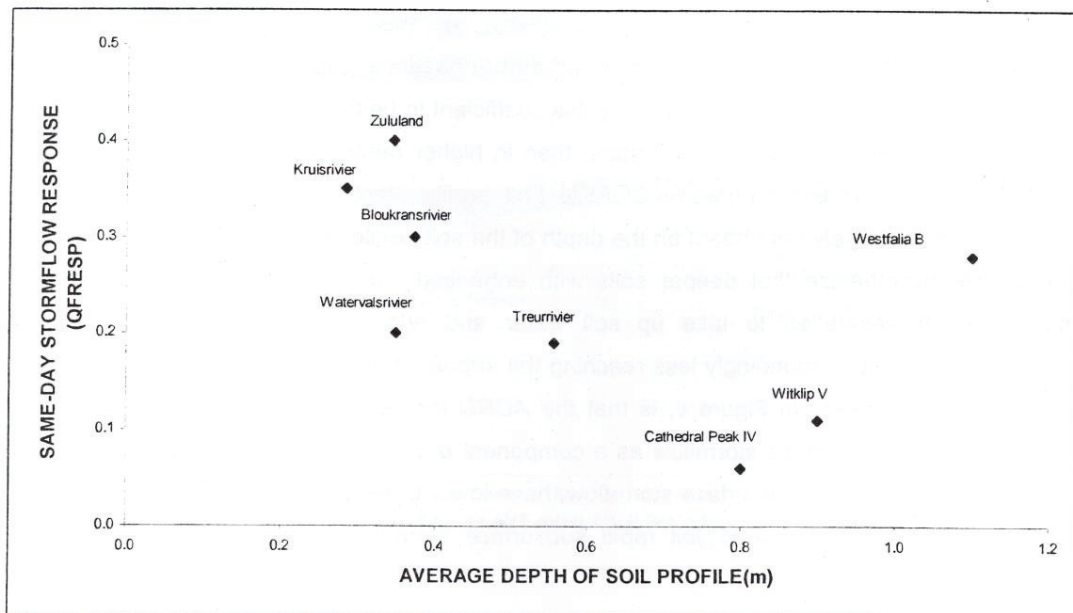


Figure 2.13 The association between the same-day stormflow response (QFRESP) and the average depth of the soil profile for a catchment.

Figure 2.14 shows a tendency for this coefficient (COFRU) to be higher in low rainfall catchments that are associated with shallow soil depths, than in higher rainfall areas. Figure 2.15 illustrates a strong negative association between COFRU and profile plant available water. Profile plant available water is largely dependent on the depth of the soil profile and includes the affects of soil texture. We hypothesize that deeper soils with enhanced soil water storage provide greater opportunity for vegetation to take up soil water and release to the atmosphere through transpiration, with correspondingly less reaching the stream channel. A second hypothesis which could explain the trends in Figure 2.15, is that the ACRU model at this stage includes rapid and delayed forms of subsurface stormflow as a component of baseflow. Therefore deep soils which will exhibit more delayed subsurface stormflow, have lower baseflow release fractions, compared to shallower soils which will exhibit rapid subsurface stormflows, and have higher baseflow release fractions.

Flow parameter values determined in the eight successfully simulated catchments indicate the importance of soil depth, and profile water storage capacity in determining streamflow parameter values. It is encouraging to note that the soil characteristics derived from the AUTOSOILS database developed by Pike and Schulze (1995 and subsequent updates) can show such a meaningful link to ACRU flow parameters.

Linear regressions between QFRESP and the catchment attributes were not significant except for average catchment altitude. However, this result is spurious, since there is no hydrological explanation for this result. Linear regressions between COFRU and catchment attributes highlight two significant relationships. These include the Average Depth of the Soil Profile ($p < 0.019$; $R^2 = 0.626$), and the Profile Plant Available Water ($p < 0.026$; $R^2 = 0.522$), which had already been identified from the scatter plots.

Geological and soil properties in a catchment may be highly variable and complex. The presence of dolerite dykes, macropores and catchment leaks are just three features encountered in South African catchments which may lead to unexpected hydrological functioning that departs from general trends. The degree to which one can regionalize the results from research catchments remains difficult to discern. A clearer picture will emerge only with further modelling experience on a wide range of new catchments. Established research catchments have been heavily researched over the years, and we believe that advancing our perspective of catchment

hydrological functioning in South Africa will be best accomplished by switching research focus to a new set of catchments.

This study has pointed to the importance of soil/subsoil depth and profile storage capacity in determining streamflow characteristics. Hillslope studies, such as those in progress in the Weatherley research catchment in the North East Cape, provide clearer insights into streamflow generation processes than we have at present, and should ideally be duplicated over a broad range of geomorphological situations when opportunities arise.”

The results from this valuable and comprehensive study provide convincing evidence for the value of detailed soil knowledge to enhance hydrological modelling. The importance of the soil characteristics soil/subsoil depth and profile storage capacity, are accentuated. Both are relatively easily obtained from soil survey results. It is very likely that if detailed soil survey data had been available for each of the catchments, results would have been better. It would be a useful exercise to provide this information and then repeat the simulations and assessment of results.

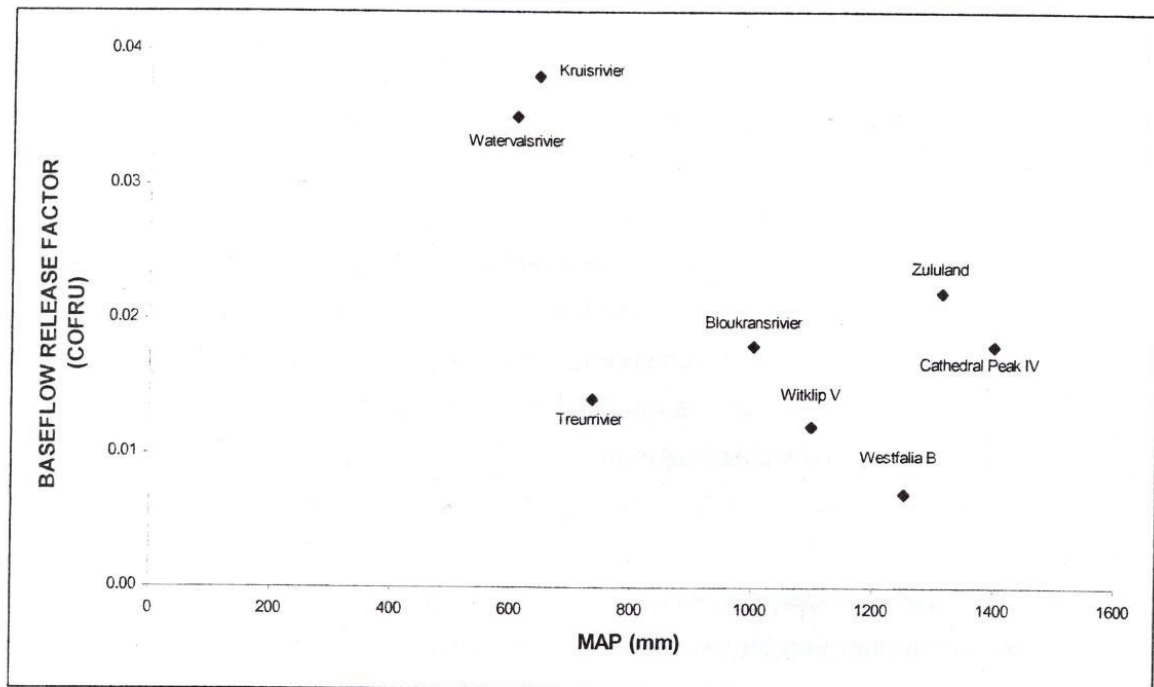


Figure 2.14 The association between COFRU for a catchment and MAP

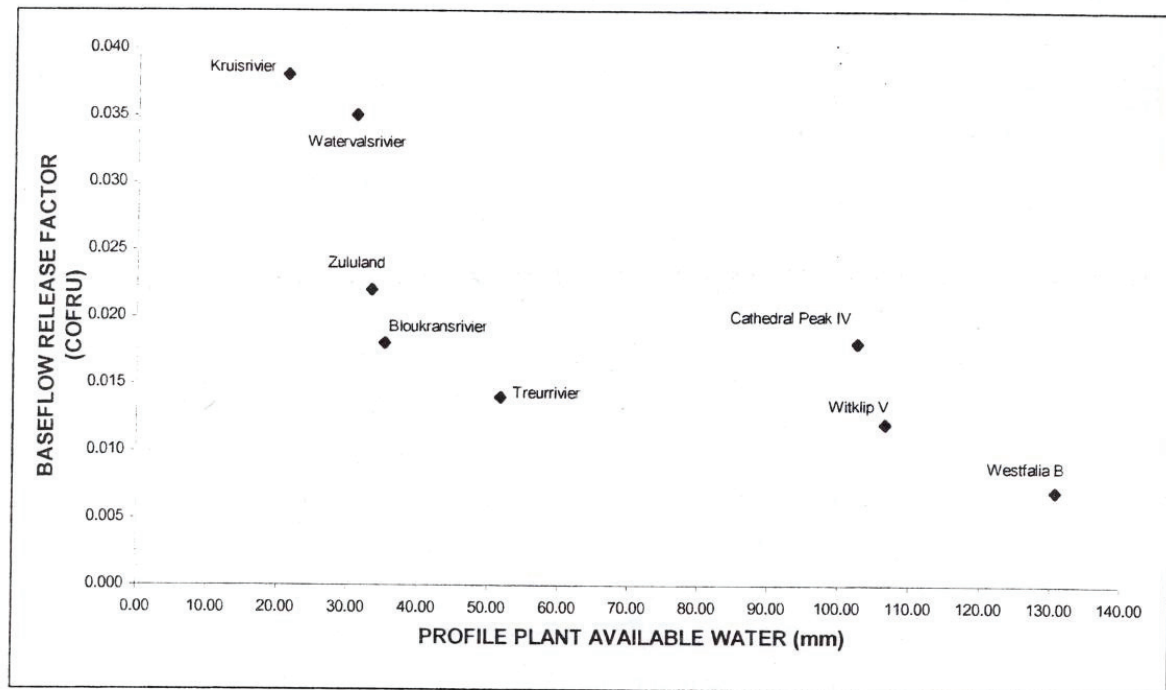


Figure 2.15 The association between the baseflow release factor for a catchment and the soil profile's available water.

Case Study No 2 "Water resources planning and modelling tools for the assessment of land use change in the Luvuvhu Catchment, South Africa." G.P.W. Jewitt, J.A. Garratt, I.R. Calder & L. Fuller, 2004.

The HYLUC and ACUR land use sensitive hydrological models were used to investigate the change in blue (runoff) and green (evapotranspiration) water under various land-use scenarios in the upper reaches of the Mutale River, an important tributary of the Levuvhu River. ACUR is considered as a relatively data intensive model for which a comprehensive database of parameter values has been developed and widely tested for South African conditions. HYLUC is relatively parsimonious (stingy) with regard to data requirements and "can be applied using previously published values for land use parameters or, if local data on flows or soil moisture are available, local values for parameters can be estimated." HYLUC has been used in various parts of the world but had not previous to this publication been applied in South Africa.

Soil data was obtained from the Land Type data base (ARC-ISCW), and translated into the required soils input properties for both models using the ACUR AUTO-SOILS programme. The inputs include the depth of the topsoil and subsoil horizons, and the values of saturated water content, field capacity and wilting point.

Results of the verification text, i.e. simulated monthly flows vs. measured monthly flows, showed that both models simulated streamflow with a fairly good correspondence to that observed. R^2 values were around 0.5. It is necessary to bear in mind that detailed soil data was not available for this exercise. It is not known how much better the models would have performed had that sort of data been available. With only the useful but relatively approximate soils data available from the Land Type database the performance of the two models was similar. It is not known what the comparison would have been like had detailed soils data been available. It appears that ACRU is better equipped to take advantage of that sort of input than HYLUC. The results showed that at the intensity scale at which the exercise was conducted both models were appropriate tools for simulating partitioning of rainfall into green and blue water for this catchment. Despite its parsimonious nature, HYLUC was shown to be able to predict mean annual and seasonal values that are in good agreement with those simulated by the ACRU model.

Case Study No. 3 “Monitoring and modelling components of the water balance in a grassland catchment in the summer rainfall area of South Africa. C.S. Everson, G.L. Molefe & T.M. Everson, 1998.

The study was undertaken in the 68 ha Cathedral Peak VI catchment. Weather and streamflow data were collected over a five year period to test the reliability of two hydrological models, TOPOG (a distributed model) and ACRU (a one dimensional model). The period included a range of hydrological conditions, including the driest year on record and a very wet year. Although detailed soil survey data for the catchment was not available, intensive soil water measurements were made over four years on a hillslope.

Computational problems prevented the successful running of the TOPOG model. ACRU generally predicted streamflow well except in wet years. The result is presented in Figure 2.16. The deviations during wet periods are clearly shown with gross overestimations at the following approximate times: 4/2/1991; 17/2/1992; between 18/1/1993 and 1/3/1993; between 8/11/1993 and 20/12/1993; between 2/1/1995 and 13/2/1995. Significant underestimation also occurred for the following periods: between 1/3/1993 and 27/9/1993 – an autumn to winter period with very little rain, during which flow gradually decreases to base flow every year; a very wet period between 31/1/1994 and 25/4/1994. Comparative monthly statistics of actual versus simulated stream flow (5 years data) yielded the following results: correlation

coefficient (Pearson's r) = 0.90; coefficient of efficiency 0.50; coefficient of agreement 0.87.

An important observation was that unsaturated subsurface flow of water from the B horizon to the groundwater zone and saturated drainage are important components of the hydrology of this and similar catchments. ACRU was unable to deal effectively with this process. This weakness seems to have been receiving attention (Lorentz *et al.*, 2007; see Chapter 2.1). Also note the relevant comments by Royappen *et al.* (2002) regarding the good inverse relationship between COFRU and plant available water. Catchment Cathedral Peak IV, evidently with very similar characteristics to Cathedral Peak VI, exhibits a behaviour predicted by Everson *et al.* (1998) four years earlier. Everson *et al.* (1998) also suggest that refinements to ACRU may be necessary to reduce the 15% under-estimation of streamflow (Figure 2.16).

2.2.2 Soil morphology as signatures of hydrology

This is one of the subdivisions of hydropedology in which our team can make a good contribution. In the South African context the results reported by Van Huyssteen *et al.* (2005) in "The relationship between soil morphology and the hydrology of the Weatherleyey catchment in the North Eastern Cape" have opened the door for us into a promising field of useful hydropedology research. It is worth noting that the title of that project was selected two years before the hydropedology launching publication by Lin *et al.* (2004) in which the importance of soil morphology as a signature of soil hydrology was highlighted.

The South African soil classification scheme is structured in such a way that it is a particularly favourable medium for providing "soil morphology as signature of soil hydrology". The diagnostic horizon can be considered as a carefully defined stratification of the entire range of soil materials which occur in South Africa. This is very advantageous since it contributes a useful degree of order into studies in soil hydrology. A researcher is not faced by a plethora of different soil materials appearing at all different depths in soil profiles, but by specific kinds of horizons occurring at specified positions in specified soil classes, the soil forms.

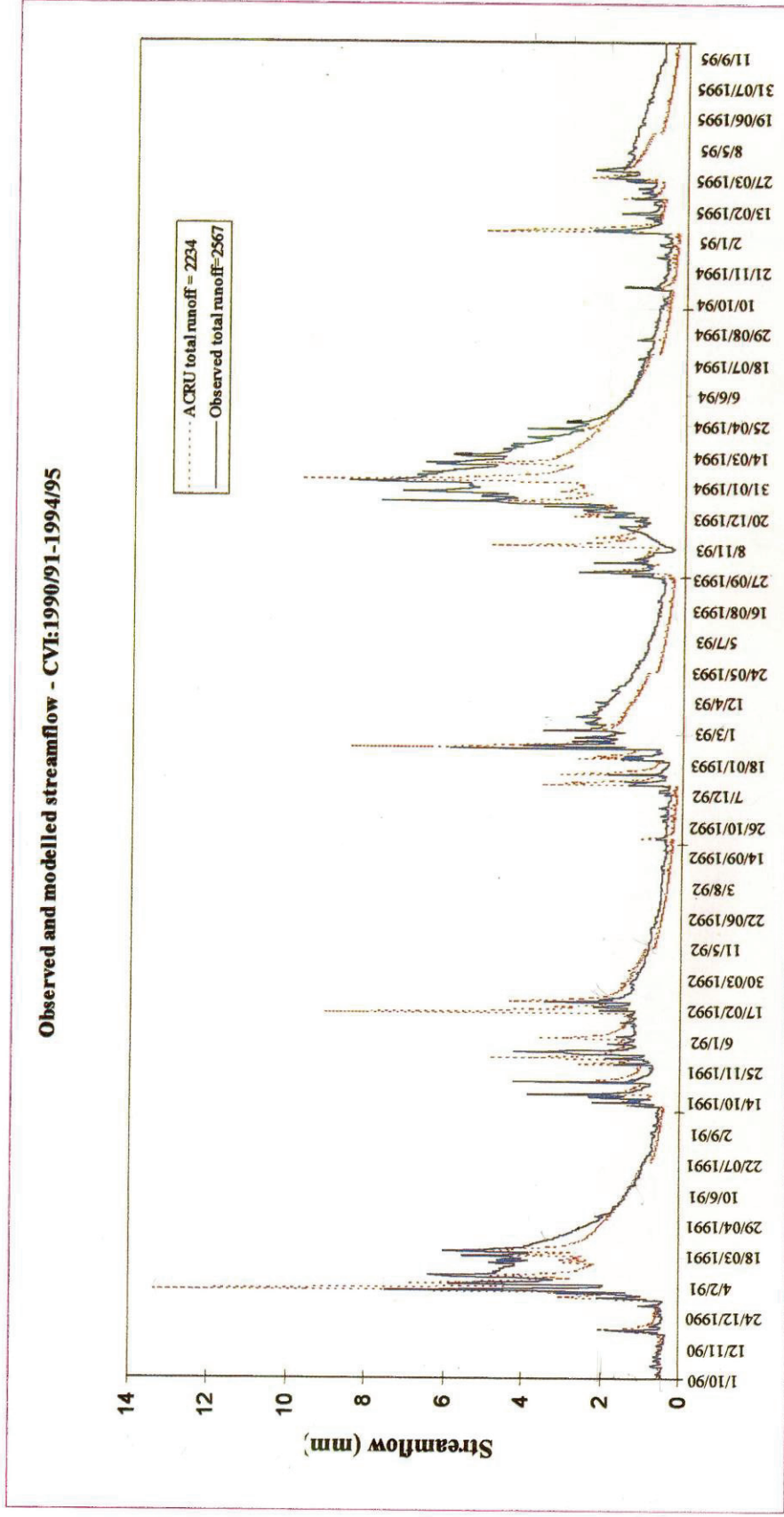


Figure 2.16 Observed and ACRU modelled streamflow for catchment VI at Cathedral Peak for the period January 1990 to September 1995. (After Everson *et al.*, 1998).

The value of diagnostic horizons in hydropedology is effectively expressed by Van Huyssteen *et al.* (2005) (Figure 2.17). A well defined relationship is exposed in quantitative terms. Additional information from other catchments and ecotopes is needed to improve the definition of the morphological signatures of these diagnostic horizons, and all the others in the classification scheme.

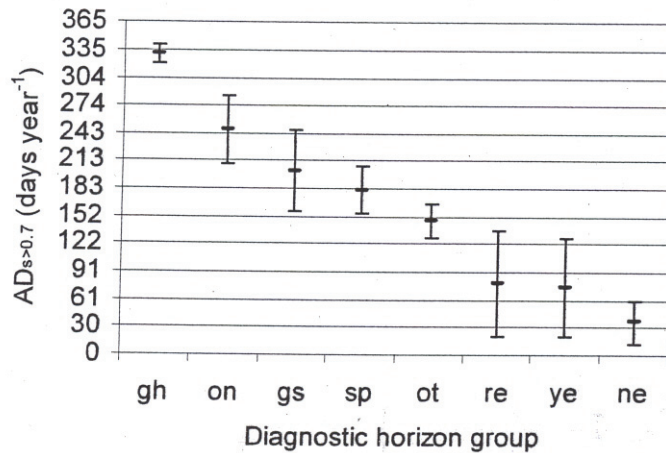


Figure 2.17 Means and standard errors of the $AD_{s>0.7}$ values per diagnostic horizon group. (After Van Huyssteen *et al.*, 2005).

2.2.3 Soil hydrology

Fundamental concepts in soil hydrology and their importance in hydropedology are described by Wösten & van Genuchten (1988) as follows: “Soil hydraulic behaviour is characterized by the soil water retention curve which defines the volumetric water content (θ) as a function of the soil water pressure head (h), and the hydraulic conductivity curve which relates the hydraulic conductivity (K) to water content or pressure head”.

Apart from overland flow all the water that reaches any stream has first to pass through any soil there is in the landscape. The amount of water the soil can store against the force of gravity, and the rate at which the water moves through the soil mantle, is determined by the hydraulic properties of the soil profiles in any catchment. Hence the importance of soil hydrology in hydrology and hydropedology. With regard to the wider importance of the hydrological properties of soils Kutilek (2004) states as follows: “Knowledge of soil hydraulic functions and parameters is required for a successful formulation of principles leading to sustainable soil management, agricultural production and environmental protection.”

The determination of soil water retention curves (SWRC) and hydraulic conductivity curves ($K\theta$) for soils are laborious. Because of this, much attention has been given to seeking ways to predict these parameters from simpler measurements, e.g. texture. For South African soils Hutson (1983) used water retentivity data from 3000 disturbed samples from the Land Type Survey data base (Land Type

Survey Staff, 2002), and 500 undisturbed samples (clods and cores) from eight different sets of published data. For the undisturbed samples he reported the regression results presented in Table 2.4 for predicting θ from clay (cl) and silt (si) content and bulk density (ρ_b). Notice the relatively high R^2 values. That does not mean, however, that his SWRC data will provide reliable predictions of $K\theta$.

Table 2.4 Regression coefficients for the model $\theta = \beta_0 + \beta_1 \text{Cl} + \beta_2 \text{Si} + \beta_3 \rho_b$ applied to data from sources 1 to 8, excluding unstable soils, variance accounted for (R^2), and standard error of the estimate of θ (s)

ψ kPa	β_0	β_1	β_2	β_3	R^2	s
-10	0.0558	0.00365	0.00554	0.0303	0.681	0.066
-30	-0.0150	0.00384	0.00572	0.0463	0.764	0.055
-100	0.0290	0.00361	0.00441	0.0049	0.769	0.059
-500	0.1588	0.00347	0.00170	-0.0838	0.823	0.047
-1500	0.0602	0.00322	0.00308	-0.0260	0.785	0.051

These results have been used for agricultural purposes for predicting plant available water (PAW) in different soils. For example in the PUTU crop model, PAW is defined as the difference in water content at -10 kPa and -1500 kPa. Hutson (1983) also attempted to predict $K\theta$ from SWRC and textural data. He found, however, that “Absolute values of K were unreliable and measured values are essential for matching”. This does not come as a surprise. His lowest suction value is at 10 kPa. The region from 1 to 10 kPa is important for the $K\theta$ relationship in relation to hydrogeology. Hutson’s focus, in line with so many other earlier studies of soil hydrology, was clearly on agricultural applications. Hutson has made a valuable foundational contribution to the study of the hydrology of South African soils. This work needs to be expanded using all the additional information and expertise that has accumulated since he completed his study 24 years ago.

Wösten & Van Genuchten (1988) investigated the reliability of the Van Genuchten (1980) equations to predict the hydraulic functions of 197 individual soils in the Netherlands. The soils were divided into 20 groups according to whether they were topsoil or subsoil and furthermore according to texture. Notice that they made no attempt to create groups using soil classification criteria. Their results led them to conclude as follows: “Results indicate that the predictive regression models established in this study can be used to derive soil hydraulic functions for large areas of land when working on scales of 1:50 000 or smaller. The models need improvement for site specific applications at scales of 1:10 000 or larger, however.”

Fredlund, Fredlund & Wilson (1995) used an ingenious procedure for predicting the SWRC from the particle size distribution curve. The basic assumption was that a soil composed of a uniform, homogeneous particle size would have a unique soil-water characteristic curve. The data base they used contained over 6000 soils, presumably mainly from Canada. An example of the results they obtained is presented in Figure 2.18. Note the good agreement of the predicted with the experimental SWRC between kPa suction values of about 11 and 40 kPa, and less favourable agreement at kPa <11. The authors fail to describe how the experimental curve was determined. If a disturbed sample was used the results are not meaningful.

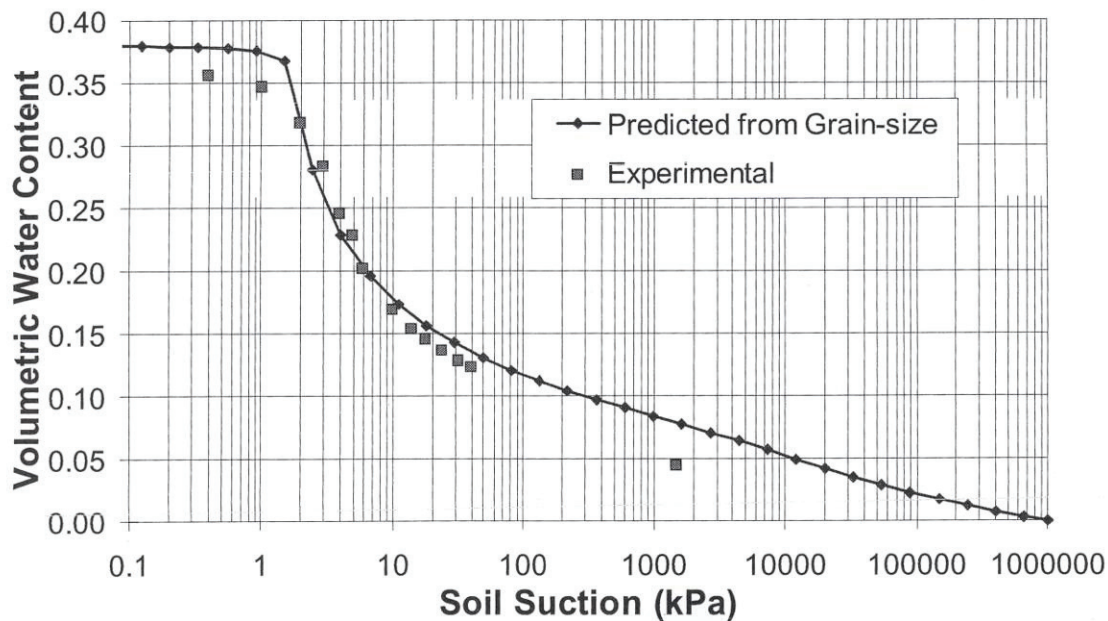


Figure 2.18 Comparison between experimental and predicted curves for a Loamy Sand (#10702) (After Fredlund *et al.*, 1995).

Their ingenious “cumulative” procedure for interpreting the influence of texture is useful, however, the USDA National Soil Characterization Database was used by Rawls & Pachepsky (2002) to obtain data for their study. Samples were selected that had: (i) values of water contents at -33 kPa and -1500 kPa on clods, and bulk densities at -33 kPa and air dried soil; (ii) structure characterized with grade, size and shape; (iii) consistence characterized with dry and moist consistency, stickiness, and plasticity; (iv) textural class determined in the field and from laboratory textural analysis; all measured and described in the same pedon. A total of 2142 and 2137 samples were found for -33 kPa and -1500 kPa water contents, respectively. Regression tree modelling was used to analyse the data. Results are presented in Figure 2.19 for the -33 kPa water contents.

The interesting thing about this work of Rawls & Pachepsky (2002) is that they are trying to include the important influence of structure and consistence on SWRC data. The results in Figure 2.19 show that they have achieved only a limited degree of success. For example although coming from very different “branches” of the tree, i.e. different kinds of structure and consistence, nodes (numbers in square brackets) No.5, No.7 and No.10 all have θ close to 26% at -33 kPa. This is also repeated elsewhere, e.g. between nodes 8, 13 and 15 with θ values of 35.5% or 35.6%. The authors conclude as follows: “... the accuracy of regression tree predictions is not high, although it might be sufficient for some applications.”

Lorentz (2001) gives a number of examples of tests he has made to ascertain the accuracy with which various procedures can predict hydraulic functions. One example is presented in Figure 2.20. The inadequacy of the procedure is clearly shown by the scatter diagram. Lorentz concludes as follows:

“These analyses reveal how difficult it is to predict hydraulic conductivities with a universal relationship, even though the air entry pressure, pore size distribution and effective porosity are used. Specific relationships may be more apt for certain classes of porous media than others, but do not appear to be applicable across a wide range of porous media as is demonstrated with this data set.”

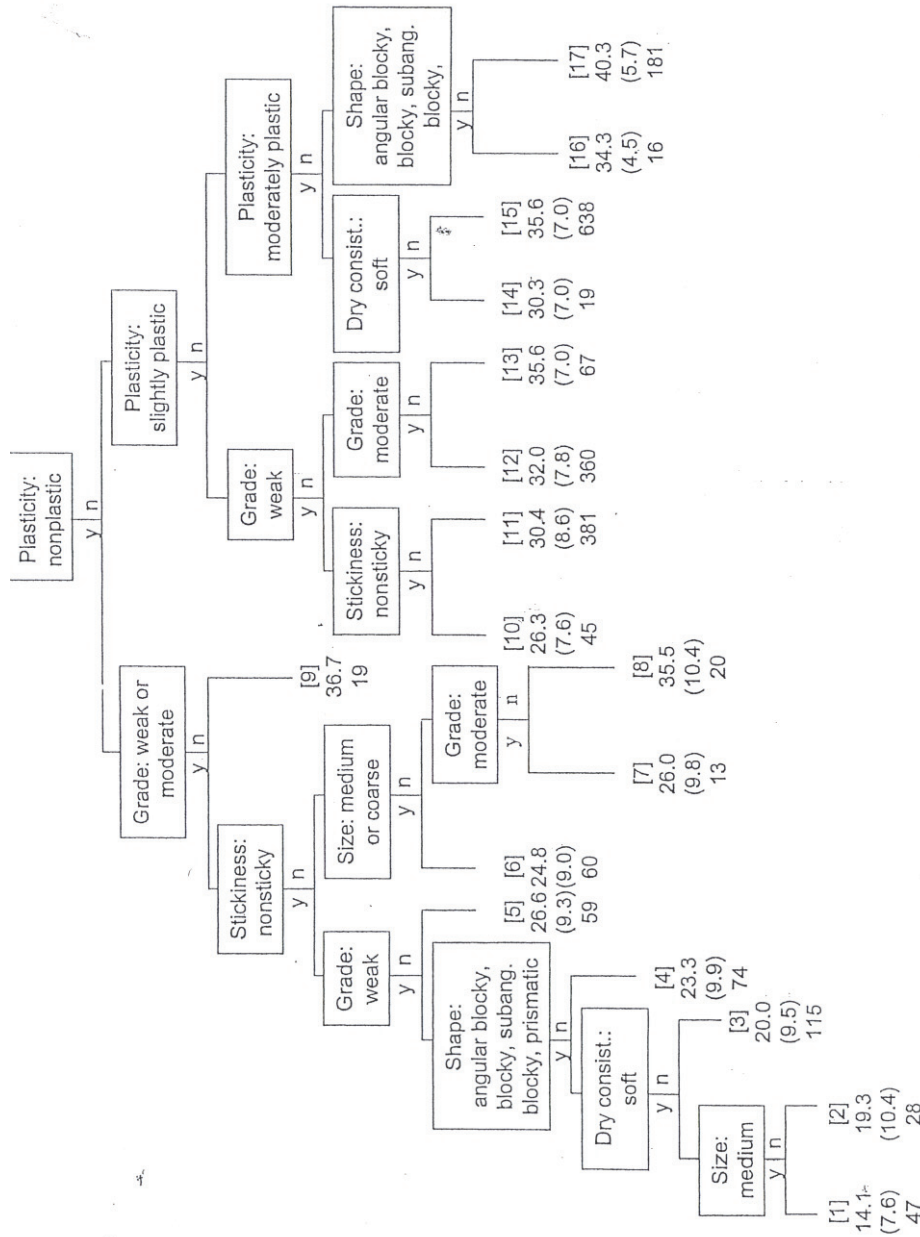


Figure 2.19 Regression tree to estimate water retention at -33 kPa from structural and consistence parameters; y, yes and n, no answers to the parameter definition in the box above. The node number in brackets, the average value of the volumetric water content at -33 kPa for the group, the standard deviation of the water content within groups in parentheses, and the count of samples in the group are shown beneath terminal nodes. (After Rawls & Pachepsky, 2002)

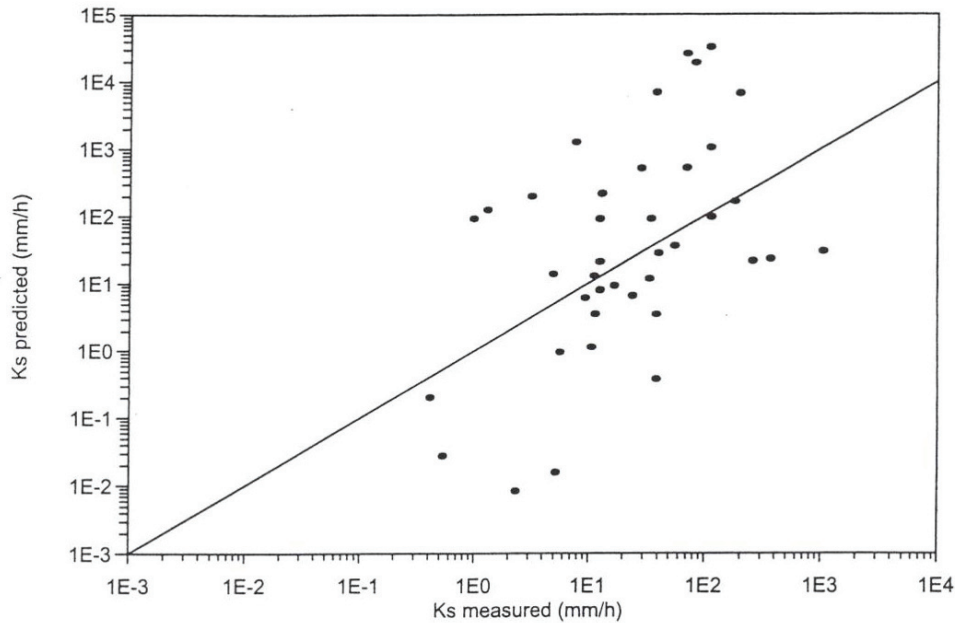


Figure 2.20 Prediction of saturated hydraulic conductivity from Campbell retention characteristic parameters using Hutson, 1983. (After Lorentz *et al.*, 2001).

Dirkson (1999) explains that the θ/h relationship, which determines the shape of the SWRC, is dependant almost entirely on the particle size distribution (PSD) and mineralogy of the soil particles at suction (h) values >100 kPa (1 Bar). For higher suctions one can therefore expect good predictions of the SWRC using PSD and mineralogy. However, this high range is relatively unimportant with regard to the processes of downward or lateral flow of water in soils which are so important for hydrological modelling. These flow processes occur mainly under natural conditions in soils at suction values between 1 and 100 kPa, and more importantly at $h < 10$ kPa (See Figure 2.21). In these important ranges, particularly the last named, it is clearly essential to only use undisturbed samples. Attempts to find correlations between PSD and the shape of the entire SWRC, as reported by a large number of researchers, therefore seem unrealistic and therefore not an avenue of research that we should attempt to follow.

Kutilek (2004b) focussing on the importance of pore geometry in soil hydrology states as follows: "Since knowledge of the soil porous system (SPS) is the basic requirement for quantification of the role of soil structure on soil hydraulic properties, I am discussing the classification of soil pores in relation to soil hydraulics and to the formulation of adequate models of the SPS. Finally, an attempt at quantification of an SPS model in hydraulic functions of a structured and a structureless soil is presented." This statement reveals deep understanding of soil hydrology and a bold attempt to solve a difficult problem. Kutilek appears to be successful in doing this for the A and B horizons of a

specific soil, a Gleyic Hapludalf. He extends results obtained by a number of other researchers using sophisticated mathematics, and identifies two domains of the soil pore system (SPS) terming them “matrix” and “structural”. Kutilek identifies two parameters α and β that are critical for the quantitative description of the SPS. The following are some of his conclusions:

- “Parameters α , β in the equation for unsaturated conductivity are different for matrix and structural domains of the soil porous system. The configuration of pores is therefore also different in the two domains.
- Parameters α , β are not identical for the specified domains of A-horizon and B-horizon. The difference of structure in horizons is reflected by the difference of parameters α , β .
- If the structure is destroyed, the bi-modal system approaches the mono-modal system and the parameters α , β change distinctly when they are compared with the original structured soil. It means that the whole configuration of pores is changed and therefore accompanied by a distinct change in the soil hydraulic functions.”

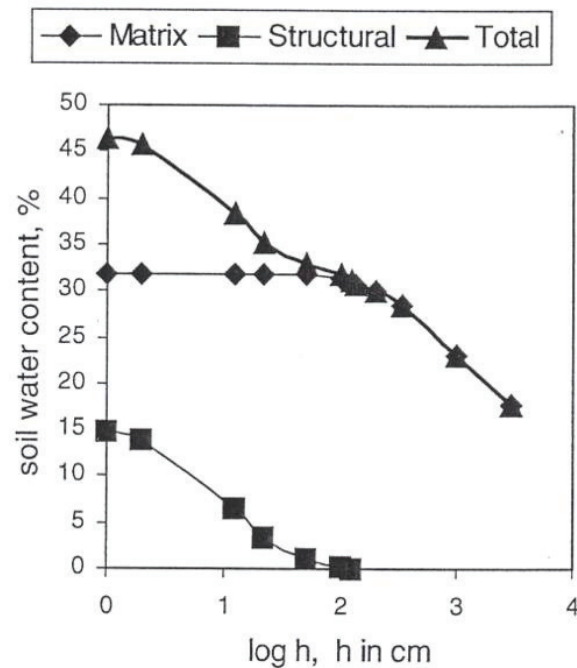


Figure 2.21 Separation of retention curves of matrix pores and of structural pores from the measured retention curve of an A-horizon, $z = 15$ cm (S15). (After Kutilek, 2004b).

The influence of the matrix pores and structured pores on the SWRC as determined by Kutilek is shown in Figure 2.21. The absence of any influence of the matrix component on θ up to a suction (h) of $\log h \text{ (cm)} = 2$ (i.e. $h = 100 \text{ cm} = 10 \text{ kPa}$) is revealing and provides strong support for the importance of using only undisturbed samples for SWRC determinations.

Insight into this important aspect of soil hydrology is reflected in the action by one of our colleagues Prof L D van Rensburg. He recently took an undisturbed soil core from the Weatherley catchment to the Hydromed Hospital in Bloemfontein for a catscan in an attempt to gain information about its pore geometry! Although only limited information was gained one valuable result was the decision that undisturbed core samples should no longer be taken using the conventional hammer action, to avoid distortion of the pore geometry. This has now been carried out wherever possible during the field work so far. The availability of the mechanical auger mounted on the bakkie has facilitated this sampling process. It will be necessary to develop additional field equipment to further facilitate this sampling process for future research work in this direction.

The procedure for quantifying the SPS by Kutilek (2004b) seems very promising and warrants further study. This is clearly a far better approach than that of attempting only to find correlations between SWRC and PSD. This is especially relevant for the all important suction range of 1 to 10 kPa, and even 10 to 100 kPa, where the SPS plays a dominant role.

In seeking relationships between relatively easily measurable parameters and hydraulic functions we must take advantage of the stratification of the whole spectrum of soil materials which our classification provides in the form of diagnostic horizons. The value of this strategy is well demonstrated by the work of Van Huyssteen *et al.* (2005) presented in Figure 2.25. Within the framework provided by each diagnostic horizon we need to identify a further level of stratification in terms of PSD and if possible also a quantitative description of the SPS as proposed by Kutilek (2004). In addition to the normal description of PSD using discreet groups of different sizes, the value of describing PSD in terms of a cumulative function, such as used effectively by Fredlund *et al.* (1995), needs to be investigated. The following statement by Kutilek (2004b) provides support for the strategy of seeking relationships between relatively easily measurable parameters and soil hydraulic functions within diagnostic horizons: "The SPS is closely related to soil macromorphology and micromorphology and through them to soil genetic processes...." Diagnostic horizons are results of soil genesis.

2.2.4 Hillslope hydrology

The identification, definition and quantification of the sources, pathways and travel times of components of flow making up stream discharge are important to capture in hydrological models. This is essential for accurate water resources prediction, for estimating impacts of climate and land use change, for predicting water quality impacts and for quantifying low flow mechanisms. It has become increasingly evident that topographic controls of water accumulation and discharge, upon which many hydrological models are based, are not as influential in these mechanisms as previously thought.

It appears that landscape organization and the combination of soil/topographic units in different sub-catchments, rather than scale alone, has the strongest influence on the hydrological characteristics of flow path partitioning and mean residence times (Rodgers, *et al.*, 2005). Landscape organization, rather than basin area, controls catchment scale dynamics. Simple topographic attributes such as median flow path length and gradient have been shown to be strongly correlated to response times at the catchment scale. This relationship allows for the regionalization of residence time and insight into process understanding at the meso-scale (McGuire *et al.*, 2006).

Just as a particular land type is composed of a particular set of ecotopes (MacVicar *et al.* 1974), so also a catchment or sub-catchment can be considered to contain a specific set of characteristic hillslopes. Hillslopes therefore become the appropriate landscape units for studying that sub-set of hydrology described by Lin *et al.* (2004) as “water movement over the landscape in relation to soil cover.” What can be described as a “generic” hillslope diagram is presented in Royappen *et al.* (2002) and shown here in Figure 2.22. The diagram attempts to depict all the different kinds of flow processes which occur in a hillslope. Note that the important process of overland flow has inadvertently been omitted! The relative importance of each of the flow processes depicted in Figure 2.22 varies widely between different hillslopes.

In any country one can expect to find a very wide range of different kinds of hillslopes. To facilitate the study of hillslope hydrology it is necessary to try to subdivide the total population of hillslopes into different classes. This is presumably one of the activities which is described by Lin *et al.* (2005) as seeking patterns. In this connection we have in South Africa an advantage in the form of the land types already delineated for the whole country (Land Type Survey Staff, 2004). Because of the way in which land types are defined each one can be expected to contain specific kinds of hillslopes somewhat different to the hillslopes in other land types. Each land type in South Africa is in fact defined in the inventory sketch by a characteristic hillslope pedosequence. It has

furthermore been shown how land types can be subdivided into more homogenous landscape units called soilscares (Tekle, 2005), each composed of a still narrower range of different kinds of hillslopes (Hensley, Le Roux, Gutter & Zerzigly, 2007). This further facilitates the task of identifying representative hillslopes for any catchment.

A number of different real hillslope diagrams are presented in Figures 2.23 and 2.24. Although there are similar processes occurring in these hillslopes and all others, the extent to which each one contributes to the outflow from the catchment, the temporal pattern of the contributions, and the quality of the water from each contribution will be different in each case. Attempting to quantify and simulate these processes in any hillslope, and consequently in the assemblage of hillslopes which form catchments, is the task of process hydrologists and hydrological modellers. The contribution which soil scientists can make is to use their skill of interpreting the morphology, depth and characteristics of the soils on the hillslopes to assist in identifying flow paths, and make a contribution towards describing the storage capacity of the soils and residence times. To do this soil surveys are essential. This is what our team has already progressed a long way towards doing at a number of different sites; three in the Bedford district, one near Cathedral Peak, one at Two Streams near Pietermaritzburg, three in the Kruger National Park. Providing this information is probably the most important contribution we can make to assist hydrologists. The mechanical auger mounted on the 4-wheel drive vehicle can facilitate this task a great deal.

With regard to the contribution which soil scientists can make towards elucidating hillslope hydrology the results reported by Royappen *et al.* (2002) are encouraging. We refer to one of the comments in their conclusion which reads as follows: "The strong associations between soil depth and profile plant available water and QFRESP and COFRU is particularly welcome, as it demonstrates that the soil characteristics derived from the national soils database by the ACRU decision support system AUTOSOILS (Pike and Schulze, 1995), are hydrologically appropriate for ACRU simulations."

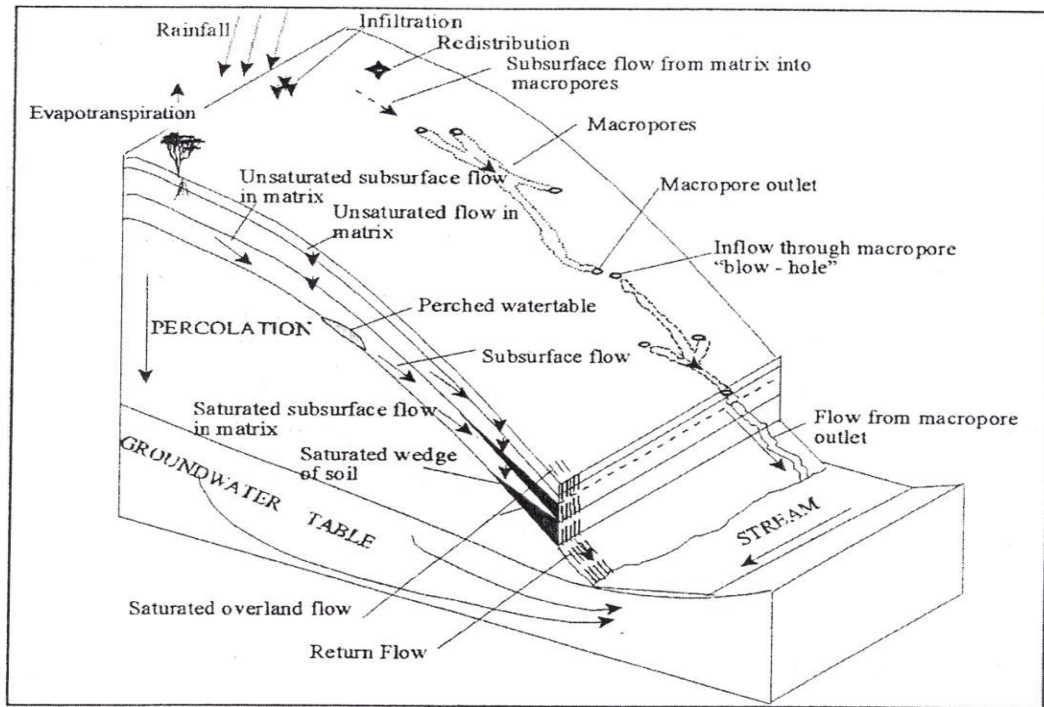


Figure 2.22 Flow routes of different hillslope processes (After Royappen *et al.*, 2002).

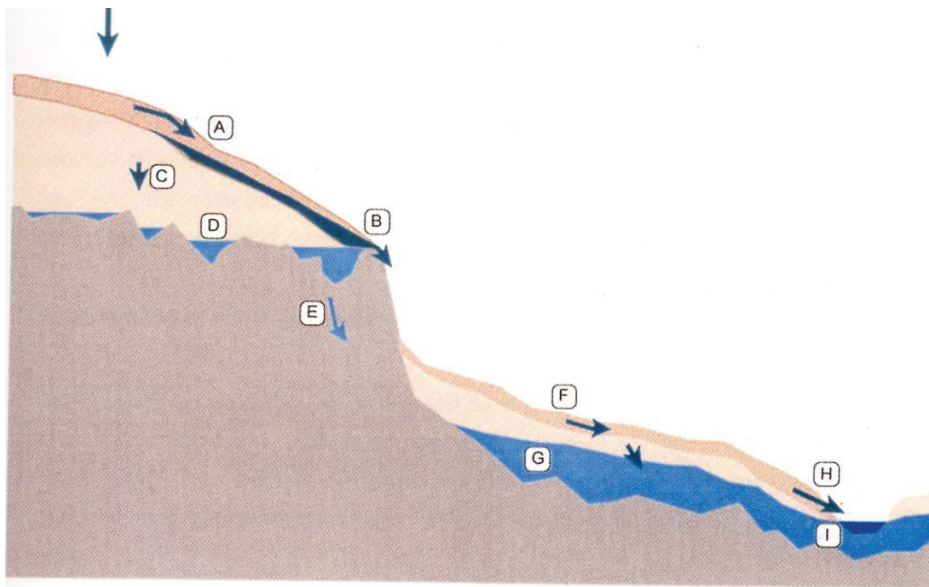


Figure 2.23 Conceptual model of flow mechanisms in the Weatherleyey research catchment (After Lorentz, 2001).

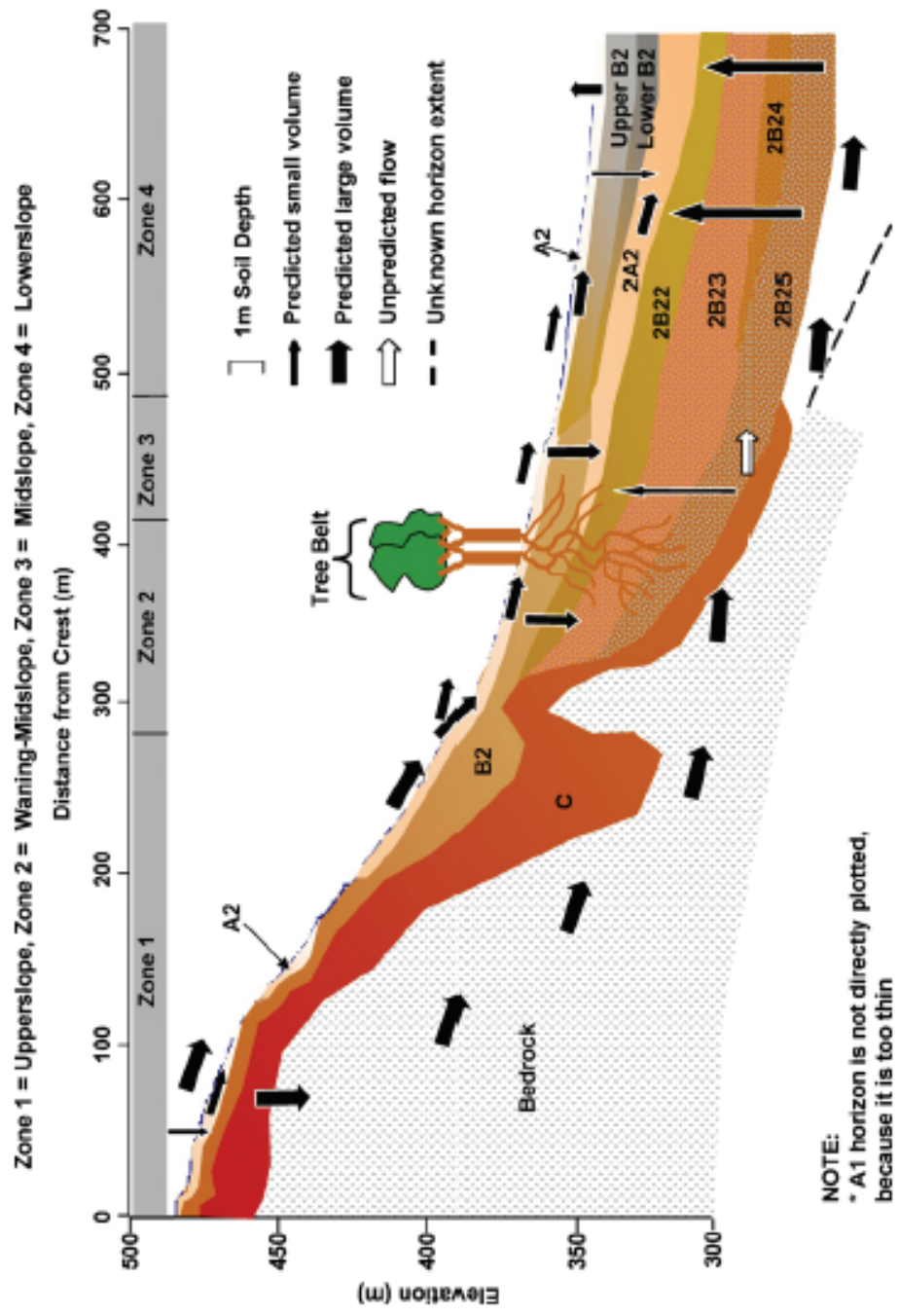


Figure 2.24 Different flowpaths on a hillslope in south eastern Australia (After Ticehurst *et al.*, 2007).

2.3 KNOWLEDGE CONTRIBUTIONS

2.3.1 Hydrology of South African soil types

The soils of South Africa can be grouped in three main types based on their hydrological response: recharge soils, interflow soils and responsive soils. Data from the Weatherleyey 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:

$$f = 1 - \rho_d/\rho_s \quad (2.8)$$

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:

$$s = V_w/V_f \quad (2.9)$$

Where: s = degree of saturation (as fraction)
 V_w = water content (mm³.mm⁻³)
 V_f = total pore volume (mm³.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 and 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 duration of events with $s>0.7$ was calculated using the sum of the $AD_{s>0.7}$ events during a particular year divided by the frequency of events during that year (Van Huyssteen *et al.*, 2005):

$$D_{s>0.7} = AD_{s>0.7}/F_{s>0.7} \quad (2.10)$$

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)

2.3.1.1 Recharge soils

Several soils in the Weatherleyey 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 2.25) 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.

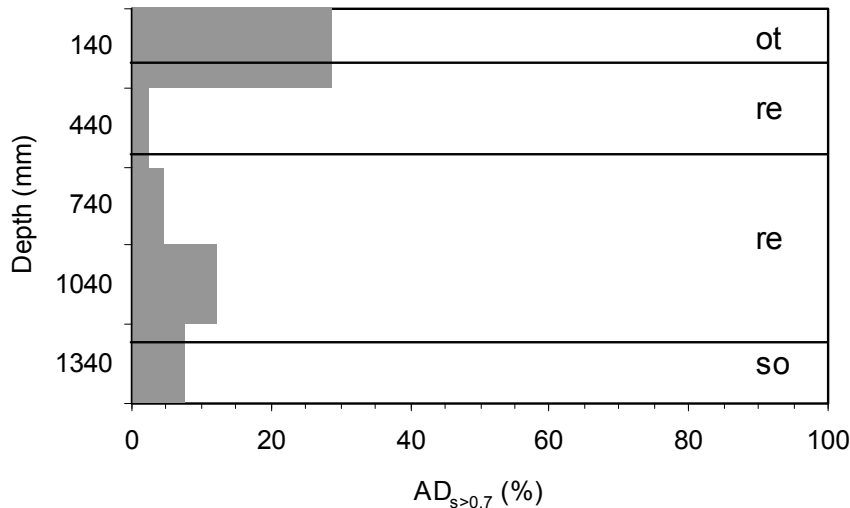


Figure 2.25 Mean $AD_{s>0.7}$ (%) values in a typical recharge soil. P221, Hutton 2100, Weatherleyey (after Van Huyssteen *et al.*, 2005).

Thus, in recharge soils, the dominant flow direction is vertical (Figure 2.26). These soils typically occur on crest and midslope 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 2.26).

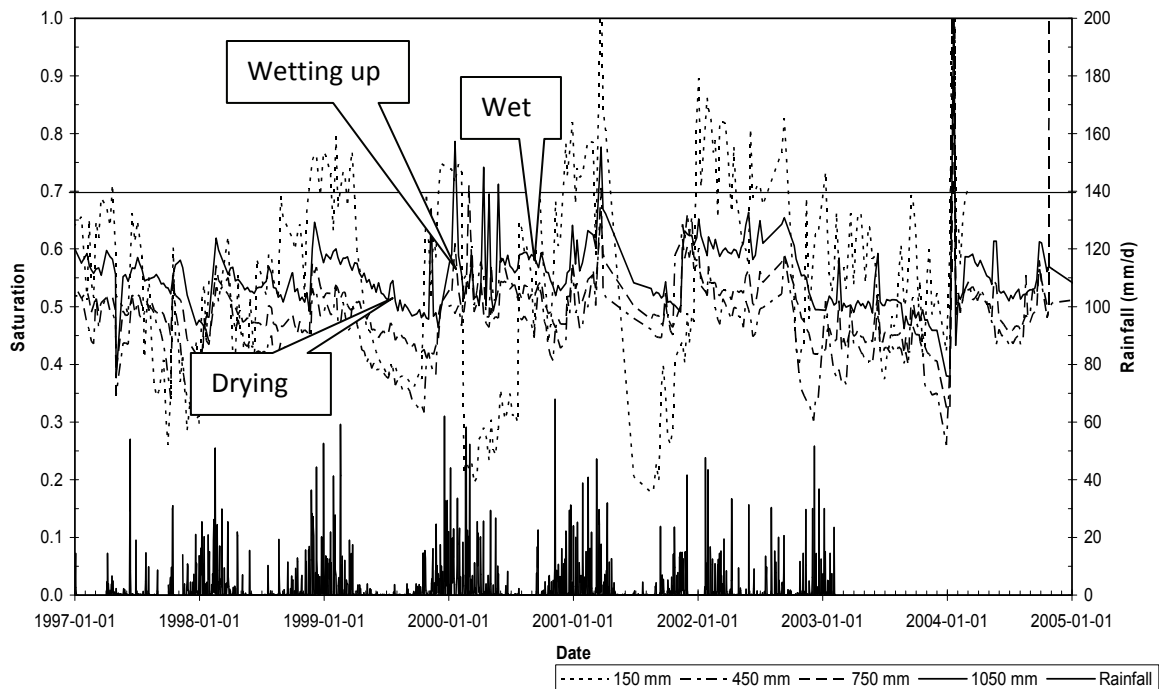


Figure 2.26 Degree of saturation vs. rainfall over 8 years of a recharge soil, P221, in the Weatherleyey catchment (after Van Huyssteen *et al.*, 2005).

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 Weatherleyey 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 Weatherleyey 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.

2.3.1.2 Interflow soils

Several soils of the Weatherleyey 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 2.27). Conditions of water contents near saturation (i.e. drainable water) occur in all horizons but typically increase with depth. The contribution of precipitation draining vertically through the soil after the rain on 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 juxtapositional higher lying fractured rock.

Interflow soils are associated with subsurface lateral flowpaths. 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.

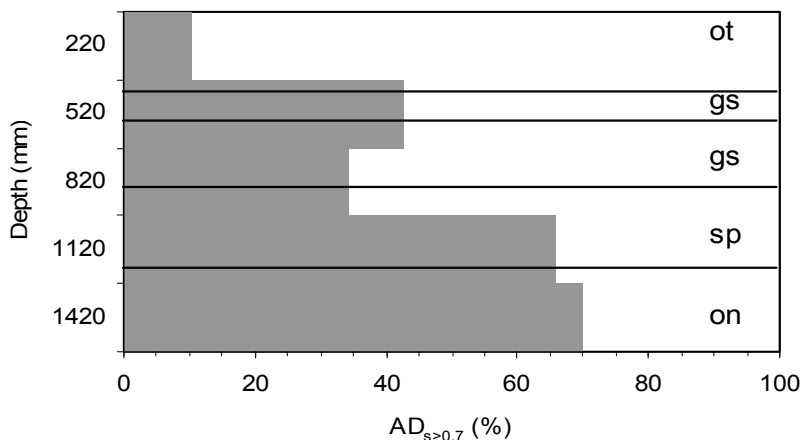


Figure 2.27 Mean $AD_{s>0.7}$ (%) values in a typical interflow soil P225, Longlands 1000, Weatherleyey (Van Huyssteen *et al.*, 2005).

Interflow soils have a distinctive drainage phase additional to the wetting up, wet and draining phase. The duration of $AD_{s>0.7}$ in the soft plinthic horizon of 8 months (Figure 2.27) is an indication that this soil body 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 Weatherleyey. The end August limit of interflow conditions coincides with the duration of interflow as predicted by the subsoil routine of ACRU (Lorentz *et al.*, 2007).

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.

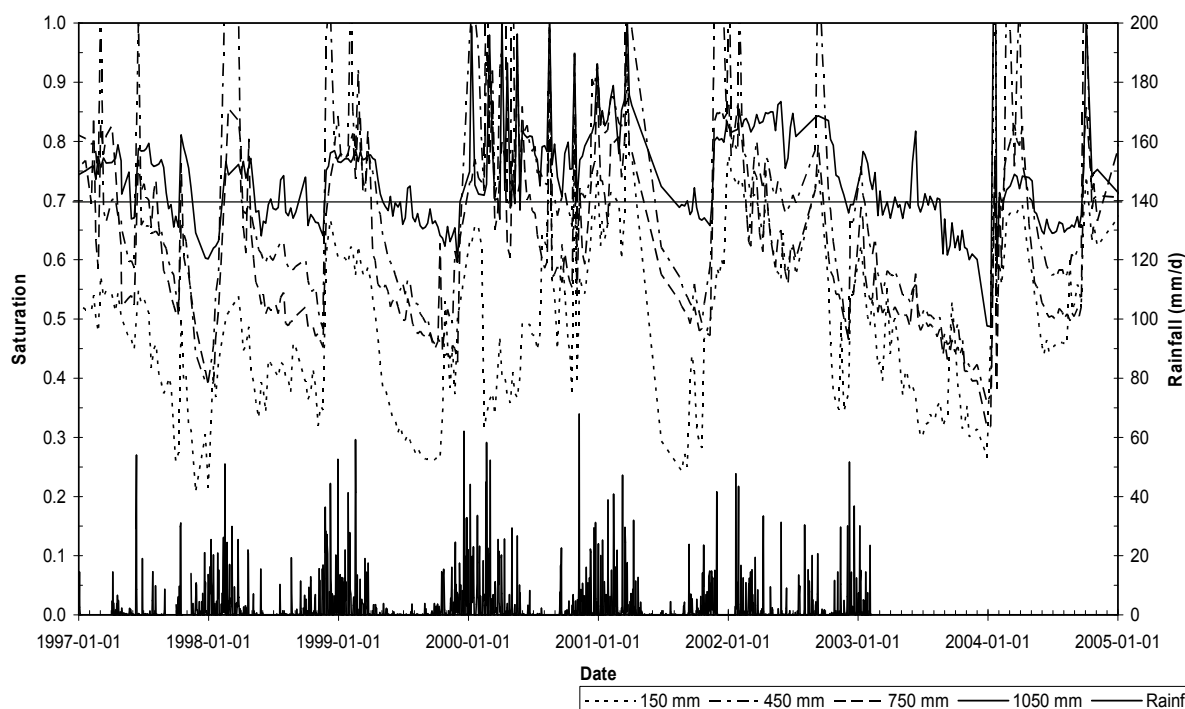


Figure 2.28 Degree of saturation vs. rainfall over 8 years of an interflow soil, P225, in the Weatherleyey catchment (after Van Huyssteen *et al.*, 2005).

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 are: Longlands, Wasbank, Estcourt, Klappmuts, Cartref, Westleigh, Avalon.

2.3.1.3 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 Weatherleyey catchment qualify as saturation excess responsive soils. These soils normally have perennial groundwater. These soils are at or near saturation for long periods (Figure 2.29), resulting in conditions called saturation excess overland flow in the rain season.

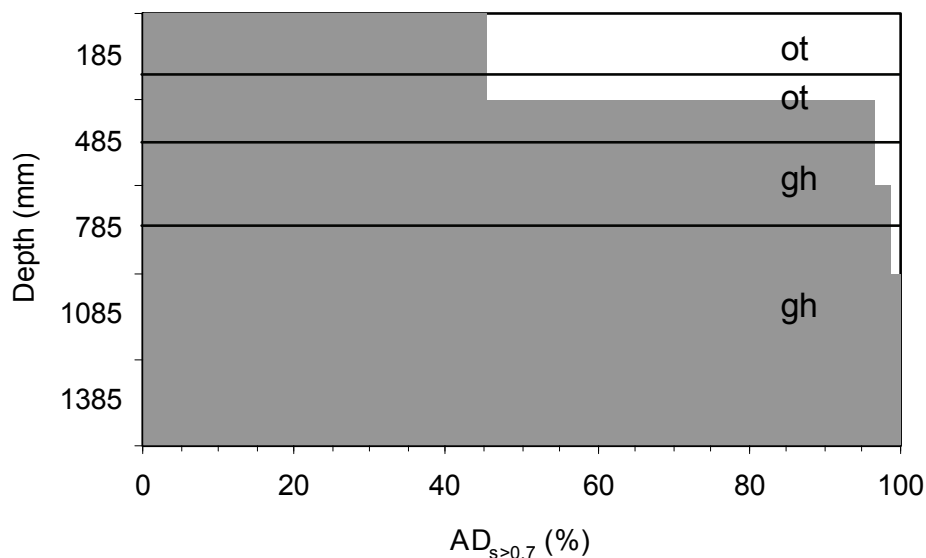


Figure 2.29 Mean $AD_{s>0.7}$ (%) values in a typical responsive soil P235, Katspruit 1000, Weatherleyey (Van Huyssteen *et al.*, 2005).

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 2.30). 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.

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.

The soils of the Weatherleyey catchment were divided into the different hydrological soil types (Chapter 5). 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).

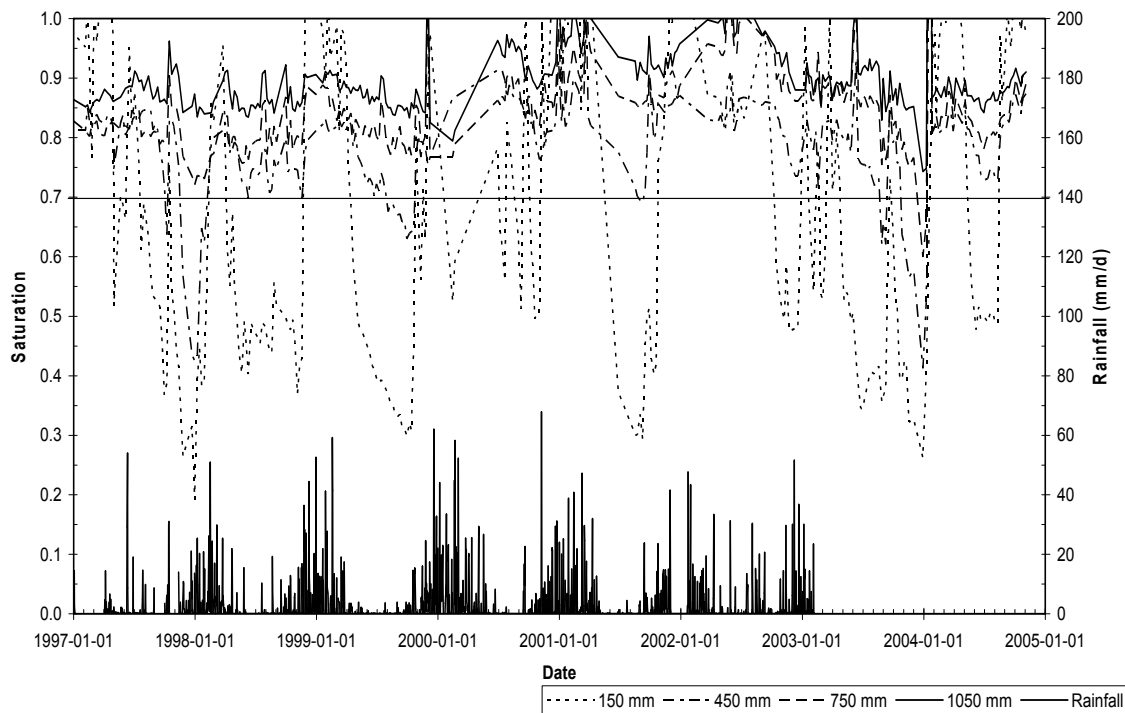


Figure 2.30 Degree of saturation vs. rainfall over 8 years of a responsive soil, P235, in the Weatherleyey catchment (after Van Huyssteen *et al.*, 2005).

2.3.2 Water storage at hillslope scale

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). Their behaviour is predictable and therefore of value in the description of hillslope behaviour. Table 2.5 summarize some of the key attributes of the various storage areas.

Table 2.5 Differences between transient and perennial groundwater

Transient groundwater	Nature	Perennial groundwater
Occurs only in the solum. The position in the solum may vary.	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	Releases water to the regional water table and to G horizons and generally wetland soils. Releases water to atypical Kroonstad soils with diffuse E/G boundaries.
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 it 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.

Forms 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 moves by near surface macro pore flow.	Permeability	Vertical permeability high in the soil and saprolite. It only reduces in cracks with depth. The water moves in cracks deep in the soil.
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.
Receives 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 extent 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 to, and affected by rain events but to a lesser extent.	Response type	Respond like a big bucket with steady state conditions and barely changes with rain events and wetter and drier seasons.

2.3.3 Summary

Hydropedology has been defined to bridge knowledge gaps between pedology, soil physics and hydrology, to bridge scales and to transform soil survey data into soil hydraulic information. Hydropedology could therefore contribute to the understanding of environmental, ecological, agricultural, and natural resource issues, including water quality and soil quality, landscape processes and management, nutrient cycling, contaminant movement, waste disposal, precision agriculture, climate change and ecosystem functions.

Pedotransfer functions relate simple soil characteristics often found in soil surveys to more complex parameters that are relatively difficult to measure. Examples include the estimation of soil hydraulic properties, such as hydraulic conductivity at zero potential and water flow rates in macro, meso, and micro pores, from soil morphological features such as texture, initial moisture state, pedality, macro porosity, and root density, usually available from soil surveys.

Hydrology of soil types (HOST), published by the Institute of Hydrology in the United Kingdom classifies soils to aid hydrological studies and analyses, based on three conceptual models of water flow processes taking place within the soil: (a) soil on a permeable substrate with a deep aquifer (>2 m); (b) soil on permeable substrate with a shallow water table (<2 m); and (c) soil (or soil and substrate) with an impermeable or semi permeable layer within 1 m of the surface. The three conceptual models are then further subdivided, based on different soil properties, into 11 models. The 11 models are, in turn, subdivided into 29 HOST classes, based on other properties or geology.

Temporal stability of spatially measured soil water contents, defined as the time invariant average of spatially measured soil water contents, offers a valuable new method to study the relationship between soil and water. Application of temporal stability has been used to reduce the number of measurements needed in catchment characterization and therefore offers a valuable tool in monitoring site selection.

Understanding the redox reactions that take place in soil provides insight into the development of redoximorphic colour patterns. These colour patterns are manifested as redox depletions and/or redox accumulations. The former are evident as grey matrices, cutans, mottles, or pore linings, while the latter are evident as masses, pore linings, nodules, or concretions.

Hydropedology fills an important niche in the study of the earth's critical zone, defined to include the atmosphere, biosphere, pedosphere, and lithosphere (NRC, 2001), with the pedosphere providing the interface between these.

The aim of this section has been to try to identify those hydropedological issues with regard to which we can make the most useful contributions to hydrologists. The following are our conclusions in this regard:

- The provision of the soils data needed for the parameters QFRESP and COFRU used in ACRU, and the equivalents used in other hydrological models, e.g. the "groundwater recharge and discharge functions" described by Hughes (2004).
- Expansion of the study of soil morphological features in a range of catchments, in particular those within diagnostic horizons, as signatures of soil hydrology. In addition to expansion to other catchments, more in-depth studies are needed to make this information more useful to hydrologists.

- We need to attempt to find an efficient way to predict the hydraulic conductivity to water content ($K\theta$) relationship for meaningful subdivisions of diagnostic horizons using measurements that are relatively easy to make. Soil water retention curves (SWRC) are important in this respect. A routine procedure is therefore needed that gives reliable SWRC, especially in the suction range 1-100 kPa and particularly in the range 1-10 kPa, using undisturbed core samples. In this connection a most valuable contribution would be quantification of the soil porous system for meaningful subdivisions of diagnostic horizons – as described by Kutilek (2004b).

Probably the most valuable contribution we can immediately make is the provision of soil/hillslope survey results for a range of catchments/hillslopes with different characteristics. We are well equipped to do this and our expertise in this connection is growing rapidly. Close cooperation with scientists like Prof Lorentz, Prof. Hughes, Dr Everson and others is extremely valuable in this regard.

Chapter 3 **ADVANCED SOIL SURVEY TECHNIQUES FOR HYDROPEDOLOGY**

3.1 BACKGROUND AND MOTIVATION

3.1.1 Soil survey and soil classification

Soil maps have always been part of soil science. To describe the existence of different soils in landscapes they need to be mapped. However, the methodology for doing this did not change much during the 20th century. The major change was that traditional geographical field maps were replaced with more detailed larger scale maps with increased accuracy and therefore continuously exposing more surface features. Ground truthing has always remained a problem.

The South African soil taxonomy (Soil Classification Working Group, 1991), similar to other soil classification systems of other countries, was developed to suite the local soils. This is in contrast to the USDA Soil Taxonomy (Soil Survey Staff, 1999) and the WRB (FAO, 2009) which aim to cover the world's soils. South African climates range from dry arid to humid. This, combined with a wide variety of lithologies and terrain forms, has resulted in a need for the accommodation of a variety of soils in the classification system.

Vast fluctuations in the water regime of South African soils are common. Although natural vegetation has adapted to these conditions cultivated crops are negatively influenced by variable soil water regimes. The thorough implementation of criteria that distinguish between soils with different soil water regimes is expressed in the South African soil taxonomy (van Huyssteen, 2005). These soil properties and their implementation in soil classification in South Africa have turned out to be very useful in hydro pedology.

Some important properties that serve as indicators of soil hydrology tend to be neglected in agricultural soil surveys. Depth criteria of 1 200 mm (MacVicar *et al.*, 1977) and 1 500 mm (Soil Classification Working Group, 1991) are used in the South African system. These criteria interfere with the logical application of diagnostic criteria and often prevent the holistic classification of soils. They are also commonly neglected as criteria for soils considered not suitable for crop production. An example is the presence of mottles qualifying as signs of wetness in the saprolite of Swartland soils. There are good reasons to include these criteria in soil classification systems as they guide the agricultural soil surveyor. However, for hydro pedological soil surveys the observations noted during the survey have to be adapted to

suite the goal. This is not a new issue in soil surveying as the rules commonly need to be adapted to suite the goal. In agriculture this means that adaptations are needed for crops like Pecan nuts with roots that extend beyond 5 m.

3.1.2 Soil distribution patterns

Grid survey methodology as practiced in agricultural surveys assumes that soil is distributed randomly in the landscape. All experienced soil surveyors know that this is not true. On local scales soils are largely related to elements of topography. Of the generally acknowledged five factors of soil formation (Jenny, 1941) time is generally quite homogeneous in the landscape and locally any difference in soil age is related to topography. Young soils are found on the depositional terrain morphological units (TMUs). Soil material is typically deposited by colluviation on steep slopes occurring on TMU3 and by alluviation on TMU5. Mature soils are typically found on stable slopes. The age of soils on TMU 1 may also vary resulting in different soil types. However, the shape of the TMU has a large influence. Flat crests typically have mature soils in the centre and young soils on the edges, and convex-convex shaped TMU 1 positions have shallow young soils.

Climate has similar relationships to those of time. Local variation in climate is related to the impact of the topographical elements of, aspect, TMU, slope and distance from the valley bottom. The temperature in turn impacts on the pedogenetic effectiveness of rainfall and therefore on soil formation.

The impact of parent material on soil properties is determined by its chemical composition and physical hardness. Locally the latter controls the topography as soft rocks form the valleys and hard rocks the ridges. Parent material also plays a role in causing catenas to be repeated, for example determining where shelves are formed. Parent material therefore influences topography.

Although the impact of the biological factor on soil formation is usually very small in South Africa the impact of soil properties on biological diversity is considerable and well known to soil surveyors. The impact of all three factors of soil formation named above on local soil distribution results in soil and environmental properties affecting the biological species composition occurring in different topographical positions. The overall implication is that topography has a strong influence on soil distribution patterns in the landscape.

Topography refers to the outline of the earth's surface (FitzPatrick, 1980). It modifies the distribution of water (Moore, *et al.*, 1993), and gives rise to local differences in soil water regime (Duchaufour, 1998). It affects erosion, colluviation, and illuviation patterns, and results in aspects that can have an effect on the microclimate (Fanning & Fanning, 1989). Topography influences pedogenetic processes by its effect on: particle stability (Beckett, 1968; Parsons,

1978); drainage and the amount of moisture in the soil (FitzPatrick, 1986); surface and subsurface water flow, and erosion and deposition distributions in the landscape (Conacher & Dalrymple, 1977; Daniels & Hammer, 1992; Gerard, 1992; Lark 1999); the redistribution of sediments, solutes and the distribution of various organic fractions over a landscape (Chen & Chiu, 2000); the status of organic matter in the soil profile (Raghubanshi, 1992). These influences generally cause soils to vary continuously downslope, while they tend to remain similar along contour lines (Duchaufour, 1998).

The close relationship between soil distribution and topography is further enhanced by the two-way interaction between soil as the upper vadose zone and the fractured rock as lower vadose zone. This interaction of soils with fractured rock as described above implies that hillslope hydrology plays such an important role in soil genesis that it should be recognised as a sixth factor of soil formation.

The hillslope is generally accepted as a fundamental landscape unit (Weiler *et al.*, 2004; Lin *et al.*, 2006). It exhibits a common form of organisation and symmetry. The interaction between topography, soils, climate and vegetation results in patterns or laws which contain valuable information on the way they function (Sivapalan, 2003a). The hillslope is therefore an important building block for understanding and simulating hydrological processes (Tromp – van Meerveld & Weiler, 2008). How catchments respond is determined by the particular mix of different hillslopes (shapes and sizes) in the particular catchment (Sivapalan, 2003b) (a detailed description of hillslopes and their influence on hydrology is given in chapter 2). Because of these observations it is not surprising that the hillslope forms the backbone for a number of hydrological models.

The result of the interaction of the factors of soil formation with the soil distribution pattern in the landscape dictates that characterising hillslopes hold the key to advanced soil surveys for hydrological purposes.

3.1.3 Land types

A land type, as defined by Van der Watt and Van Rooyen (1995) is "A class of land with specified characteristics used in South Africa as a map unit denoting land, mappable at 1:250 000 scale, over which there is a marked uniformity of climate, terrain form, and soil pattern." The aim of the land type survey in South Africa was to make a systematic inventory of the natural agricultural resources of the country (Land Type Survey Staff, 2000).

The survey was carried out in the following manner: each land area, covered by a 1:250 000 map, was surveyed in a stepwise fashion on each of its component 1:50 000 maps. First, areas displaying a marked uniformity of terrain form (called terrain types) were delineated on 1:50 000 topo-cadastral maps. Where available, satellite imagery was used to facilitate the task. The

major soils in each terrain type were identified by traversing each terrain type, augering and observing exposures such as road cuttings and digging occasional soil pits. From this information areas displaying a uniform terrain and soil pattern (called pedosystems) were delineated. Modal profiles of the main soils were described and sampled for detailed analysis. Next, a separate map showing the distribution of climate zones was drawn based on data from available climate stations, natural vegetation, soils, crop performance, altitude and topography. The climate map was superimposed upon the pedosystem map to produce a land type map, where each land type displays a marked uniformity in terms of terrain form, soil pattern, and climate. The boundaries of the land types were transferred from the 1:50 000 to 1:250 000 maps. Finally, an inventory of each land type was compiled to describe the terrain, soil and climate (Land Type Survey Staff, 2000).

The land type data is available in the form of paper copy maps and memoirs as well as in GIS format. It includes the following:

- Delineations of land types at a scale of 1:250 000.
- Descriptions (called inventories) of the terrain and soil pattern in each terrain unit. (Detailed description of Figure 3.1)
- Detailed soil profile descriptions and detailed soil analyses of representative soil profiles (called modal profiles).
- Detailed descriptions of the climate of each land type.

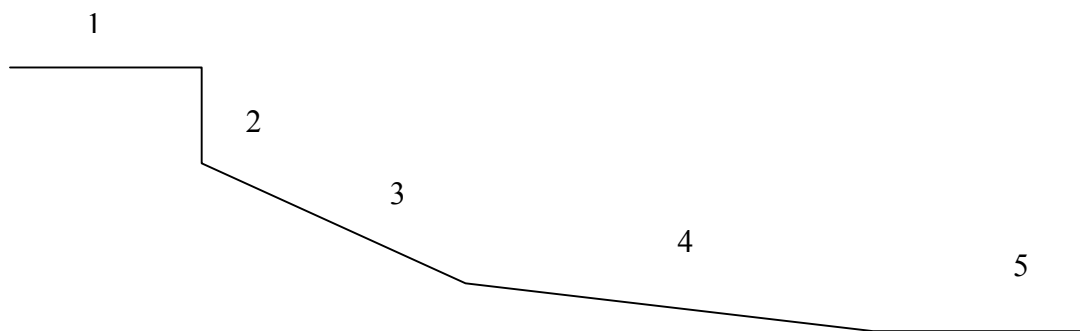


Figure 3.1 Terrain morphological units (TMUs) 1 = crest, 2 = scarp, 3 = midslope, 4 = footslope, 5 = valley bottom (Soil Classification Working Group, 1991)

With regard to developing advanced soil survey techniques for hydropedology it is of primary importance to note that each land type in South Africa is described in terms of a characteristic hillslope (Figure 3.1).

3.1.4 Tacit knowledge

Two statements by Ahrens *et al.* (2002) summarise the importance of the concept of tacit knowledge to soil surveying: Firstly, *'Perhaps the greatest modern breakthrough in soil classification is the recognition that soil-forming processes frequently leave markers in the form of diagnostic horizons and features. The diagnostic horizons and features can be defined in terms of observable and measurable properties. Concepts and models of soil genesis have guided the selection of soil classification criteria. Soil genetics is important as it plays a major role in soil mapping because it helps us to develop our predictive model of soil-landscape segments that can be delineated on usable soil maps with viable interpretations.'* Secondly, *'Soil classification systems provide soil scientists with a system to communicate their findings.'* It is this pedotransfer ability to the community of natural scientists that is exploited in developing advanced soil survey techniques for hydropedology.

Tacit or intuitive knowledge of the soil surveyor governs the delineation of soil units. Soil surveyors soon find a system of knowledge taking form when surveying. This tacit knowledge is qualitative and gained by experience; the rationale behind the decisions cannot be stated (Hudson, 1992). Tacit knowledge is an accepted method of soil mapping (Sinowski, & Auerswald, 1999). Long-term research knowledge has confirmed the validity of such tacit knowledge. For example In the case of the Land Systems of Western New South Wales, they implemented numerical factors of expression for information contained in the map unit descriptions: relief category, percent area occupied by each facet, and dominant soil type in each facet. They noticed that it is only by devising such strategies (which might combine models, indices, expert knowledge, and/or direct measurement) that they would be able to manage the soil resource to achieve desired ends (Wander, *et al.*, 2002). This procedure was also used in the international SOTER differentiating criteria, where mandatory data are missing; the SOTER database will accept expert estimates for these values if flagged as such in the database (ISRIC, 1993).

Zhu & Band (1994) developed a knowledge based approach to data integration for soil mapping. In their model they used the famous formula of Jenny, i.e. $S = f(E)$, where S represents soil formation, E is the vector of environmental conditions and f reflects the relationship between soils and the formative environment. The value of f is approximated using the empirical knowledge of local experts who have studied the phenomenon and its distribution and its environmental conditions.

3.2 SOILSCAPES, HILLSLOPES AND HYDROLOGICAL RESPONSE UNITS

3.2.1 Building tacit knowledge

The first step in hydrogeological soil surveying is to build tacit knowledge. As land type data is available for the whole of South Africa that information is of basic importance for any hydrogeological survey, irrespective of scale. Land type data indicates what soils can be expected and where they can be found in the landscape. An example of the contribution that land type data can make to the tacit knowledge of the surveyor is where both Swartland and Estcourt soil forms are recorded on the TMU3 position. The implication is that the Swartland soils probably occur on the convex-convex slopes while the soils of the Estcourt form rather occur on the concave-concave slopes.

Small scale maps lack the relationship with terrain and usually need to be digitised and georeferenced and overlayed on a binary file of an aerial image and DEM before the soil distribution can be analysed. This needs no field work and contributes tremendously to the quality of knowledge of the surveyor.

A field visit to the area is a good investment in the first stage. A few observations on selected terrain positions and shapes will enhance ones knowledge of soil distribution in the landscape and their association with terrain features.

3.2.2 Terrain analysis and scale

The second step in hydrological soil mapping is to consider the relationship between terrain analysis and scale. This feature is part of soil surveys at a variety of scales. At all levels of land survey some degree of uniformity in terrain or topography is expressed (Table 3.1). Smaller units of land are expected to be more homogeneous in terms of the other factors of soil formation, and therefore also in soil distribution pattern and soils.

The terrain features used in defining land types, namely dominant slope gradient and relief, are also used as criteria by SOTER at the highest level. Included in the terrain type is the associated influence of geology (hardness, permeability, layering, dykes) and the result of interaction of the lower vadose zone (fractured rock hydrology) with hydrogeology. This controls subsoil wetness and to a lesser extend mid-soil and topsoil wetness in and out of the rainy season. The presence of subsoil clay layers also impacts on both soil type, soil hydrology, geohydrology and yield potential.

In the hillslope the source of variation in climate is linked to TMU and impacts more on land suitability, which is not relevant here, than on soil distribution. The soil component of the HRU may be more than one soil but they are similar in hydrological response.

Table 3.1 Relationship between the terrain, climate and soil variation in different land units

Land unit Land element	Land type	Soilscape	Hillslope	HRU
Terrain	Terrain type: Dominant slope gradient & relief intensity.	Streams and divides Slope gradient	Slope shape (profile & planform curvature) Aspect (relief & altitude)	Slope Aspect (relief & altitude)
Climate	Macro	Meso	Meso to field	Field
Soil	Distribution pattern	Limited variation in distribution pattern dependant on the characteristics of the particular land type	Toposequence	Soil series

3.2.3 Demarcation of soilscales

The third step is the improvement of existing data. Land type data and its associated uniformity are limited by scale and the methodology that was available at the time of the survey. It therefore contains variation that can be improved using terrain analysis. The terrain parameters slope gradient and elevation parameters are the most important terrain features that should be considered but more parameters should always be tested.

Current knowledge shows that the delineation of soilscales effectively accommodates this improvement in homogeneity in terrain and associated soil distribution. Soilscales can be demarcated at a scale of 1:50 000 (Hensley *et al.*, 2007). Dominant streams are preferably used for delineation of the lower and side boundaries of soilscales. The headwater's hillslopes of the soilscape can be delineated using the divide. Where soilscales have steep slopes and high relief the catchment divide should be used as a border.

Different genetic factors prove to be dominant in the definition of soilscales. If the nature of the *parent material* is the dominant factor, there is a lithosequence of gentle slopes cutting across contrasted stratigraphic units with variable substrate depth. If *relief* dominates there is a toposequence due to a transfer of products (suspended or dissolved) from upstream to downstream. If the influence of *water tables dominate*, a hydrosequence is present. If *time* dominates there is a chronosequence, *e.g.* progressive soil differentiation of different materials of geomorphological origin forming relief units such as a succession of terraces. Different qualifiers may however be applied to the same soilscape. The most frequent sequences that are

closely linked to the dominance of one genetic factor seem to be topographical and lithological sequences (Jamagne & King, 2003).

A fundamental requirement is that the map scale must accommodate legible delineations of the smallest size map units. From a cartographic viewpoint, delineated polygons at 1:250,000, should be consistent with field areas of at least 1.5 km². Since soilscape are mapping units, one soilscape may be presented by more than one polygon (Finke & Montanarella, 1999).

Terrain components are mappable on soilscape maps and therefore also soil associations as defined by the land type inventory. However, because of variation in relief, the interpretation of slope gradient and slope shape is limited in soilscape mapping. Soil associations can be described with more accuracy with a little fieldwork. The benefit of applying the tacit knowledge of the surveyor who did the original work can be significant. The importance of local tacit knowledge can also not be overaccentuated.

Dissection (stream density) and slope length are examples of terrain elements that are not specified on any level but may be used to distinguish between land types, soilscape or hillslopes combined with slope gradient.

Experience shows that topographical variation accommodated in land type demarcation allows for subdivision of land types into several classes of soilscape in a land type. The classification of soilscape into different groups depends to some extent to the objective of the survey.

3.2.4 Identification of modal hillslopes

The fourth step is the demarcation of hillslopes with similar topographical morphology. Modal hillslopes are identified using profile and planform slope shapes. This can be done using topographical maps at a scale of 1:50 000 by analysing the contours. Contours that are closer indicate steeper slopes, and their relationship with neighbouring slopes indicates a concave, straight or convex profile shape. Bent contours indicate converging or diverging planform shapes. A terrain analysis computer model improves one's ability to identify the slope shapes shown in Figure 3.2.

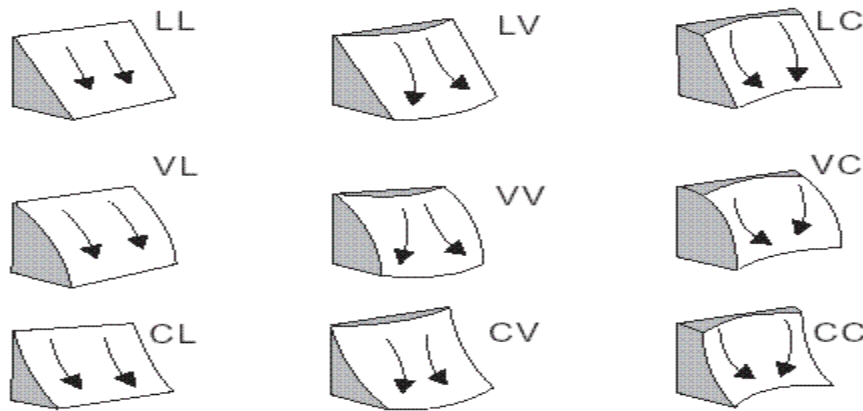


Figure 3.2 Slope shape is described in two directions: The first and second letters describe the downslope and lateral or contour patterns respectively. Adapted from Wysocki *et al.* (2000).

3.2.5 Transect survey

The fifth step is a transect survey. This technique is not new and is effectively communicated in land type data. Transects are made on selected hillslopes starting with observations at close distances (<20 m). The distance is enlarged as the survey progresses. The rate of increase depends on the basic level of knowledge and the rate of increase in tacit knowledge. Whereas the first observation is made with limited information, the each subsequent one adds to the knowledge of the surveyor. The knowledge system is therefore upgraded with each new observation. The improvement in the level of knowledge is not quantifiable and the surveyor is often poorly equipped to describe the contributing factors controlling the formation of the soils. The focus is often rather on surface properties that coincide with soil properties. Although all assistance should be used to improve the prediction ability, the focus should rather be on factors controlling soil formation than on co-variables that cannot be seen in terrain analysis. Typical co-variables are soil colour, vegetation, rockiness, etc. Useful associated terrain features are slope gradient, changes in slope gradient, TMU, repeating TMU, shelving, terrain shape (profile slope shape, plan form slope shape), aspect, etc.

Soil observations for hydropedological surveys differ from those for agricultural surveys with regard to the following:

- Soil depth: Observations are made to refusal wherever possible. Flow paths on the soil/rock interface can only be detected at refusal.
- Observation quality: To a depth of about 2 m best results are obtained from very detailed soil profile descriptions in soil pits. It will however generally be necessary to rely mainly on augered observations, in which case the soil features are recorded as well as possible from the soil core/auger mix exposure.

- Hydrological indicators: All soil properties associated with hydropedology are carefully recorded (mottles – all colours; colour; lime; interpedal macropores and other macropores, including the kinds of coatings on these pores; kind of structure and degree of development).

Profile descriptions and analysis of representative soils in the hillslopes forms an important part of the survey as the soil profile descriptions are considered to be the most important pedo transfer functions available.

There is a need to improve the efficiency of soil profile descriptions, particularly those aspects related to soil hydrology; the inclusion of colour photographs of modal profiles is strongly recommended. The identification and description of different terrain types associated with different hydrological characteristics could also make a valuable contribution to hydropedological soil surveys.

3.2.6 Interpolation and extrapolation

The knowledge gained in the survey process can be used to interpolate and extrapolate the observation data to develop the soil map. The degree of extrapolation depends on the scale and the accuracy of the DEM. DEM data on a 90 m grid scale is generally available for the whole world. It works well for soilscape and hillslope delineation but more detailed DEM data are needed for large scale soil surveys.

As the surveyor goes through this survey process, terrains with similar characteristics are exposed. Areas can now be delineated on which similar soils can be expected. The main benefit is the identification of similar soils rather than similar soil forms or families. It must be kept in mind here that this is a value adding step for improving the survey. Extrapolation is not just a money saving step or a replacement for field data collection. It is an effective way of extrapolating soil data, especially hydropedological data, to areas between and outside observation points, with the objective of improving the degree of accuracy. This enhances the soil survey map, making it useful for application in hydrological modelling.

Chapter 4 **IMPACT OF LAND-USE CHANGE ON SOIL WATER REGIME IN THE WEATHERLEYEY CATCHMENT**

4.1 Introduction

Motivations for the hydrological and hydropedological research in the Weatherleyey catchment, and the characteristics of the catchment, are described in detail in numerous WRC reports and other publications and will therefore not be repeated here. The original main overall long-term objective of the Weatherleyey project was to compare, over a number of years, the hydrology of the catchment under its natural grassland vegetation with that under afforestation, and in the process improve hydrological models. Detailed hydrological aspects for the six year period 1/7/1997 to 30/6/2003 are presented in van Huyssteen *et al.* (2005). The objective of the present study is to augment the previous soil water measurements with those made during the following years up to the end of 2008.

Three species of afforestation trees were planted on carefully selected separate portions of the catchment in September 2002. Special soil area selections were made by forestry experts. Details of the soils on which the different species were planted are presented in van Huyssteen *et al.* (2005). The location of these areas is shown in Figure 4.1, together with the location of soil profiles and water content measuring sites.

In relation to hillslope hydrology the contribution of pedology is enhanced by subdividing soils into three groups, viz. recharge soils, interflow soils and saturation excess soils. These terms are defined and discussed in detail in Chapter 3.

4.2 Procedure

Soil water measurements are now available for the 12 year period 1/17/1996-30/6/2008 at the 28 neutron water meter measuring sites (Figure 4.1). The focus will be placed on the soil profiles at measuring sites 202, 203, 221, 222 and at 211; the first four of these because they occur in afforested areas and 211 as a representative of the marsh area. Because the soil water regime at any profile is strongly influenced by seasonal rainfall, average soil water content values over a number of seasons are presented; for the period under grass over seven rain seasons (1/7/1996-30/6/2003), and for the period under trees over four rain seasons (1/7/2004-30/6/2008). The rainfall for each rain season over the whole period is presented in

Table 4.1. Soil water content changes over the whole period for three profiles are also presented in graphical form in Figure 4.2 a, b and c. The graphs are presented as in Van Huyssteen *et al.* (2005) with time on the x axis and the soil water content of each 300 mm soil layer separately on the y axis. The units chosen for the latter are the degree of saturation (S), defined as the ratio of the measure soil water content to the soil water content at saturation. There are three reasons for this choice. Firstly, redox reactions, which only occur in very wet soils (above about 0,7S and hence the horizontal line on the graphs at this value) have a profound effect on soil morphology. Because of this their long-term effect is visible to trained pedologists in the form, for example, of mottles (different forms, colours and distribution patterns) and bleaching (different degrees). Water content units unrelated to saturation would not facilitate the valuable process of relating redox related soil morphology to soil water regime – as S values do.

Secondly, the use of S values is normalising and therefore facilitates comparisons between the water regimes of different horizons and different soil profiles. The third reason is related to our intention to provide information that is useful to hydrologists. It is well known that the hydraulic conductivity of a soil decreases very rapidly as the water content decreases from field saturation (often about 0,9S) down to the drained upper limit (around 0,6S). No significant long-term interflow, i.e. excluding quick lateral macropore flow, can therefore be expected to occur in soil horizons with S values generally below about 0,6S. Soils containing these horizons will be termed recharge soils. A significant amount of interflow can be expected to occur in soil horizons in which S values fluctuate for significant periods above and below 0,7S. Soils containing these horizons will be termed interflow soils. Soil horizons in which S values remain close to 1,0S for most of the year will be termed saturation excess soils. They quickly become saturated during a rain storm and make a large contribution to overland flow. These characteristics of the water regimes of recharge, interflow and saturation excess soils are depicted in the three selected graphs presented here i.e. Figure 4.2, 4.3 and 4.4. Rainfall in the form of a bar chart is also presented on the graphs.

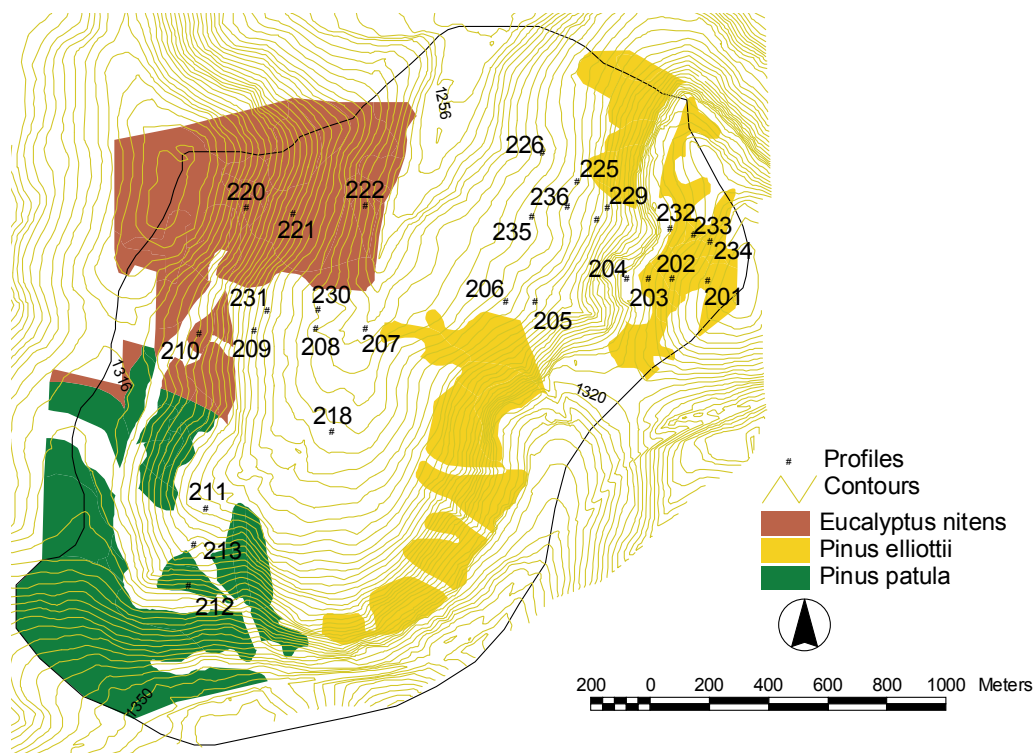


Figure 4.1 Location of profiles and the extent of trees planted in the Weatherley catchment.

4.3 Results

4.3.1 Rainfall

Weatherley rainfall covering the study period is presented in Table 4.1.

Table 4.1: Annual seasonal rainfall measured at Weatherley for 1996-2008 (BEEH 2003 and 2008)

Year	Rainfall (mm)
	Means for monitoring periods
96/97	1162
97/98	709
98/99	1074
99/00	1353
00/01	982
01/02	764
02/03	905
03/04	728
04/05	1012
05/06	967
06/07	865
07/08	989
Mean	959

An important objective of the Weatherleyey project is to quantify the influence of afforestation on the hydrology of the catchment. Variation in rainfall will obviously have an important influence on the conclusions drawn. The planting was done on 76 ha of the 160 ha catchment during September 2002 (Figure 4.1). According to the data in Table 4.1 the average per annum seasonal rainfall for the seven years under grass was therefore 993 mm, and 958 mm for the five years with trees planted on approximately half of the total area. The 2003/2004 season has been excluded from the mean for the 'forestry' period because the trees would still have been small and would therefore have probably had a negligible influence on soil water regime. Since the rainfall averages for the grassland and forestry periods are reasonably similar, meaningful comparisons regarding the influence of trees on the hydrology of the soils are possible.

4.3.2 Soil water content data for the period 1/07/96 to 30/06/08

Eight year means (1996-2003) have been calculated to represent the grassveld period to provide a value to against which to compare the results for 2004-2008, with trees five and a half years old at the end of the period. These results are presented in Table 4.2 for the representative profiles 202, 203, 221, 222, and 211. The water contents deeper than 300 mm for the first four profiles were used to estimate average water use by trees compared to grass. Profiles 202 and 203 are surrounded by *P. elliottii* trees (Figure 4.1). The polygons on the Weatherleyey soil map represented by 202 and 203 are shown in Van Huyssteen *et al.* (2005). Their combined area is 10 210 m². Using this together with the information in Table 4.2 (including that for the 0-300 mm layer) makes it possible to estimate how much more water the trees on this area have used compared to grassveld. The result is 453.3 m³ yr⁻¹ for the whole area or 444 m³ha⁻¹yr⁻¹. A similar calculation for profiles 221 and 222 located in the *E. Nitens* area (Figure 4.1) yields a value of 290 m³ ha⁻¹ yr⁻¹. There is a gain in soil water content (-ve water contents) in the topsoils of profiles 203, 221 and 222 (Table 4.2) under the trees, presumably because of the litter underneath the trees which limits the loss of water through evaporation. It can also be inferred that water dripping from the branches after rainfall or fog contributes to the increase of water content in the surface layers of these horizons. Profile 211, which is located in the marsh (Figure 4.1), shows an increase in water content in every layer (Table 4.2), totalling to 62 mm for the profile. It is suggested that the reason for this is that the dense tree growth of *P. patula* in the catchment above 211 has suppressed overland flow to a significant extent, thereby enhancing deep percolation into the deep vadose zone, resulting in an increase in the water available for flowpath 3b of Figure 5.2 of Chapter 5.

Table 4.2 Soil water contents representing the grassveld (1/7/96-30/6/03) and afforestation (1/7/04-30/6/08) periods at selected sites in the Weatherleyey catchment

		Measurement depth (mm) and volumetric water content (%)					
Profile no.	Period	0-300	300-600	600-900	900-1200	1200-1500	1500-1800
202	1/7/96-30/6/03	15.5	15.8	25.9	29.4	27.8	26.5
	1/7/04-30/6/08	15.0	13.9	24.1	27.5	25.0	22.7
	Deficit (%)	0.5	1.9	1.8	1.9	2.8	3.8
	Profile mean deficit deeper than 300 mm (%)						
	Profile deficit 300- 1800 (mm)			2.4			
203	1/7/96-30/6/03	15.3	16.3	20.6	22.7	22.7	20.5
	1/7/04-30/6/08	16.7	14.1	17.6	18.5	17.3	17.0
	Deficit (%)	-1.4	2.2	3.0	4.2	5.4	3.5
	Profile mean deficit deeper than 300 mm (%)						
	Profile deficit 300- 1800 (mm)			3.66			
221	1/7/96-30/6/03	20.6	20.0	19.2	21.6	25.8	26.1
	1/7/04-30/6/08	20.7	18.4	16.5	18.6	22.8	23.0
	Deficit (%)	-0.1	1.6	2.7	3.0	3.0	3.1
	Profile mean deficit deeper than 300 mm (%)						
	Profile deficit 300- 1800 (mm)			2.68			
222	1/7/96-30/6/03	24.6	23.0	25.7	36.6	0.0	0.0
	1/7/04-30/6/08	25.8	22.8	22.8	32.5	0.0	0.0
	Deficit (%)	-1.2	0.2	2.9	4.1	0.0	0.0
	Profile mean deficit deeper than 300 mm (%)						
	Profile deficit 300- 1200 (mm)			2.40			
211	1/7/96-30/6/03	30.0	32.5	30.6	32.7	33.0	29.7
	1/7/04-30/6/08	38.0	36.3	33.3	34.6	35.2	31.8
	Deficit (%)	-8.0	-3.8	-2.7	-1.9	-2.2	-2.1
	Profile mean increase 0-1800 (%)						
	Profile mean increase 0-1800 (mm)			-3.45			
211	1/7/96-30/6/03	30.0	32.5	30.6	32.7	33.0	29.7
	1/7/04-30/6/08	38.0	36.3	33.3	34.6	35.2	31.8
	Deficit (%)	-8.0	-3.8	-2.7	-1.9	-2.2	-2.1
	Profile mean increase 0-1800 (%)						
	Profile mean increase 0-1800 (mm)			-62.3			

4.3.3 Soil water content graphs for the period 1/7/97-1/1/08

4.3.3.1 Profile 221 (Hutton form): Figure 4.2

This is a good example of a recharge soil. It is only for very short periods that the soil water content in any horizon in the solum exceeds 0.7S. After each rainfall event the water above the drained upper limit (DUL), at around 0.6S, drains vertically out of the soil and eventually into the phreatic water table and then downslope to the stream. Because there is evidently a negligible amount of lateral water movement into the profile the drying out caused by the higher consumptive use by the trees compared to the grassveld is accentuated compared to interflow soils. The graph shows that for the grassveld and “young tree” years the S value varies around 0.55, whereas in 2008 the value drops to around 0.4.

4.3.3.2 Profile 202 (Pinedene form): Figure 4.3

This is an interflow soil. The third and fourth depth readings coincide with horizons which show morphological signs of wetness, whereas these signs do not occur in the first two horizons. The validity of these visual morphological observations is confirmed by the graphs. Throughout the grassveld period 1997 to 2003, and even during the immediately following “young tree” period before 2007, the water contents of the “unspecified material with signs of wetness” (on) horizons (last two depths) are most of the time above the 0.7S line. There is a marked change in 2007, an average rainfall year. The third horizon remains below 0.7S virtually for the whole year with an average S value around 0.55. The fourth layer varies around 0.7S during 2007 whereas it seldom fell below 0.7 during the previous 10 years. The exceptionally high rainfall in 2006 clearly prevented decreases of this nature during that year. The drying out influence of the trees is clearly shown.

4.3.3.3 Profile 211 (Katspruit form): Figure 4.4

This is a good example of a saturation excess soil. No trees were planted at this site (Figure 4.1) situated in the marsh. None of the three species planted at Weatherleyey would grow satisfactorily under the conditions prevailing here. The soil is evidently fed with interflow water from the surrounding slopes (Figure 5.2 of Chapter 5). The graphs show no significant evidence of drying out, caused by the trees (*Pinus patula* in this case, Figure 4.1) on the surrounding hillslopes. It is hypothesized that because of the slow movement of water via the phreatic water table into the marsh, the relatively large amount of water resulting from the high rainfall in 2006 probably boosted the water content of this profile during 2007. It is expected that the drying out influence of the trees on the surrounding hillslopes will show up in this graph after a dry previous year.

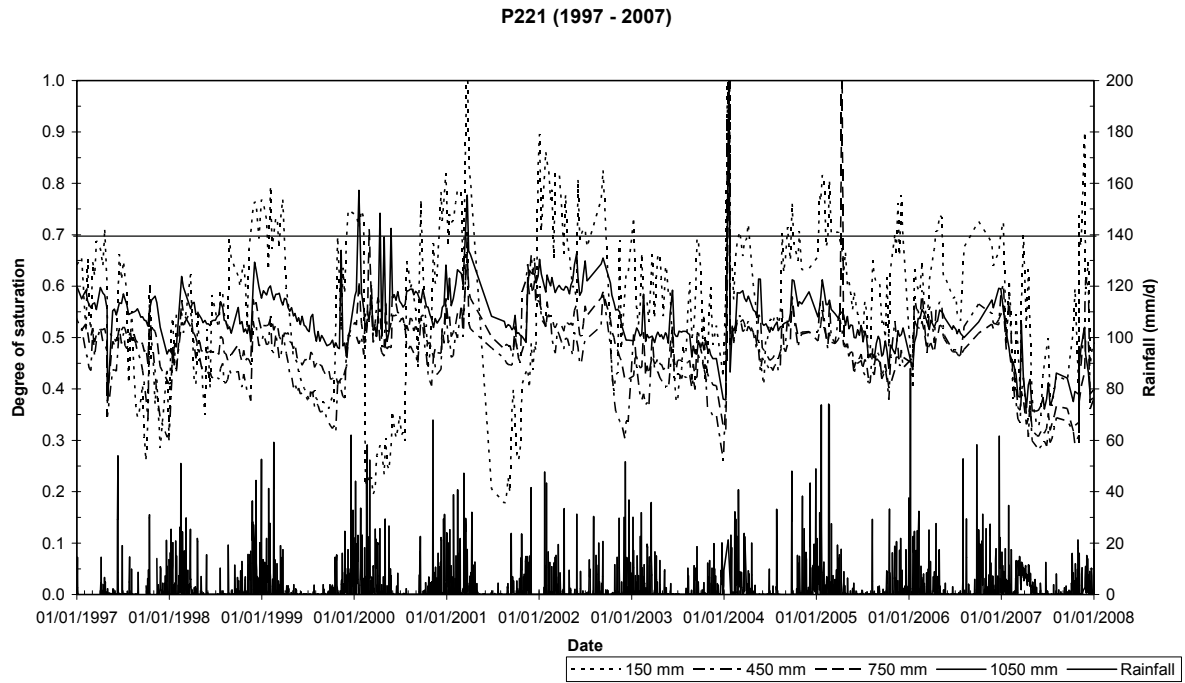


Figure 4.2 Degree of water saturation of a recharge soil (P221) in the Weatherleyey catchment for the period 1/1/97-1/1/08.

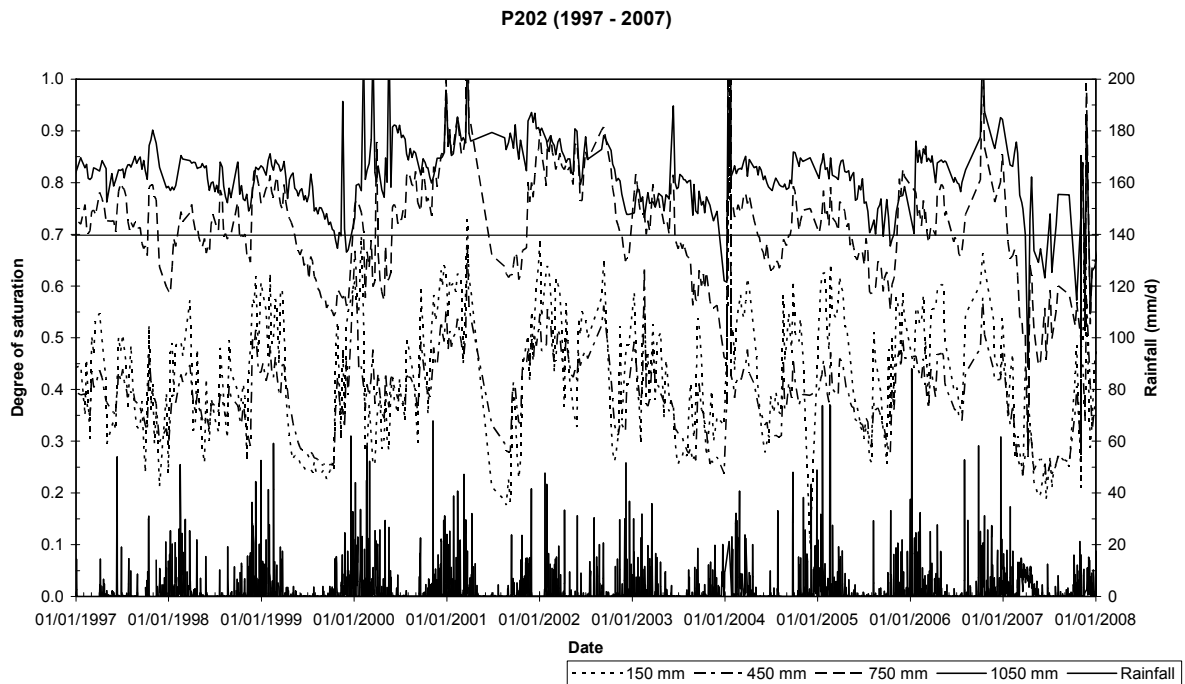


Figure 4.3 Degree of water saturation of an interflow soil (P202) in the Weatherleyey catchment for the period 1/1/97-1/1/08.

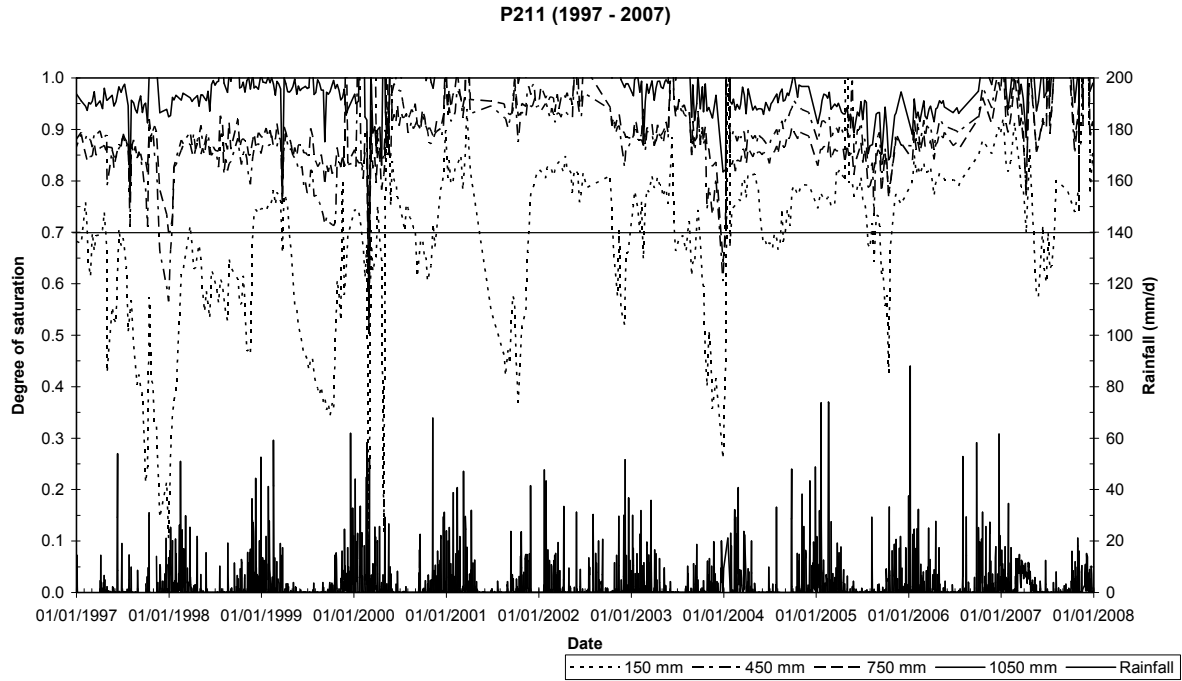


Figure 4.4 Degree of water saturation of a responsive soil (P211) in the Weatherleyey catchment for the period 1/1/97-1/1/08.

4.3.4 Conclusions

The results show a considerable deficit in soil water during the afforestation phase of the hydrological monitoring in the Weatherleyey catchment. The deficit is caused by increased evapotranspiration by the trees compared to grassland.

Chapter 5 **HYDROPEDOLOGICAL ASPECTS OF THE WEATHERLEYEY CATCHMENT**

5.1 INTRODUCTION

Soil properties serve as signatures of hydrological behaviour. Interpreting these properties and relating them to their hydrological response at hillslope scale can facilitate the formulation of conceptual models of hillslope hydrological behaviour. This will improve our understanding of the complex hydrological system and may contribute to the challenge of predicting hydrological processes in ungauged basins.

The aim of this chapter was of two kinds:

- To develop a conceptual model of hillslope hydrological behaviour and then to test this model in relation to hydrological measurements.
- To present different levels of soil information to hydrologists for incorporation into hydrological models in order to evaluate the contribution of soil in hydrological modelling. Modelling results will be discussed in chapter 10

It is important to note that the first aim was not merely to study ‘yet another hillslope’, but rather to serve as a template for future hillslope hydro-pedological studies in other regions with a variety of climates, geologies and topographical attributes.

5.2 MATERIALS AND METHODS

5.2.1 Study area

The Weatherleyey research catchment is situated in the Eastern Cape, 4 km south-west of Maclear. The catchment covers approximately 160 ha and is one of many small tributaries of the Mooi River. The highest point in the catchment occurs in the south western corner at 1352 m and the stream exits the catchment at 1254 m above mean sea level. The geology consists of sandstone and mudstone of the Elliot Formation above 1300 m above mean sea level. Below this, sandstone and mudstone of the Molteno Formation predominates. The Molteno Formation forms a prominent ‘shelf’ around most of the catchment at an altitude of approximately 1320 m, which has a dominating influence on the hydrology of the catchment, especially on the eastern and southern sides. Two small dolerite dykes with a north-south strike occur in the catchment. The mean annual precipitation (MAP) is approximately 1000 mm. year⁻¹

(Van Huyssteen *et al.*, 2005). The mean annual 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 during the winter. The summers are warm with a mean maximum temperature of 25°C (Roberts *et al.*, 1996). The natural 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. 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.*, 2007).

A hillslope in an upper sub-catchment (Uc) of the Weatherleyey catchment was selected for this study. The Uc was used due to its small size (30 ha) and the relatively simple soil pattern compared to the whole catchment. Hydrological data were collected at a crump weir at the outlet of Uc. Seven soil profiles, 8 auger observations, five tensiometer nests (Uc4-Uc8), as well as three neutron probe access tubes were included in the selected hillslope. The experimental network of the Uc is presented in Figure 5.1.

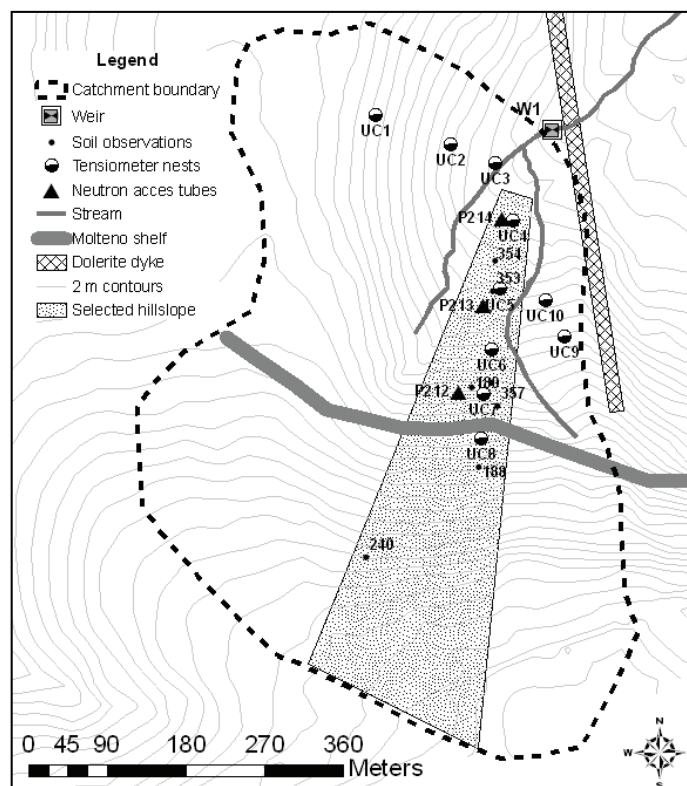


Figure 5.1 The Weatherleyey catchment and experimental network (Lorentz *et al.*, 2004) and the selected hillslope. Streamflow data were observed at crump weir W1.

5.2.2 Soil data

Soil data from a soil survey (Roberts *et al.*, 1996), profile descriptions (Van Huyssteen *et al.*, 2005) as well as auger observations were used to describe the soils. A brief description of soil observations in the selected hillslope is presented in Table 5.1. More detail is available on CD as Appendices. The observations are presented in sequence starting from P211 near the stream towards 240 close to the southern catchment divide (Figure 5.1). Observation numbers with a 'P' prefix refer to profile descriptions; with a number only, refer to auger observations of Roberts *et al.*, 1996 and numbers prefixed by Uc refer to additional auger observations at measuring sites of Lorentz *et al.*, 2004. The soils were divided into three 'hydrological soil types' according to their expected hydrological behaviour. The different soil types are: (1) responsive soils where saturated conditions favour saturation excess overland flow, (2) interflow soils with lateral flow either at the soil/bedrock or A/B horizon interface and (3) recharge soils where vertical drainage through and out of the soil profile are dominant (Table 5.1).

5.2.3 Evaluation of conceptual model

The conceptual model based on soil information was evaluated using hydrological and hydropedological measurements (BEEH, 2003 & 2007). Two periods towards the end of the rain seasons of 2001 and 2002 were selected for evaluation purposes (2002 was selected due to the lack of continuity in the tensiometer data of Uc7 during 2001). These periods were selected to illustrate the dominant hydrological processes active when the catchment is delivering water to stream flow mainly by drainage i.e. the catchment was not being recharge to a significant extent by precipitation. For hydrograph analysis it was assumed that the selected hillslope is representative of the whole Uc.

The tensiometer nests for evaluation purposes were selected to illustrate different dominant hydrological pathways of various hydrological soil types (Table 5.1): responsive soils are presented by Uc4 (Ka1000); interflow soils (soil/bedrock) by Uc7 (Tu2220) and recharge soils by Uc1 (Bd1100). Although the latter is part of the interflow soil type it was utilized since there are no tensiometer measurements in the recharge soils (Hu2100) of the selected hillslope and due to the pedological similarity of the first 1200 mm between Uc1 and 240. The tension (daily average) is expressed as a capillary pressure head (mm). Zero values indicate a water table; negative values a hydrostatic pressure below the phreatic surface above the tensiometer cup and increasing positive values indicate increasing drying.

Table 5.1 A brief description of the soil observations in the hillslope shown in Figure 5.1

Observation	Terrain morphological unit (TMU)	Soil form	Soil family	Horizons	Depth (mm)	Clay (%)	Moist colour	Hydrological behaviour ^{1*}	Hydrological soil type
P211 Uc4	5	Katspruit (Ka)	Ka1000	orthic A (ot) G-horizon (gh)	150 1200	32 38	10YR4/2 10YR5/1	Macropore flow Water logged	Responsive
354	5	Ka	Ka1000	ot gh	350 1500	25 40	2.5YR4/2 2.5YR6/0	Macropore flow Water logged	Responsive
Uc5	5	Ka	Ka1000	ot gh	400 1500	15 50	7.5YR4/6 7.5YR5/2	Macropore flow Water logged	Responsive
353	5	Ka	Ka1000	ot gh	300 800	10 40	10YR4/2 10YR5/3	Macropore flow Water logged	Responsive
P213	5	Ka	Ka1000	ot gh	500 1500	27 30	10YR3/2 10YR4/1	Macropore flow Water logged	Responsive
Uc6	4	Kroonstad (Kd)	Kd1000	ot E –horizon (gs) gh	300 1000 1500	30 30 55	7.5YR3/2 10YR5/2 10YR6/1	Macropore flow Lateral flow Water logged	Interflow
358	3	Tukulu (Tu)	Tu2220	ot neocutanic B (ne) unspecified material with signs of wetness (on)	550 1450 1510	18 25 30	10YR4/3 7.5YR4/4 5YR4/4	Vertical drainage Vertical drainage Lateral flow	Interflow
357	3	Tu	Tu2110	ot ne on	400 900 1510	8 10 10	10YR4/1 10YR5/2 10YR5/3	Vertical drainage Vertical drainage Lateral flow	Interflow
180	3	Tu	Tu2210	ot ne on	400 900 1500	15 15 20	10YR3/4 5YR5/6 ND ^{2*}	Vertical drainage Vertical drainage Lateral flow	Interflow
P212 Uc7	3	Tu	Tu2220	ot ne on	300 1300 1500	10 12 17	10YR3/2 7.5YR4/4 7.5YR4/4	Vertical drainage Vertical drainage Lateral flow	Interflow
188	3	Kd	Kd2000	ot gs gh	200 600 900	20 16 30	ND ND ND	Macropore flow Lateral flow Water logged	Interflow
Uc8	2	Longlands (Lo)	Lo1000	ot gs soft plinthic (sp)	300 700 900	12 25 25	7.5YR3/2 10YR3/2 7.5YR5/6	Macropore flow Lateral flow Periodic saturation	Interflow
240	1	Hutton (Hu)	Hu2100	ot red apedal B (re)	380 1500+	12 15	5YR3/2 10R3/4	Vertical drainage Vertical drainage	Recharge
Uc1	1/3	Bloemdal (Bd)	Bd1100	ot re on	500 1200 1500+	15 20 30	5YR2.5/1 5YR4/6 2.5YR5/6	Vertical drainage Vertical drainage Lateral flow	Interflow

^{1*} The expected dominant hydrological behaviour of various horizons based on morphological properties

5.3 RESULTS AND DISCUSSION

5.3.1 Conceptual model of hydrological behaviour

The soil forms and their associated properties along with their spatial distribution were interpreted to develop a conceptual model of the hydrological behaviour of the hillslope. The model reflects the expected dominant hydrological processes (Figure 5.2).

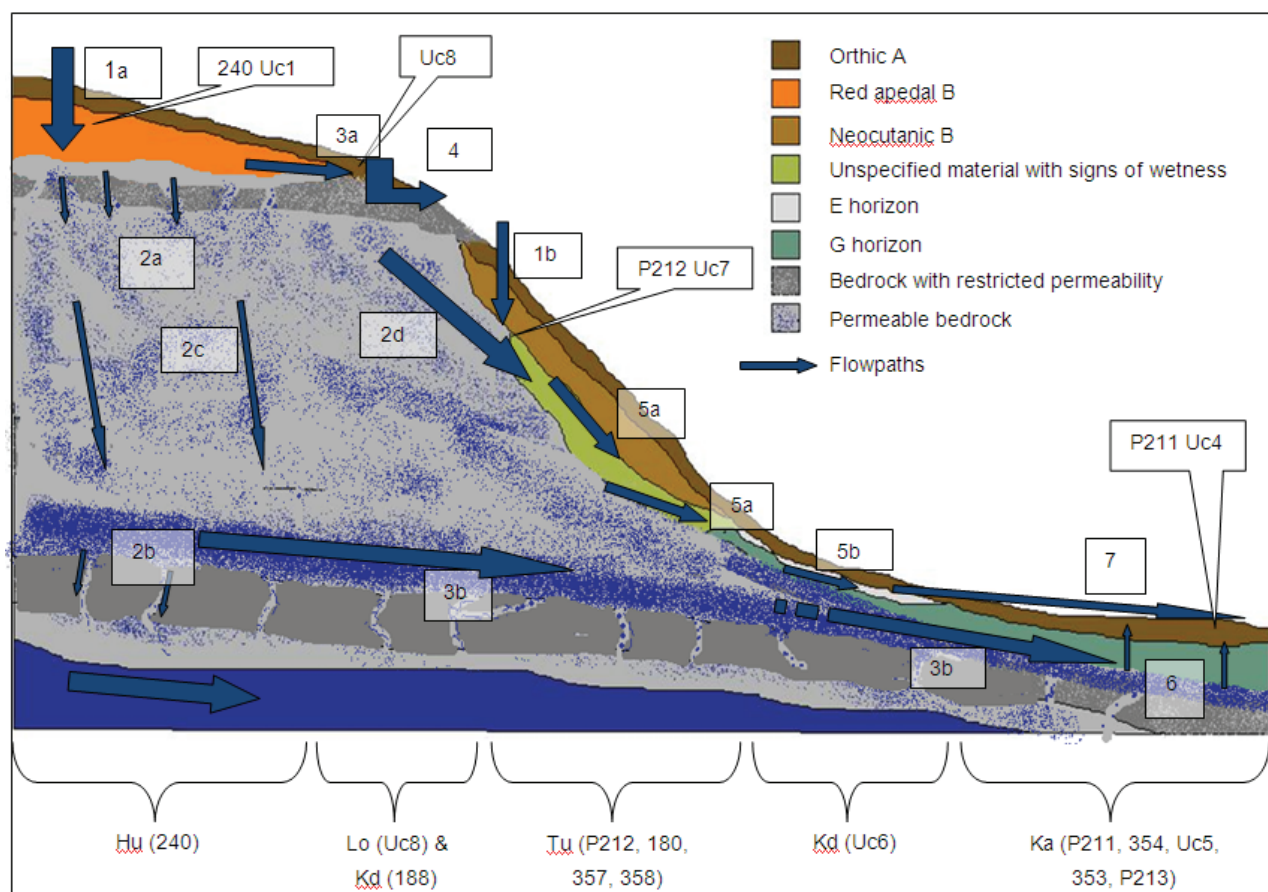


Figure 5.2 Conceptual hydrological behaviour of the selected hillslope based on soil interpretations. Various processes are indicated by the numbered arrows.

The dominant processes (flowpaths and storage mechanisms) are indicated by numbered arrows in Figure 5.2 (for example 1a refers to arrow number 1a in Figure 5.2). A discussion of these processes follows in what can be considered as a hydropedological hypothesis of the hillslope hydrology of the Uc:

When it rains infiltration dominates in the upper regions of this hillslope (1a). Gentle slopes as well as dense vegetation impede overland flow and facilitate infiltration. Absence of any signs of wetness in the Hu2100 (240; Table 5.1 and Figure 5.1) soil of the upslope indicates that

vertical drainage through the profile is dominant. The texture is non-luvic and the clay content is therefore relatively uniform with depth. No, or very little, lateral flow is expected to occur at the A/B horizon interface. These are considered to be true recharge soils since no signs of wetness were recorded in 240 up to a depth of 1500 mm, indicating that water does not perch in the pedon within this depth. Water draining through 240 therefore either infiltrates the subsurface layers (2a) or flows at the soil/bedrock interface (3a), which was not reached with auger observations down to 2.4 m.

Any water which does infiltrate the fractured rock would then either flow vertically and recharge regional aquifers (2b) or, when it encounters a layer with restricted permeability (aquitard), it would flow laterally (3b) and recharge perennial hillslope groundwater downslope.

The presence of interflow soils (Lo1000 and Kd2000 soil forms) located where the rock bedding plain surfaces near Uc8 (Figure 5.1) is an indication that the bedding plane (Molteno shelf) has restricted permeability promoting considerable flow at the soil/bedrock interface (3a). The greater part of the water draining through the Hu soil of the upper slope is therefore expected to flow laterally at the soil/bedrock interface.

Return flow (ex-filtration) to the soil surface (4) is expected as water flowing at the soil/bedrock interface reaches the protruding Molteno shelf. The amount of water exceeds the storage capacity of the soil and returns to the surface contributing to overland flow. It is expected that the overland flow has a short duration as the water will re-infiltrate when it reaches the Tu soils below the rock outcrop (1b).

Subsurface lateral flow (5a) in the form of flow at the soil/bedrock interface is indicated by the on horizon present in the deep subsoil of the Tu soil of the midslope. This soil body is situated on the Molteno Formation. Groundwater responsible for the redoximorphic features of the on horizon is evidently supplied from the recharge soils (Hu2100) as return flow from the bedrock (2d). This return flowpath is expected to result in a fairly constant supply of water during the wet seasons to the on horizon, reflecting its association with perennial groundwater.

The E horizon in the Kd1000 form (Uc6; Table 5.1 and Figure 5.1) of the lower slopes is an indication of the lateral flow of groundwater dominating at the A/B horizon interface (5b). Ka 1000 and Kd 1000 soils cover the entire TMU 4 & 5 positions of this hillslope. The gleyed conditions (P211, 354, Uc5, 353 and P213; Ka1000; Table 5.1 and Figure 5.1) are indications that these profiles are saturated for long periods. The gh horizons have a low hydraulic conductivity that impedes infiltration. Precipitation does not infiltrate into these soils due to the saturated state of the gh horizon. The water maintaining saturation in these lower areas must therefore have another origin. It is believed that there is another layer with restricted permeability present in the hillslope (Figure 5.2). This layer deflects water which has infiltrated through the recharge soils (Hu2100) of the upperslope towards the lower lying areas (3b), resulting in the

presence of a perennial aquifer. These very wet Ka1000 soils respond rapidly to precipitation providing overland flow to the stream, the process described as saturation excess overland flow (7). Near surface macropore flow might also play a significant role in this area, as water from the gh horizon push up into the more porous ot horizon and flow laterally. The ot horizons of the Ka 1000 soils in the lower slope have Fe and Mn mottling, confirming periodic saturated conditions.

Since the gh horizons Ka and Kd soils (Table 5.1) in the lower footslope and toeslope positions (Figure 5.2) are saturated for long periods, the dominant flow direction within the pedon is upwards (6). Evapotranspiration will presumably extract more water from the soil than can infiltrate.

5.3.2 Evaluation of the conceptual model using tensiometer measurements

Results for the selected period from the tensiometers in the Bd soil (Uc1, Table 5.1) show changes in the matric pressure in the ot horizon after rainfall and slight changes in the re horizon (Figure 5.3).

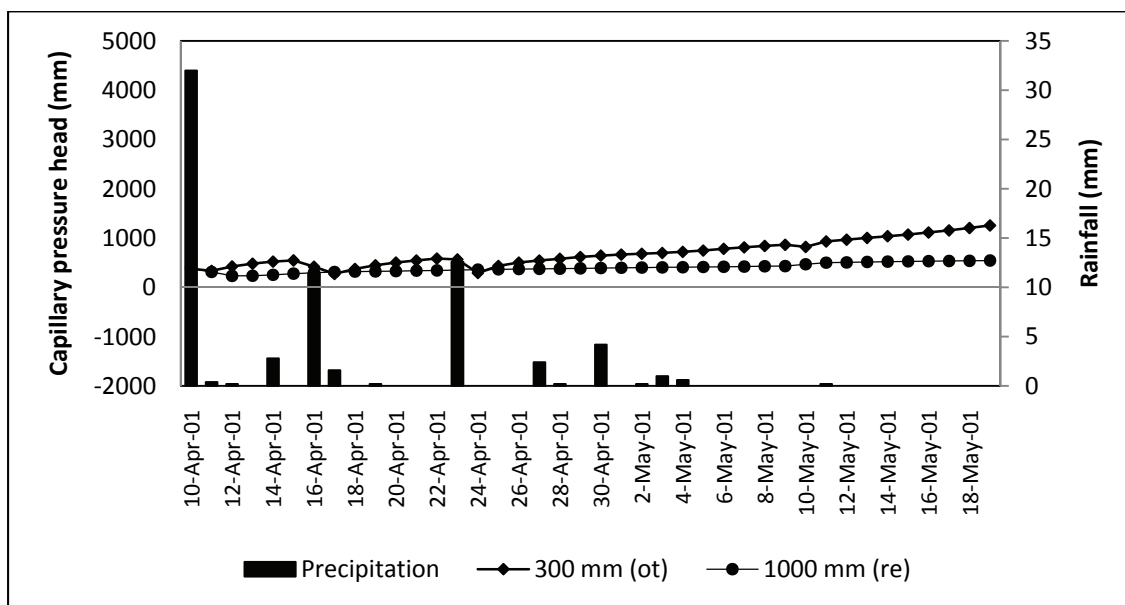


Figure 5.3 Matric pressure head (mm) and rainfall (mm) in different horizons of a recharge soil (Bd1100, Uc1) during April and May of 2001.

The ot horizon is only affected by rainfall during the first part of this period (Figure 5.3). It seems that particular events greater than 5 mm affected this horizon on the same day, indicating rapid infiltration (1a). The horizon gradually dries out towards the end of this period (1500 mm of suction), reflecting water extraction through ET.

The re horizon was only affected by a 32 mm rain storm on the 10th of April and became wetter approximately a day after the particular rain event due to infiltration (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 than the A horizon.

Tensiometer measurements of the ot horizon (300 mm) in the Tu soil (Uc7, Table 5.1), reflects rapid response after the 34 mm rain storm on the 10th of April 2002 (Figure 5.4). This horizon came close to, but never reached saturation during the selected period and gradually dried out towards the end of the period.

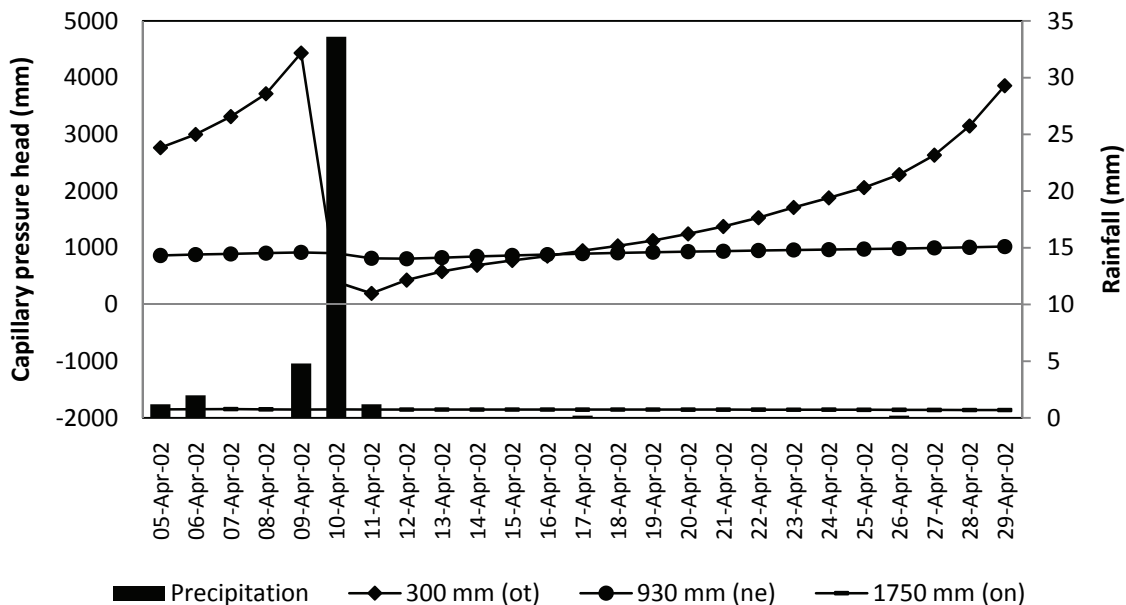


Figure 5.4 Matric pressure head (mm) vs. rainfall (mm) in different horizons of an interflow soil (Tu2220, Uc7) during April 2002.

The ne horizon responded slightly to the rain on the 10th of April, implying vertical drainage from the ot horizon. The on horizon however was saturated throughout the selected period. It did not respond to the rain storm on the 10th implying that this horizon received water from another source and not through vertical drainage. The nearly constant capillary pressure of the on horizon further implies that this horizon loses water at a rate equal to the rate of obtainment (steady state flow). Supply from the bedrock to (2d in Figure 5.2) is considered to be the dominant source of water saturating this horizon.

The matric potential of the horizons of the Ka soil responded differently to those of the Hu and Lo soils (Figure 5.5). The ot horizon was saturated for long periods during this period (Figure 5.5). Although it gradually dried out, this horizon remained saturated for approximately

20 days after the last significant rain. This implies that water seeped towards this horizon (3b in Figure 5.2) which satisfied the evaporative demand (6 in Figure 5.2) 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 due to saturation excess (7 in Figure 5.2). The gh horizon (1000 mm) remain saturated throughout the event confirming a constant recharge of these horizons (3a in Figure 5.2) and the presence of perennial groundwater. This Ka1000 soil form is therefore a true saturation excess responsive soil.

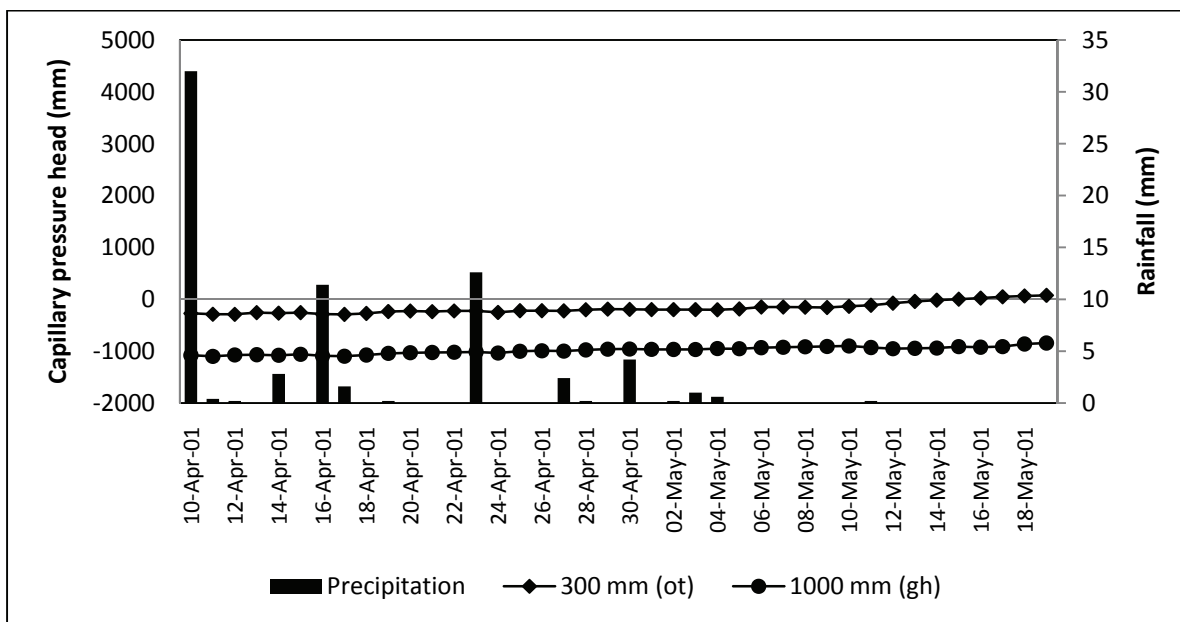


Figure 5.5 Matric pressure head (mm) vs. rainfall (mm) in different horizons of an interflow soil (Ka1000, Uc4) during April and May, 2001.

5.3.3 Peak flow generation

It is hypothesized in the conceptual model, based on soil morphological information, that saturation excess overland flow and/or near surface macropore flow dominates in the lower lying areas (7). Tensiometer data confirm the saturated state of these soils.

Data implies that responsive soils next to the stream will be the main contributors to peak flow generation. These soils occupy approximately 50 000 m² of the Uc area. 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 5.2 presents rainfall and flow volumes as well as rainfall intensities for selected rain events.

Table 5.2 Rainfall volumes on responsive soils adjacent to stream, streamflow volumes and rainfall intensities for six rainfall events

Event	Date	Rain (mm)	Rain on responsive soils (m ³)	Runoff (m ³)	Intensity (mm.h ⁻¹)
1	19-Sep-00	23	1150	296	1.05
2	13-Sep-01	24	1190	23	1.26
3	25-Sep-04	72	3600	77	3.06
4	27-Mar-00	22	1100	1110	1.4
5	10-Apr-01	32	1600	1731	79.17
6	10-Apr-02	34	1650	666	1.74

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 is because the ot 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 have 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 responsive soils are the main contributor to peak flow with saturation excess overland flow and/or near surface macropore flow as the flowpaths. During event 5 the runoff exceeds the rainfall, which indicates that a greater area must have contributed to peak flow or else there were subsurface contributions from upslope. This may result from contributions through infiltration excess as the high intensity storm clearly exceeds the final infiltration rate of these soils and overland flow (Hortonian flow) is generated on more soils. Event 6 follows a period where the evapotranspiration exceeded the rainfall and recharge of the ot horizon was needed prior to any overland flow explaining the lower runoff compared to rainfall.

5.3.4 Baseflow generation

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

The gh horizon of P213 was selected as representative of the gh 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-Burdine equation and parameter values from Lorentz, Gopa & Pretorius (2001) for a gh horizon in the Weatherleyey catchment:

$$Se = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{h_d}{h}\right)^\lambda \text{ for } h > h_d \quad (5.1)$$

$$\text{and } K(h) = K_s(Se)^{(2+\frac{3\lambda}{\lambda})} \quad (5.2)$$

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

$$\text{thus } Se = (30.4/h)^{0.562} \quad (5.3)$$

$$K(h) = 7.2\left\{\left(\frac{30.4}{h}\right)^{0.562}\right\}^{6.559} \quad (5.4)$$

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

A water retention curve based on this equation was drawn and from that a linear regression line in order to predict the $K(h)$ at different water contents. The resulting linear regression was:

$$(\log Kh + 3) = (39.3 \times \log \theta) - 75.5 \text{ in } \text{mm. h}^{-1} \quad (5.5)$$

This equation for P213 is extrapolated to all gh horizons of the Uc. These horizons occupy an area of $74\,630 \text{ m}^2$. The volume of water draining from these soils is expressed in $\text{m}^3 \text{day}^{-1}$ and compared to the stream runoff ($\text{m}^3 \text{day}^{-1}$) for the selected period (Figure 5.6).

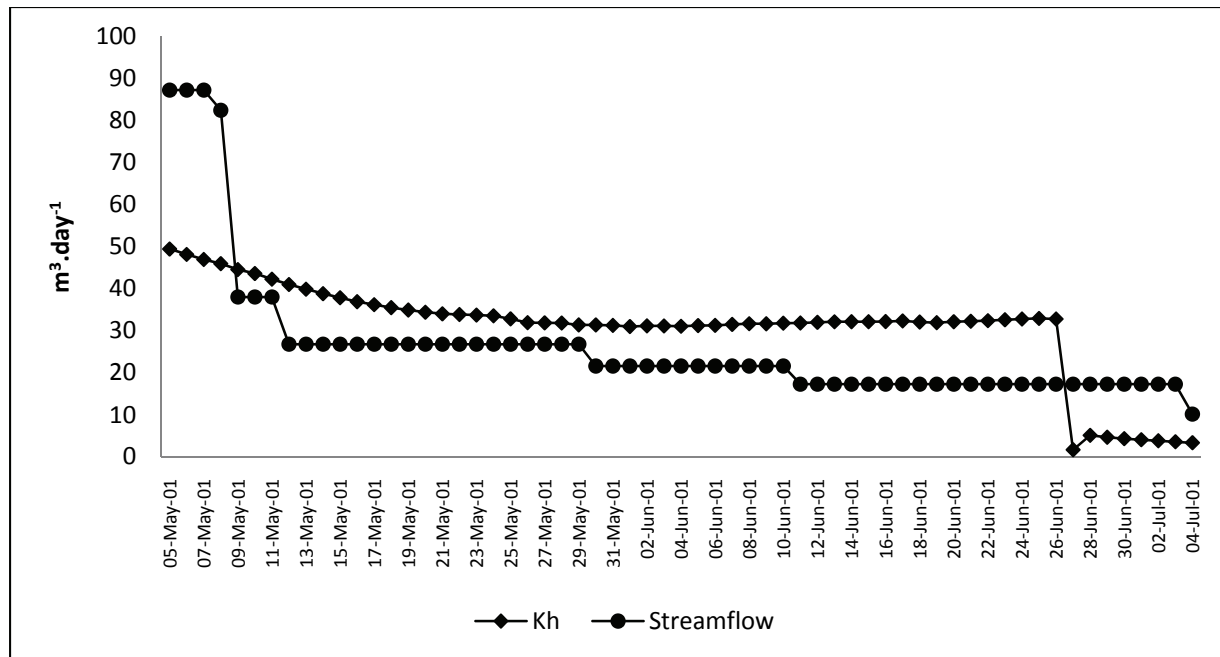


Figure 5.6 $\Delta K(h)$ ($\text{m}^3 \text{ day}^{-1}$) vs. streamflow ($\text{m}^3 \text{ day}^{-1}$) for 60 day period starting 5 May 2001.

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 predominantly through outflow from the gh horizons in the lower slopes.

5.4 SOIL DATA FOR HYDROLOGICAL MODELLING

In this section a summary of the data given to hydrologists from the University of KwaZulu-Natal and Rhodes University are presented. More detail is available on CD as Appendices. Three levels of detail were presented namely: Land Type (level 1), soil survey (level 2) and hillslopes (level 3)

- Level 1 (Land Type) – interpretation of Land Type information of selected catchment.
- Level 2 (Soil survey) – observations made during soil survey as well as laboratory analysis.
- Level 3 (Hillslopes) – hydrological interpretation of level 2 (section 2.9), delineation of dominant hillslopes, formulation of conceptual hillslope hydrological response models.

5.4.1 Level 1 (Land Type)

A summary of the interpreted soil information from Land Type Ac492 are presented in Table 5.3.

Table 5.3 Soil forms, coverage, average and weighted average depths as well as clay contents of the soils of Land Type Ac492

Soil form	Coverage (%)	Depth (mm)	Weighted average depth (mm)	Average clay content (%)
Rock	1.2	0	0	
Gs	11.4	300	34.2	20
Ms	11.5	200	23	20
Cv	19.2	900	172.8	24
Hu	19.1	850	162.35	27
Gf	9.5	950	90.25	24
Pn	8.8	850	74.8	18
Cf	7	650	45.5	23
Ss	4.6	350	16.1	34
Ka	3	300	9	28
Av	2.8	800	22.4	20
Streams	1.8			

5.4.2 Level 2 (Soil Survey)

A summary of the soil survey data are presented in Table 5.4.

5.4.3 Level 3 (Hillslopes)

The soil map from Roberts *et al.*, 1996 (Figure 5.7a) together with observations made during survey (Table 5.4) were interpreted and related to the hydrological response, from these interpretations a hydrological response map were created based on the dominant hydrological response of the various soil types (Figure 5.7b). The relative sequence, extent and position of the various soil types in the landscape served as basis for deleniating hillslopes with different expected hydrological behaviours. The position and coverage of the different hillslopes are presented in Figure 5.7c.

Table 5.4 The different soil forms their extent, depths and bulk densities of the Weatherleyey catchment

Soil form	Area (ha)	% of catchment	Horizon	Horizon Depth (mm)	Soil depth (mm)	Bulk density (Mg.m ⁻³)	Weighted average bulk density (Mg.m ⁻³)
Hu	33.8	21.6	ot	400	1235	1.55	1.60
			re	835		1.62	
Cv	8.7	5.6	ot	400	900	1.55	1.61
			ye	500		1.65	
Gf	1.3	0.8	ot	400	1735	1.55	1.61
			ye	500		1.65	
			re	835		1.62	
Bd	5.3	3.4	ot	400	1825	1.55	1.63
			re	835		1.62	
			on	590		1.71	
Pn	13.1	8.4	ot	400	1490	1.55	1.65
			ye	500		1.65	
			on	590		1.71	
Ka	48.2	30.8	ot	400	1325	1.55	1.70
			gh	925		1.76	
Kd	6.2	4.0	ot	400	1725	1.55	1.68
			gs	400		1.61	
			gh	925		1.76	
Se	7.6	4.9	ot	400	1390	1.55	1.66
			vp	400		1.71	
			on	590		1.71	
Gs	10	6.4	ot	400	400	1.55	1.55
Gs(wet)	9.8	6.3	ot	400	990	1.55	1.65
			on	590		1.71	
Fw	0.2	0.1	ot	400	800	1.55	1.58
			gs	400		1.61	
Vf	0.7	0.4	ot	400	1360	1.55	1.61
			gs	400		1.61	
			ne	560		1.66	
Tu	1.2	0.8	ot	400	1550	1.55	1.65
			ne	560		1.66	
			on	590		1.71	
Oa	10.4	6.6	ot	400	960	1.55	1.61
			ne	560		1.66	

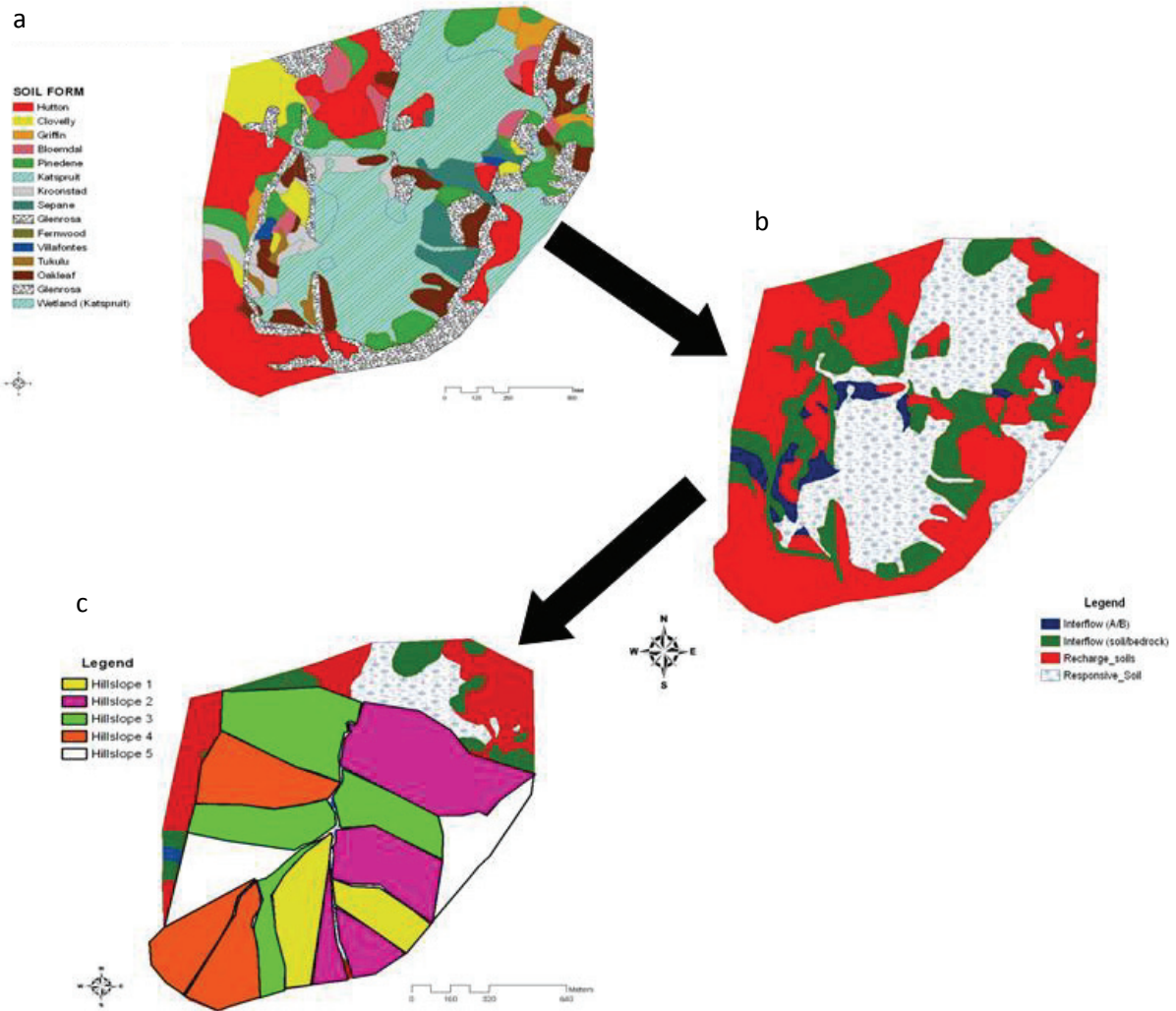


Figure 5.7 Soil map (a), hydrological soil type map (b) and hillslopes of the Weatherleyey catchment.

Each of the hillslopes in Figure 5.7c has their own conceptual model and is presented in Figure 5.8 (hillslope 4 are presented by Figure 5.2). More detail is available on CD as Appendices.

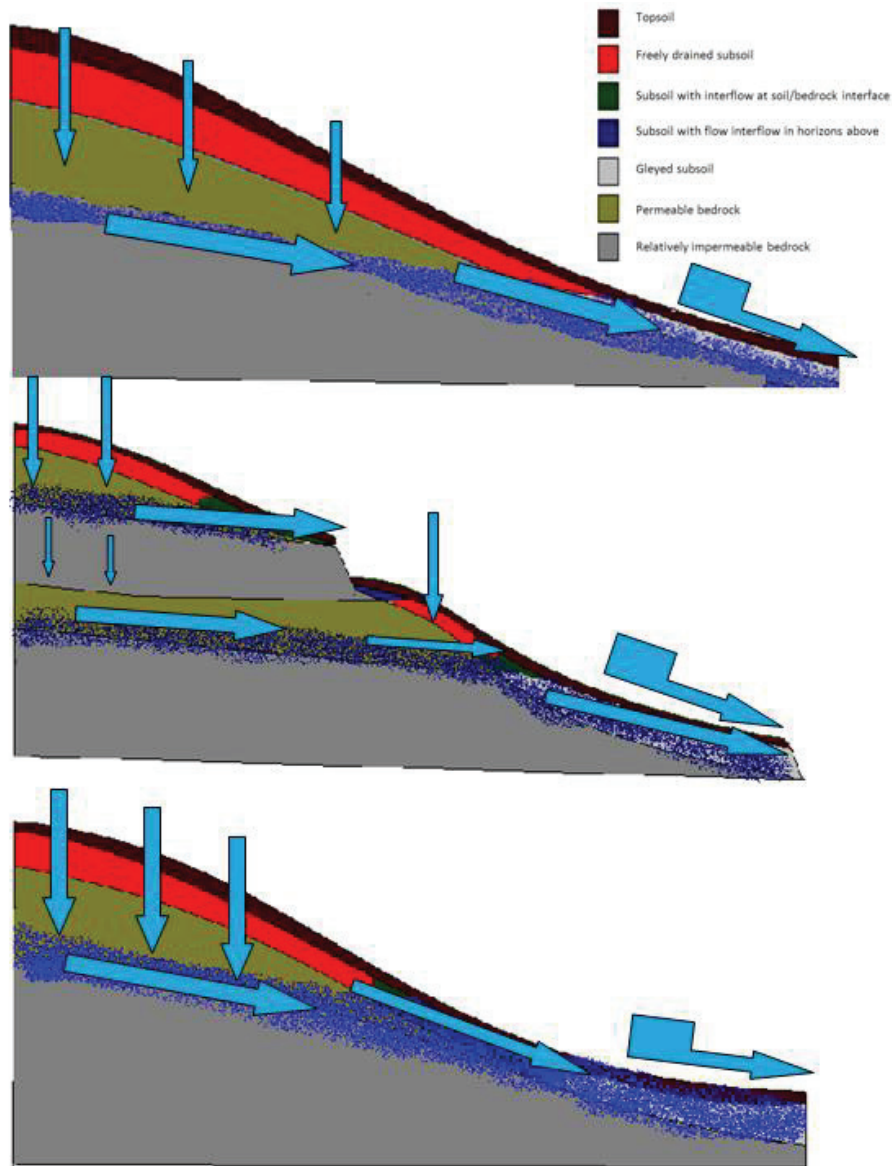


Figure 5.8 Dominant hillslope processes of hillslope 1(a), 2(b) and 3(c) in the Weatherleyey catchment.

5.5 CONCLUSIONS

The conceptual model based solely on soil morphological properties gave an acceptable indication of the hillslope hydrology for the selected hillslope in the upper catchment of the Weatherleyey research catchment. Tensiometer readings and stream hydrograph analysis confirmed the conceptual model. This model serves as a basis for distinguishing between different streamflow generation mechanisms. Results produced estimates which are comparable with the actual streamflow volumes obtained from the stream hydrograph. Soil

information is readily available and indentifying and interpreting soil properties and their relative distribution might aid in the understanding and predictions of hydrological processes and can especially be useful for predictions in ungauged basins.

Chapter 6 **HYDROPEDOLOGICAL ASPECTS OF THE CATHEDRAL PEAK VI CATCHMENT**

6.1 DESCRIPTION

6.1.1 Introduction

Specific aspects of the hydrology of the Cathedral Peak VI catchment were studied in detail over a four year period in an earlier Water Research Commission funded project by Everson *et al.* (1998). The project title was “Monitoring and modelling components of the water balance in a grassland catchment in the summer rainfall area of South Africa”. Their findings provide an excellent framework in which to incorporate the results of our soil studies.

The Cathedral Peak VI catchment is situated at S28° 59' 35.9" and E29° 15' 05.7" in the foothills of the Drakensberg Mountains in KwaZulu-Natal at an altitude of 1860-2060 m above mean sea level. The topography is steep with slopes ranging between 8% and 24%. The catchment is 67.7 ha in extent. The catchment is moderately dissected by streams and there are two saturated zones (Figure 6.1). The upper one occurs on a topographic convergence midway in the catchment where the streams come together, and the other where the stream flattens out before the catchment outlet at its northern end. The catchment is located in the international designated biodiversity conservation area of the Maluti-Drakensberg Transfrontier Project funded by the World Bank.

6.1.2 Geology

Basalt rock consisting of alternating compact and highly amygdaloidal varieties forms the geological foundation of the catchment. This basaltic rock is the result of basaltic lava flows from magma of basic composition. These lava flows were probably very mobile as they have been found to extend for as much as several kilometres in almost parallel and horizontal strata (Van der Eyk *et al.*, 1969). Mineralogical analysis of a basalt rock sample taken at 2000 metre above sea level (m.a.s.l.) confirms that extrusive basic rock is the major capping material of the Drakensberg mountain range. The elemental mineralogical analysis reveals that weathering of such rocks results in high concentrations of Ca and Mg in the intermediate weathering stages (Duncan *et al.*, 1983). Ca and Mg have been leached out of these soils under high rainfall and intense weathering conditions, and Fe and Al have tended to accumulate.

6.1.3 Climate

The climate of the catchment is described in detail by Everson *et al.* (1998). The relevant information reported here is from that report.

The rainfall in the catchment shows seasonal patterns. The mean annual rainfall for 4 years (1990/91-1994/95) is 1 175 mm, and annual rainfall amounts of below 1000 mm are considered as dry years. The seasonal records indicate a modal distribution with peaks in January/February, and annually a very dry period from April to September. The major rain season occurs in the summer months of December, January, and February. Their average accounts for 84% of the average annual rainfall. Air temperatures are never excessively high with a long-term annual mean of 13.8°C. Mean maximum monthly temperatures are less than 25°C with the highest being 23.4°C recorded in February. The lowest mean monthly temperature occurs in June at 3.3°C. Winters are therefore cold and dry while summers are hot and wet. Temperature and rainfall in this grassland catchment promotes vigorous growth of *Themeda triandra* spp. which dominates in the catchment. This grass is burnt biennially in the spring (Everson *et al.*, 1998). Measurements of evaporation from the grassland were done using the Bowen ratio technique, the Penman-Monteith model, and the equilibrium equation during summer, autumn and winter. The Penman-Monteith model proved to be the most reliable, yielding the following results (mm per month) for the six months January to June, respectively: 93.2, 59.2, 50.5, 44.5, 28.8, 16.4. Using the data presented by Everson *et al.* (1998) an annual aridity index for the catchment was calculated and found to be 0.78. For the calculation potential evapotranspiration estimated by Everson *et al.* (1998) using A-pan data was used. Valuable data about the water balance of the catchment are presented in Table 6.1.

Table 6.1 Components of the water balance equation measured in the Cathedral Peak VI catchment (1990/91 to 1993/94)

Year	P	-	E _a	-	SS	=	Q	Q _a	Difference	% of P
1990/91	1223	-	681	-	(-11)	=	553	603	-50 mm	4.100
1991/92	1092	-	752	-	(-45)	=	385	366	+19 mm	1.700
1992/93	1093	-	698	-	(+07)	=	388	391	-03 mm	0.274
1993/94	1469	-	651	-	(-14)	=	822	863	-41 mm	2.790

P = precipitation; E_a = actual evaporation; SS = soil storage; Q = streamflow calculated using the water balance equation; and Q_a = actual streamflow.

The results in Table 6.1 show that evapotranspiration from the grassland uses approximately half of the rainfall. Since there is reliable evidence that there is no significant leakage of water out of the base of the catchment (Everson, personal communication, 2009), it is legitimate to estimate E_a as $P - Q_a$. This yields very similar results to those obtained by the E_a measurements, i.e. 620, 726, 702 and 606 for the four years, respectively, confirming the validity of the E_a measurements.

6.1.4 Land type information

The results of soil genesis produce a common form of organization and symmetry in the morphology of soil profiles. This morphological pattern is expressed in the typical distribution of soils in the landscape. It was first described as a catena by Milne (1936), but later modified by Bushnell (1942) who used the term toposequence. The original concept of the catena involves processes that cause differentiation down the hillslope and therefore also influence vertical differentiation of horizons in the component soil profiles. These principles form the scientific backbone of the land type survey of South Africa (Land Type Survey Staff, 2002). A land type is “A class of land with specified characteristics used in South Africa as a map unit denoting land, mappable at 1:250 000 scale, over which there is a marked uniformity of climate, terrain form, and soil pattern.” (Van der Watt and Van Rooyen, 1995). The land types delineated for the whole of South Africa by the ARC-ISCW provide a valuable framework within which to conduct intensive soil surveys. Comprehensive appreciation of this fact is a fundamental first step towards developing a cost-effective intensive soil survey technique for catchment hydrogeological research. The Cathedral Peak VI catchment is located within land type Ac265 of the Memoirs on the Agricultural Natural Resources of South Africa (Land type survey staff, 2002). Land Type Ac265 is characterised by soils of the Clovelly, Mispah, Glenrosa, Magwa, Hutton, Kranskop, Inanda, Nomanci and Champagne forms listed here in their order of dominance. Detailed land type information for the whole of South Africa is easily available on <http://www.agis.agric.za>. To serve as clarification some information is provided below about land type Ac 265 (Table 6.2). The estimated spatial distribution of soils in the landscape is described in terms of what can be described as a toposequence. A toposequence has different terrain morphological unit (TMU) shown as numbers 1, 3, 5 on the terrain form sketch in Table 6.2. The estimated area of each soil or group of similar soils occurring on each TMU, e.g. on 3 position, is presented in the inventory format as 10% for Mispah, Glenrosa and Magwa; 5% for Inanda, Hutton, and Clovelly. The slope for this TMU can range from 4-60%, indicating how steep this area can be. In TMU 5 which is a valley bottom position, Champagne soils account for 10% while the rest is streambeds. At TMU 1, which is the top of the hills, rock, Mispah and Glenrosa are dominant. The clay content can also be high for these soils increasing from 10% in the A horizon to 45% in the B horizon. The distribution of soils and their properties in relation to

topography and hydrological processes is captured in the terms pedosequence or hydrosequence, respectively, in relation to hillslopes (Weiler *et al.*, 2004).

Table 6.2 Soil and terrain form inventory of land type data Ac 265

LAND TYPE / LANDTIP : Ac265		Inventory by Inventaris daur : A L Smith-Baillie Modal Profiles Modale profilele : P1828	
CLIMATE ZONE KLIEMATSONE : 1875S		Occurrence (maps) and areas Voorkoms (kaarte) en oppervlakte : 2828 Harrismith (1636 ha) 2928 Drakensberg (7827 ha)	
Area / Oppervlakte : 9463 ha			
Estimated area unavailable for agriculture Bersaamde oppervlakte onbeskikbaar vir landbou : 0 ha			
Terrain uni. Terreinteenhede	1	3	
% of land type % van landtipe	10	85	5
Area Oppervlakte (ha)	946	8044	473
Slope / Helling (%)	4 - 8	4 - 60	4 - 60
Slope length Helling Lengte (m)	25 - 100	200 - 800	2 - 25
Slope shape Helling-vorm	X	X	X
MB0 MB1 (ha)	0	5728	47
MB2 - MB4 (ha)	946	2815	426
Soil series or land classes Grondseries of landklasse	Depth Diepte (mm)	MB	
Soil-rock complex			
Grond-rotskompleks:			
Rock/Rots	4	189 20	804 10
Mispah Ms10	100-300 3	426 45	804 10
Williamson Gs16	200-450 2	331 35	804 10
Ontsidade Cv16, Clovelly Cv17	500-1200 0	2011 25	
Milford Ma10	600-1200 0	804 10	
Fountainhill Ia10	600-1200 0	402 5	
Kipipiri Kp10	600-1200 0	402 5	
Ofazi Cv23, Annandale Cv33	500-1200 0	402 5	
Lichtenburg Hu23, Mangano Hu33	500-1200 0	402 5	
Hutton Hu16, Farmingham Hu17	500-1200 0	402 5	
Williamson Gs16	200-450 0	402 5	
Mispah Ms10, Nonanci No10	100-500 2	402 5	
Ivanhoe Ch21	800-1200 0	47 10	
Stream beds/Stroombeddings	4	426 90	426 4,5

LAND TYPE / LANDTIP : Ac265 Continued Terenlg

Terrain type Terrein tipe : C3

Terrain form OerbeeldTerreinvormsêters



Remark(s): Topsoil have a high content of humified organic matter
Opmerking(s): Begroete mst-hoe inhoud van gehumifiseerde organiese materiaal.

Geologie Basaltiese lava van die Formasie Drakensberg.

For an explanation of this table consult LAND TYPE INVENTORY (table of contents)
Ter verduideliking van hierdie tabel kyk LANDTIP - INVENTARIS (inhoudsopgawe)

Geology: Basaltic lava of the Drakensberg Formation.

6.1.5 Modal hillslopes

Apart from overland flow, all outflow from a catchment must have flowed through the soil at some point. The way in which this process has occurred in different locations in the catchment over the years has played a role in pedogenesis. The hillslope therefore becomes a fundamental landscape unit for a holistic understanding and simulation of hydrological processes. A detailed account of hillslope hydrology is given in section 2.2.4 in the literature review. The purpose of this section is to describe the soils and conceptual flow paths in the modal hillslopes of the Cathedral Peak VI catchment.

6.2 SOIL SURVEY

6.2.1 Procedure

The procedure used was in line with what is described in Chapter 3. A number of strategically located auger transects were conducted. Soil profiles could not be dug due to strict biodiversity conservation regulations of Maluti-Drakensberg designated area. Only one representative profile was opened at site C7 and described in detail, sampled and analysed. More detail is available on CD as Appendices. A computer software programme 3D Mapper was employed to facilitate the soil survey. A generalized soil map is presented in Figure 6.1.

6.2.2 Hillslopes

The procedure followed to identify hillslopes is based on the fact that different soils behave in different hydrological ways. They can be grouped into three types of soils based on their hydrological behaviour: recharge soils, interflow soil and saturation excess responsive soils. The presence, sequence and extent of different soil types were used to identify different hillslopes in the catchment. 3dMapper software was used to determine topographical attributes of the different hillslopes. A conceptual model of the hydrological behaviour of each hillslope was then developed.

6.2.3 Soil survey results

Soils with a diagnostic humic A horizon predominate in the catchment. The humic A horizon may be underlain by red apedal B (Inanda form, Ia); yellow brown apedal B (Magwa form, Ma); yellow brown apedal B over red apedal B (Kranskop form, Kp); lithocutanic B (Nomanci form, No) (Soil Classification Working Group, 1991). The soil in the marshy area of the catchment is Champagne form (Ch). In this case the land type information presented in Table 6.2, collected at a scale of 1:250 000, is significantly different from that collected here at a scale of around 1:10000. The enormous difference in the study scales is probably the main reason for the

discrepancies. Important aspects of agreement are the dominance of TMU 3, the high content of organic carbon in the topsoils and the large fraction of highly weathered soils consisting mainly of Clovelly in the land type inventory.

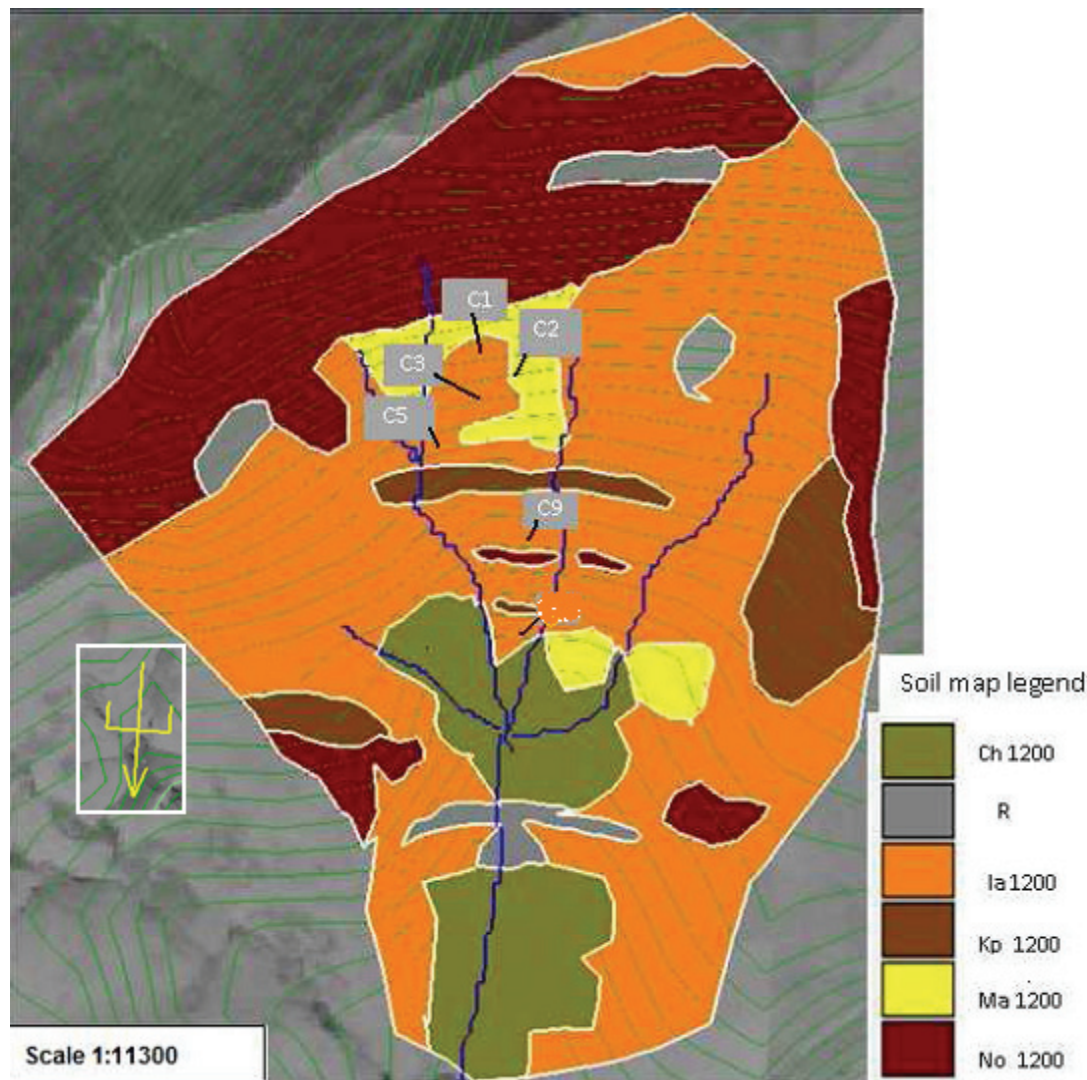


Figure 6.1 Generalised soil map of the Cathedral Peak VI catchment and location of the neutron probe access tube sites (Everson *et al.*, 1998) reported in section 6.4 (i.e. C1, C2, etc.).

The areas covered by each of the soils in the catchment are presented in Table 6.3. Deep Inanda predominates. This soil has a large soil water storage capacity that releases water continuously, during the rain season that flows into the steep stream channels dissecting the catchment (Figure 6.1). The steep slope at the top of the catchment is covered by Nomanci soil. It has a thin solum underlain by cracked bedrock. This cracked bedrock forms an important flow path of water to the regional water table. Champagne soil occurs on most of the marsh area which exists on a topographic convergence

midway in the catchment and where the stream flattens before the catchment outlet. This soil shows a marked accumulation of organic material as a result of long-term wetness and cool temperatures. Because of the large amounts of undecomposed organic material the soil is commonly black (10YR 2/2). The fairly continuous wetness has resulted in signs of gleying in the subsoil. This is therefore a wetland soil. Since it remains close to saturation for most of the year, runoff response from this soil is very rapid after the start of a storm, and also ends relatively abruptly. This soil serves as a hydrological buffer by absorbing the lateral drainage water from the upslope parts of the catchment, and retaining it for a considerable time.

Table 6.3 The different soils of the Cathedral Peak VI catchment, their extent, depths and bulk densities

Soil form	Area (ha)	% catchment	Horizons	Average Horizon depth (mm)	Average soil depth (mm)	Db (Mg/m ⁻³)	Average Db of the profile (Mg/m ⁻³)
Ia	35.1	51.8	ah	0-200	1800	0.70	0.93
			re	200-1800		1.00	
Ma	2.8	4.1	ah	0-150	1800	0.70	0.93
			ye	150-1800		1.00	
Kp	4.3	6.4	ah	0-150	1600	0.70	0.93
			ye	150-450		1.00	
			re	450-1600		1.00	
No	16.4	24.2	ah	0-150	500	0.70	0.70
			lc	150-500			
Ch	7.7	11.4	oo	0-400	2300	0.60	0.60
			gh	400-2300			
R	1.4	2.1					
Catchment size	67.7	100					

ah=humic A, re=red apedal B, ye=yellow brown apedal B, lc=lithocutanic B, oo=organic O, gh=G horizon.

6.2.4 Hydrological soil types

A hydrological soil type map was created from the generalised soil map. Three hydrological soil types were identified and delineated. They are shallow recharge soils, deep recharge soils, and saturation excess responsive soils. These hydrological soil types are shown in Figure 6.2.

Shallow recharge soils

Nomanci is considered to be a shallow recharge soil because the dominant flow is vertical. Water drains rapidly through the soils, out of the reach of ET, into the bedrock. These soils are

therefore considered to be important contributors to baseflow. They cover 24% of the catchment (Table 6.4).

Deep recharge soils

Deep recharge soils occupy the largest part of the catchment (Table 6.4). Drainage from this deep soil is an important source of recharge for the intermediate vadose, the lower vadose zone, and the groundwater. As the rains start and these two zones become wetter after the dry winter, the hydraulic conductivities increase until they become sufficiently wet to allow for mainly lateral downslope flow and probably some vertical flow to the groundwater. Deep very wet saprolite, probably saturated during periods of high rainfall, beneath the solum (upper vadose zone) acts as an impeding layer in the vadose zone profile, limiting vertical drainage and creating anisotropy between vertical and horizontal hydraulic conductivities in the intermediate vadose zone. It is hypothesized that as the intermediate and lower vadose zones become wetter a stage is eventually reached in the hydraulic conditions of the hillslope during the rain season that enables widespread lateral flow to occur, especially in the intermediate vadose zone, to the high level channels dissecting the catchment (Figure 6.1).

Saturation excess responsive soils

The soil in the saturated zone is Champagne (Figure 6.1). It remains close to saturation for most of the year. Because of this the runoff response from the saturated zones is expected to be very rapid after the start of a storm, and also to end relatively abruptly. The soils are therefore called saturation excess responsive soils. They occupy 14% of the catchment (Table 6.4). Because of their high organic matter content they probably have a significant macropore component which will presumably promote some lateral macropore flow into the stream.

Table 6.4 The extent of different hydrological soil types in the Cathedral Peak VI catchment

Soil type	Area (ha)	% area	Average depth (mm)
Shallow recharge	16.4	24.2	500
Saturation excess responsive	7.7	11.4	2300
Deep recharge	42.2	62.3	1800
Rock	1.4	2.1	
Total catchment size	67.7	100	

6.2.5 Hillslopes

Two different hillslopes were identified based on the flow paths resulting from the sequence of different soil types along the hillslope (Figure 6.2). The hillslopes form a catena like sequence from the best drained to the least drained soils in this system.

6.2.5.1 Hillslope 1

Hillslope 1, which drains most of its water into the high level channels of the catchment, covers 30 ha (44%) of the catchment. The average length of the hillslope is 658 m. The average slope is 19.8%. Conceptual flow paths based on the topographical and soil type aspects are presented in Figure 6.3. Flows are annotated with numbered arrows, the size of the arrows indicating expected volumes. A significant fraction of the rain falling on the hillslopes infiltrates vertically (arrow 1) in the high lying area of the catchment where Nomaci soils are found, into the weathered rock via preferential pathways (arrow 2) to recharge the regional water table and intermittent water table in the high lying areas of the catchment. The regional water table sustains the perennial streamflow of the catchment described as baseflow (arrow 3). Another commonly observed flow path is return flow (arrow 4) which has resulted in some patches of riparian zones in the upper slopes of the catchment. This returnflow is by way of lateral flow at the soil/bedrock interface, especially in the Nomanci soils where at some places the humic A overlies less permeable bedrock. Vertical recharge occurs into the transient water table in the deep saprolite of Inanda and Kranskop soils (arrow 8) occupying the midslopes of the catchment. Once the saturated conditions have been generated lateral flow will occur. This water exits the intermediate zone into the high level channels (arrow 5). This lateral subsurface flow into the high level channels is considered to be a major flow path in this hillslope. Macropore flow in upper horizons probably occurs especially after substantial rainfall, but probably only lasts for a short period. In the wetlands upward water movement occurs (arrow 6) as a result of a combination of processes.

6.2.5.2 Hillslope 2

Hillslope 2 covers 37.7 ha (56%) of the catchment. The average length of the hillslope is 633 m, with an average slope of 14%. Conceptual flow-paths are presented in Figure 6.4. On the hillslope most of the water drains into the deep groundwater system of the catchment. It does not have the return flows noticed in hillslope 1. Some water enters the soil vertically (arrow 1) in the steep terrain to recharge regional water tables through cracked rocks (arrow 2). Some water recharges intermittent water tables (arrow 3) in the saprolite (intermediate vadose zone) of Inanda soils. In the intermediate vadose zone, lateral flow is often in the transmissive mineral saprolite above the intermittent water table. This water exits mainly into the adjacent high level channels.

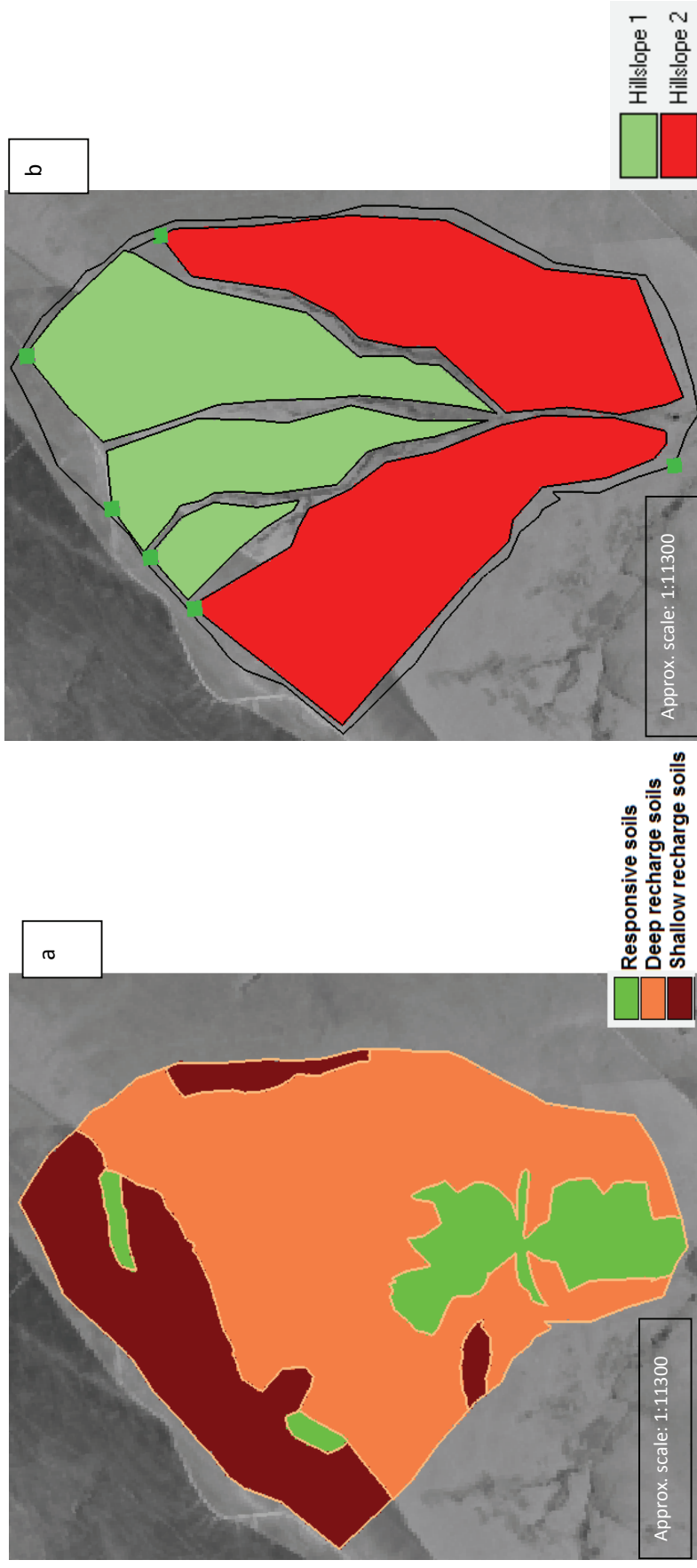


Figure 6.2 Hydrological soil type map (a) and selected hillslopes (b) in the Cathedral Peak VI catchment.

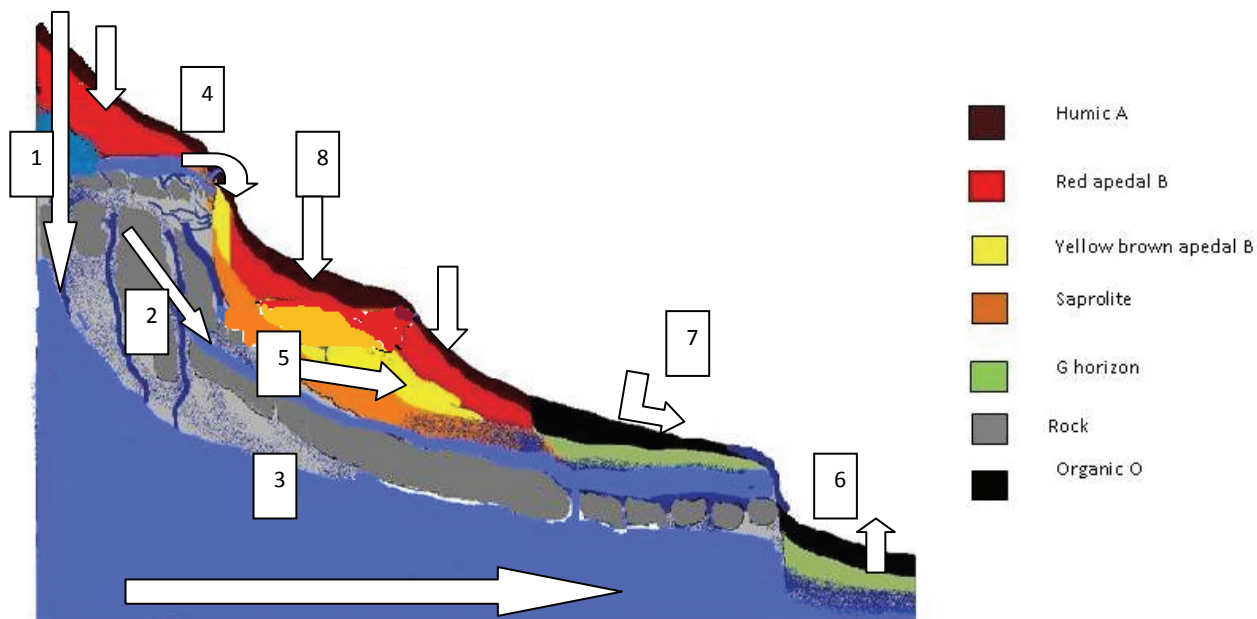


Figure 6.3 Conceptual flow paths in hillslope 1 of the Cathedral Peak VI catchment.

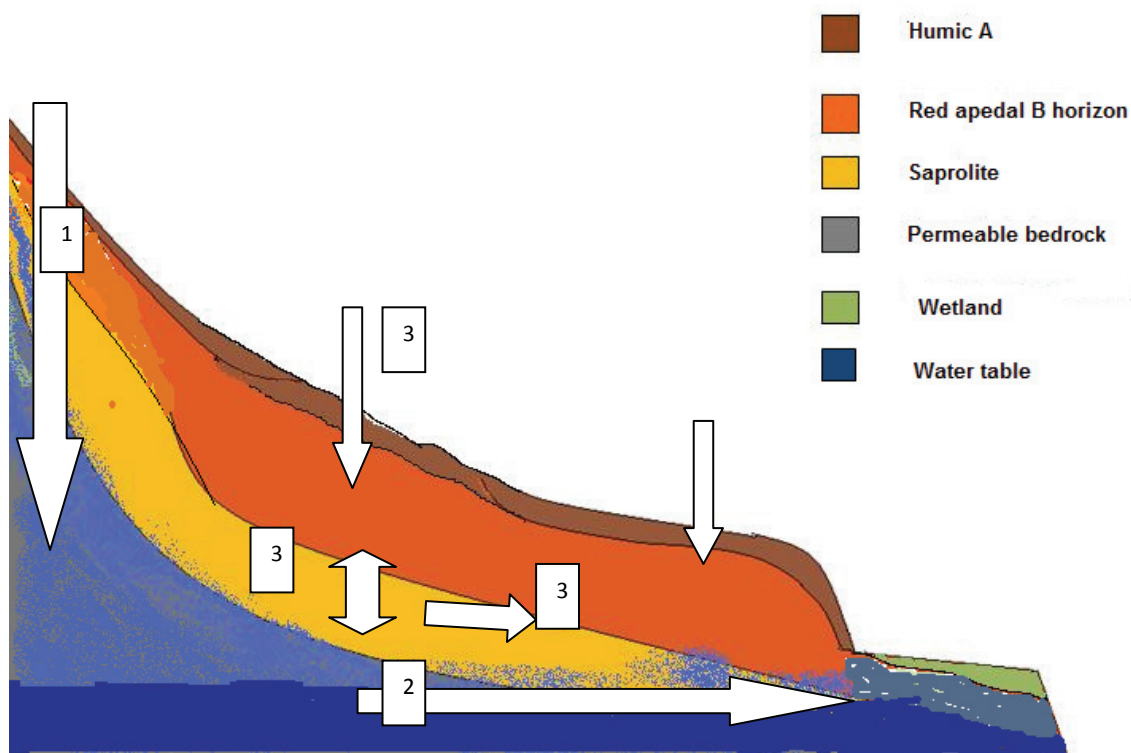


Figure 6.4 Conceptual flow paths in hillslope 2 of the Cathedral Peak VI catchment.

6.3 HYDROPEDOLOGICAL CHARACTERISTICS OF IMPORTANT SOILS

6.3.1 Introduction

Studies included morphological and physico-chemical properties and the soil water regime. The latter was described in terms of degree of saturation (S) of the soils. S is defined as the fraction of the porosity that is occupied by water. This is considered to be a useful parameter due to its correlation with oxidation – reduction conditions. It was shown by van Huyssteen *et al.* (2005) that for the Weatherleyey catchment high S values (>0.7) for relatively long durations are associated with defined morphological signs of wetness, especially colour. They refined the parameter to include a threshold value, and the annual duration (AD) in days that the water content remained above the threshold value, thereby defining a single value parameter that described the ‘wet end’ of the soil water regime of a particular soil horizon. Plotting S values of specific horizons against time presents a valuable overall view of the horizon’s soil water regime. The symbol $AD_{S>0.70}$ was used to indicate the average numbers of days per year that the water content of a particular soil layer was above 0.70 of saturation. Expressing soil water content as S enables comparisons between different soils, and facilitates pedological interpretation, especially with regard to redox reactions in the soils. Jennings (2007) found an S of 0.78 to be a suitable first approximation threshold value for the onset of significant redox reaction in a yellow brown apedal B horizon at Weatherleyey. This assumption is in line with the observation by Jenkinson *et al.* (2002) that reduction in a soil horizon begins before 100% saturation is attained, and progresses more rapidly as the horizon becomes more saturated.

6.3.2 Field site and methods

Soil water contents for Cathedral Peak VI measured by Everson *et al.* (1998) at 5 neutron water meter (NWM) access tubes were used to calculate S values for diagnostic horizons of the soils. From the overall dataset weekly soil water contents for 4 selected layers at 5 NWM sites (C1,C2,C3,C5,C9, Figure 6.1), for the period from 1990 to 1995 were extracted. All the data is expressed in terms of S values. At each site auger observations were made to enable the soil profile to be classified and samples to be collected for analysis. Soil chemical studies were made on the augered soil samples. The soil profiles selected are situated on the north facing hillslope of the catchment (Figure 6.1). Soil matrix colours and mottles were read using a Munsell colour chart. Soil samples were dry-sieved to remove coarse (> 2 mm) fragments. Particle size distribution was determined by pipette method. Soil pH was measured on 1:2.5 soil:water suspension; free Fe and Mn were extracted with dithionite-bicarbonate-citrate and determined with an atomic absorption spectrophotometer (AA); exchangeable cations were extracted at pH7

with NH_4OAC and determined with AA; organic carbon and nitrogen were determined using the Leco CN apparatus. Analyses were done according to standard methods (The Non-Affiliated Soil Analysis Work Committee, 1990). Soil forms (Table 6.5) were identified and classified according to Soil Classification Working Group (1991).

S was calculated as follows for each measurement depth representing a particular horizon:

$$S = \frac{V_w}{V_f} \quad (6.1)$$

Where S = degree of saturation (as a fraction)

V_w = water content ($\text{mm}^3 \text{ mm}^{-3}$)

V_f = total pore volume ($\text{mm}^3 \text{ mm}^{-3}$)

The total porosity (f) was calculated as follows (Hillel, 1982):

$$f = 1 - \frac{\rho_d}{\rho_s} \quad (6.2)$$

Where: ρ_d = bulk density (Mg m^{-3})

ρ_s = particle density (Mg m^{-3})

Duration of S was calculated using the following equation (Van Huyssteen *et al.*, 2004):

$$AD_{s>0.78} = \sum_{s_n>0.78}^{\text{year}} \text{DOY}_n - \text{DOY}_{n-1} \quad (6.3)$$

Where:

$AD_{s>0.78}$ = duration of s above 0.78 of porosity during a particular year (days year^{-1})

DOY_n = date of measurement (day of the year)

DOY_{n-1} = date of previous measurement

S = degree of saturation

year = calendar year (365 days)

Duration of S was calculated by adding the duration of individual $s>0.78$ events. A $s>0.78$ event is defined as a measurement where s is in excess of 0.78 and s for the previous measurement is less than 0.78. This was based on the assumption that in the long-term, a particular measurement is representative of the soil water regime for the period between half way from the previous measurement that had $s<0.78$, to half way towards the following measurement which also had $s<0.78$. For consecutive measurements with $s>0.78$ the entire period was included when using

the above equation. The $AD_{S>0.78}$ values were quantified as a hydropedological characteristic of the Cathedral Peak VI soils with the units of days per year. The duration of $S>0.78$ for a particular year is calculated as the number of days during the year that S was above 0.78 of porosity.

6.3.3 Results and discussion

6.3.3.1 Morphological, physical and chemical properties

Colour and texture

The colour of A horizons is black (10YR 3/3) and attests to the high accumulation of organic matter in these soils (Table 6.5 & Figure 6.7). The general phenomenon of a decrease in clay content and increase in silt in the lower horizons suggests a slower intensity of weathering at this depth mainly as a result of relatively high water contents (Dr D. Turner, personal communication, 2010). Supporting evidence for this is provided by the fact that the texture of the B horizons changes downslope from dominantly clay in the upper profiles to dominant sandy clay to clay loam in the midslope and lowerslope positions. The colour of the subsoil is red in most of the profiles because of high Fe content which oxidizes to produce the red colour under unsaturated conditions. The high contents of CBD extractable Fe reflects the influence of basaltic parent material and high weathering process in these soils. Fe gets reduced together with Mn in some profiles to form Fe-Mn related redoximorphic features identified at the depth of 2 m, mostly in the saprolite. The saprolite appears to be less drained and remains saturated longer, and this may be explained by the development of mottles.

Mn and Fe content

The Fe content of the A horizons is fairly consistently around 65000 mg kg^{-1} in all profiles, whereas in the B1 horizons it seems to decrease downslope from around 75000 mg kg^{-1} at C1 and C2 to around 65000 mg kg^{-1} at C5 and C9. In the B2 the value is very variable over the range approximately 58000 to 80000 mg kg^{-1} , whereas in the C horizons the value is fairly consistently around 63000 mg kg^{-1} (Figure 6.5).

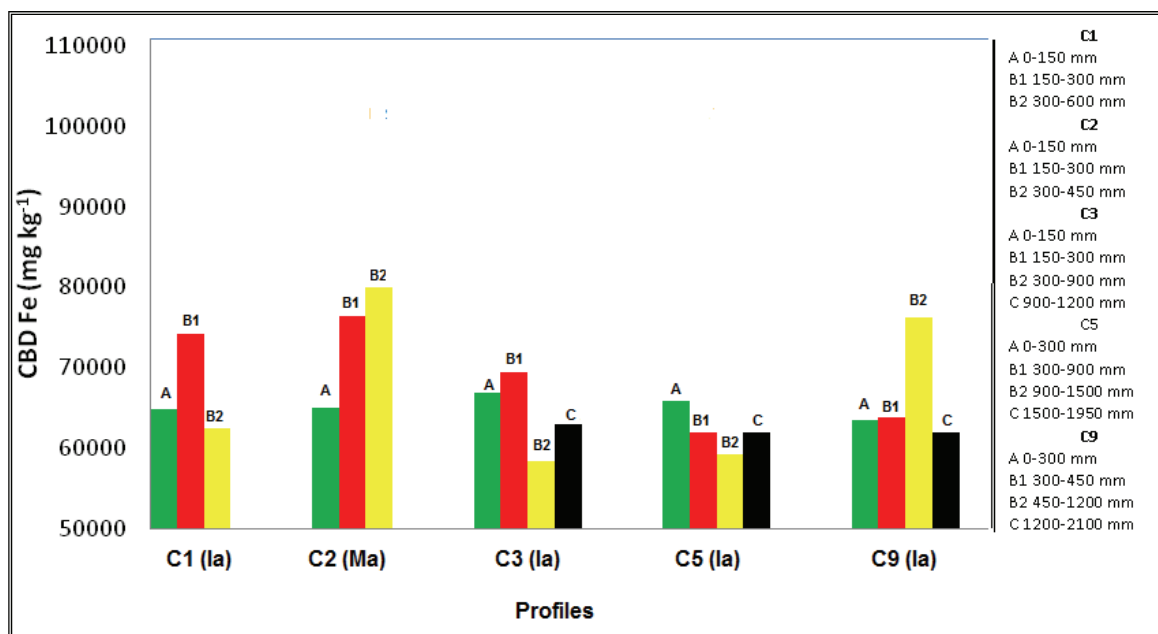


Figure 6.5 Distribution of CBD Fe for the profiles studied.

Table 6.5 Morphology and classification of soils sampled

Profile name	Soil form	Horizon	Depth (mm)	Matrix colour (moist)	Mottles				PSD		
					Occurrence	Size	Contrast	colour	cause	Sand	Silt Clay
C1	Inanda	ah	0-150	10YR 3/3						39	38 21
		re1	150-300	5YR 4/4						10	33 54
		re2	300-600	5YR 4/4						23	25 51
C2	Magwa	ah	0-150	10YR 2/2						31	27 43
		ye1	150-300	10YR 5/4						19	29 52
		ye2	300-450	10YR 4/4						16	36 48
C3	Inanda	ah	0-150	10YR 3/3						41	25 33
		re1	150-300	5YR 3/4						26	32 41
		re2	300-900	5YR 3/4						27	29 44
		so	900-1200	5YR 4/6						25	42 33
		ah	0-300	10YR 3/3						26	38 37
C5	Inanda	Re1	300-900	5YR 3/4						13	26 60
		Re2	900-1500	5YR 4/6	common	prominent	med	10YR 2/1 2.5YR3/4	Mn ³⁺ Fe ³⁺	27	41 33
		so	1500-1950	5YR 5/6	few	faint	fine	10YR6/1	Fe ²⁺	26	51 23
C9	Inanda	ah	0-300	10YR 3/3						64	10 26
		re1	300-450	5YR3/4						68	10 20
		re2	450-1200	5YR 4/6	few	prominent	fine	2.5YR4/6	Fe ³⁺	38	18 44
		so	1200-2100	2.5YR3/4	common	prominent	med	10YR2/1	Mn ³⁺	43	18 37

Mn increases unsystematically with depth in all studied profiles (Figure 6.6). The association of increased manganese concentrations with wetter depths of the profile is an example of migration and concentration of specific soil constituents facilitated by vertical internal water movement. In all the profiles there is an apparent loss of Mn in the B1 horizon and accumulation in the B3 horizon and the saprolite, mainly localized in fine to medium black mottles. The presence of Fe and Mn mottles are a good indicator of periodic saturation, and generally an increase in their abundance and size correspond to an increase in the degree of saturation.

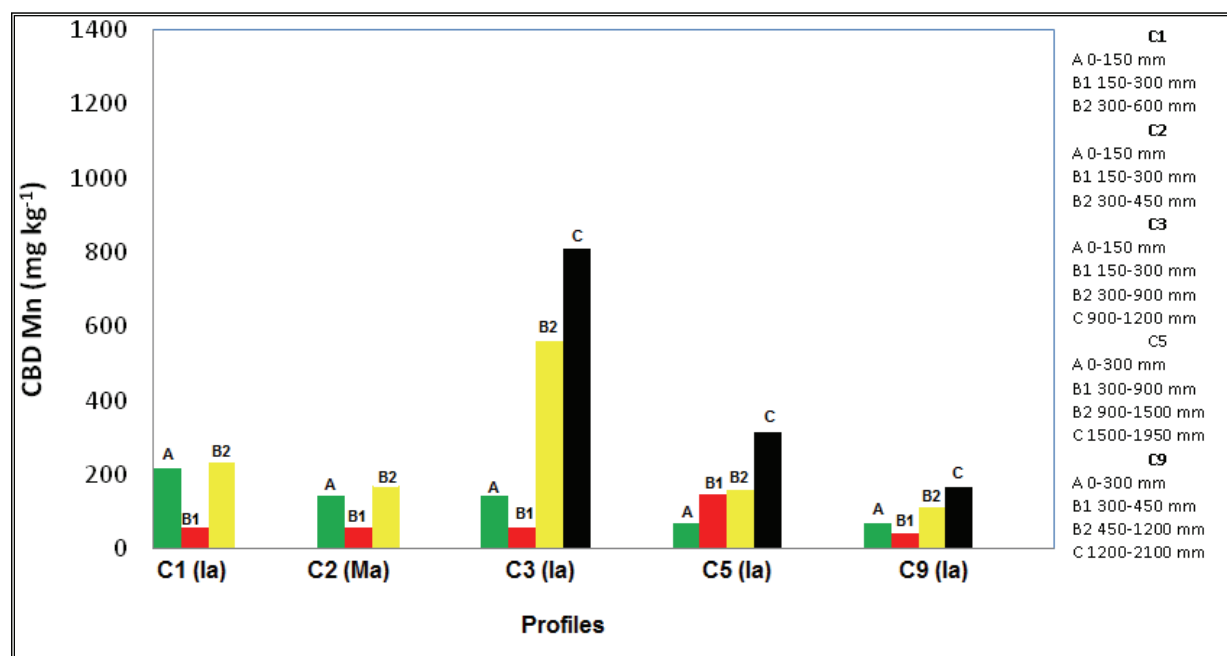


Figure 6.6 Distribution of CBD Mn for the profiles studied.

Organic carbon content

Organic carbon (OC) is generally high in the topsoils and decreases linearly with depth in all studied profiles (Figure 6.7). It ranges in the topsoils from 4.6% at C9 to 6.0% at C1. The high amount of OC is attributed to dense vegetation in the catchment as a result of high rainfall and cool temperature which minimizes oxidation of organic matter. Also, as these sites are uncultivated, the exposure of organic matter to an oxidative environment is minimal.

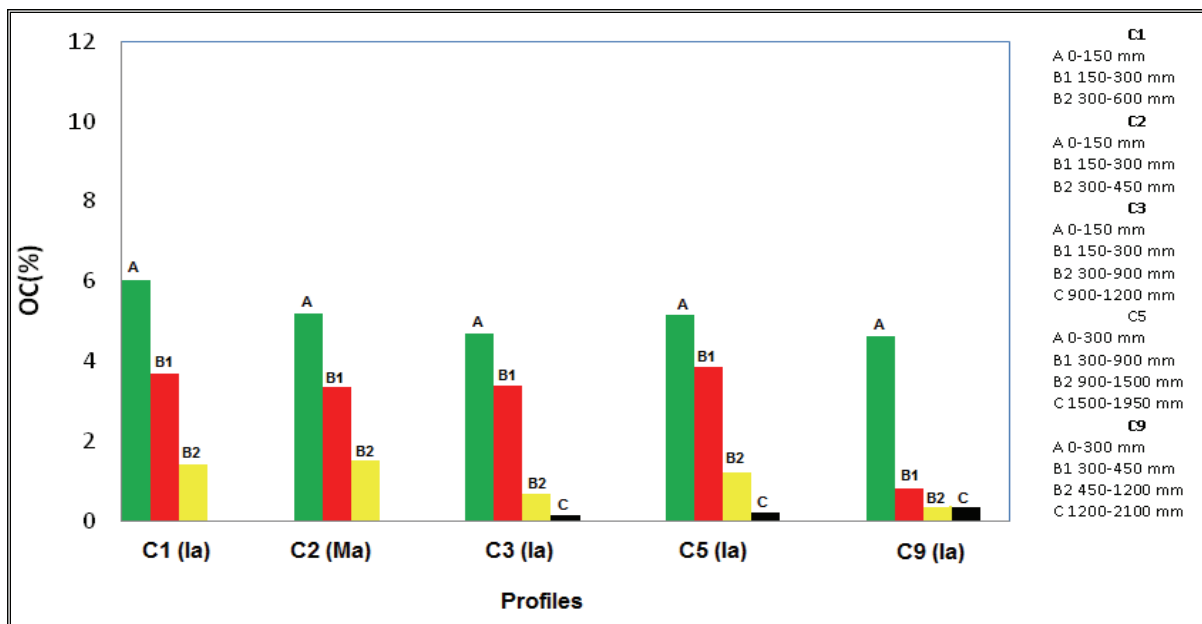


Figure 6.7 Distribution of organic carbon for the profiles studied.

pH

Most pH(H₂O) values in the A and B1 horizons of upslope soil profiles are below 4.8 and increase to above 4.8 in lower lying profiles (Figure 6.8). The high acidity in these soils is caused by higher rainfall that leaches out basic cations, and by greater activity of acidic humic substances as a result of slowed organic matter decomposition at these higher elevations.

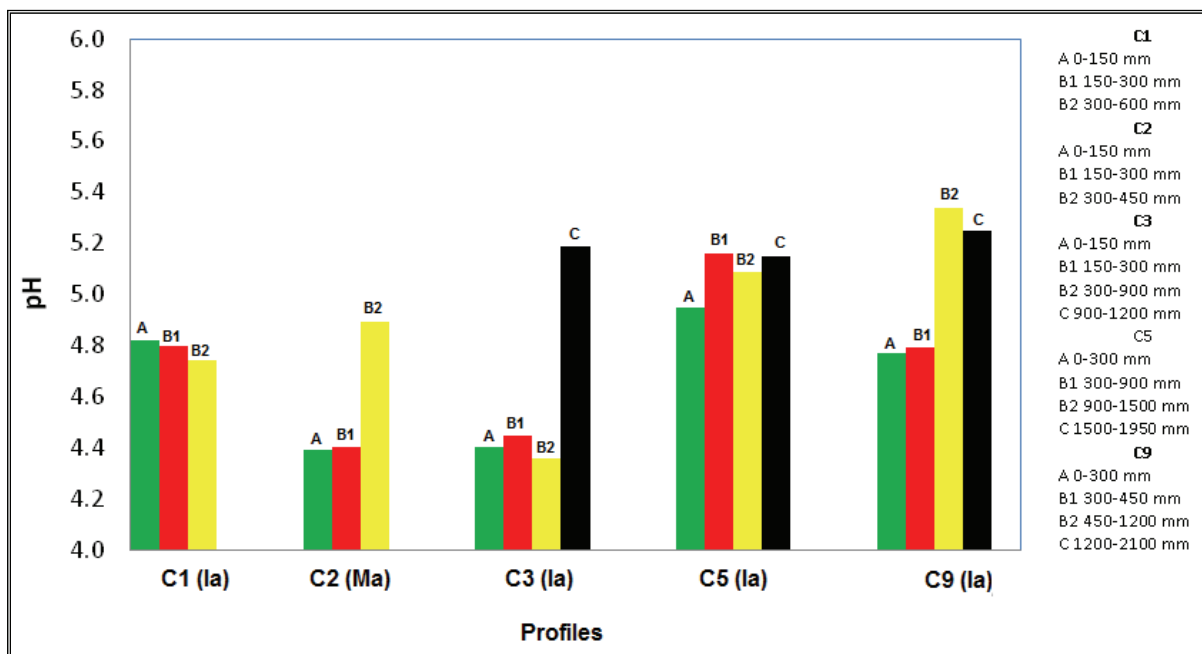


Figure 6.8 Distribution of pH for the profiles studied.

6.3.3.2 Soil water regime

The soil water content data used to calculate the degree of saturated were measured by Everson *et al.* (1998). Their neutron access tubes were all drilled to a standard depth of 1875 m. This depth was found to be in the saprolite of most profiles. The location of the access tubes is shown in Figure 6.1.

Neutron access tube C1

The profile was classified as Inanda 1200 and is situated at the start of a 200 m downslope transect. The profile is situated in an upper midslope, with a slope of 19%. The rainfall and S values in the humic A (measured at 125 mm) and red apedal B (measured at 625 mm) horizons shows a strong seasonal trend (Figure 6.9).

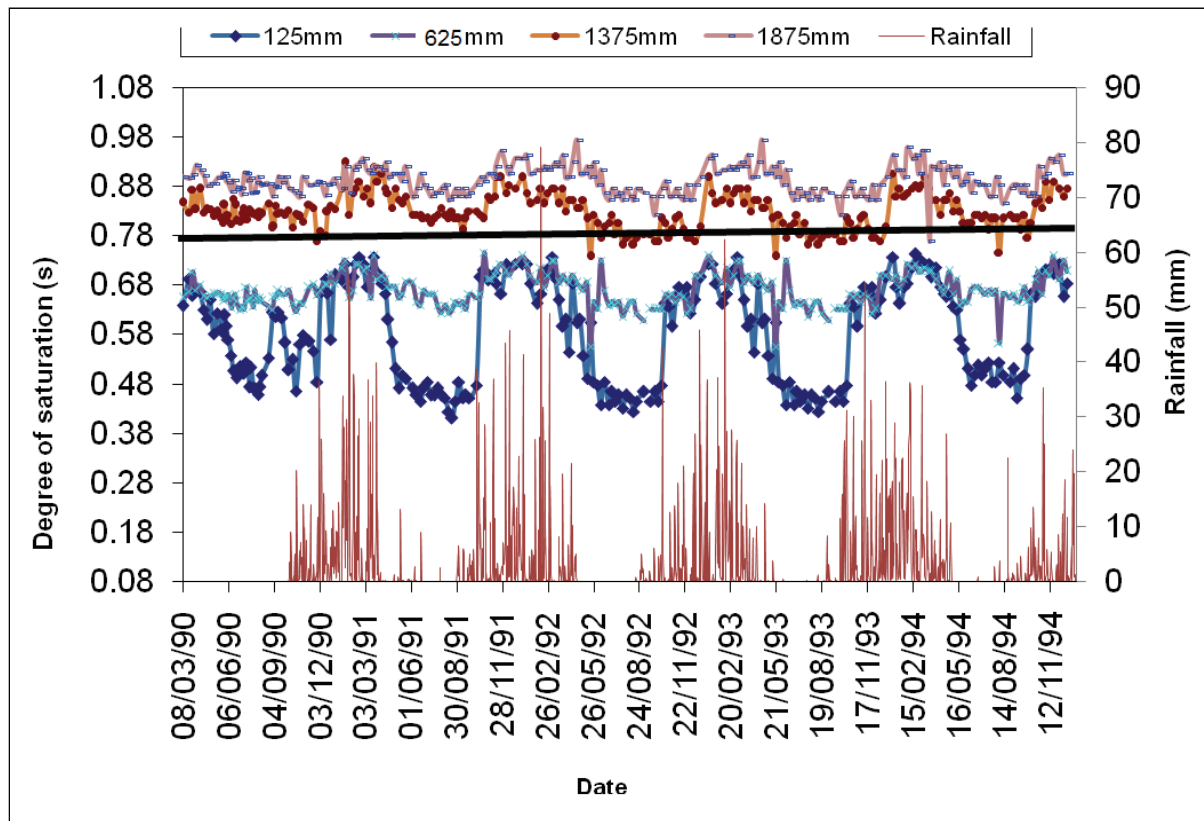


Figure 6.9 Degree of saturation for the Inanda soil profile at C1 for the period March 1990 to November 1994 with associated rainfall.

The water content (θ) in this profile is on average > 0.78 S in the saprolite at 1375 mm for 319 days year⁻¹ and at 1875 mm depth for 357 days year⁻¹ (Table 6.6). The saprolite was reached at 700 mm depth and no distinct morphological signs of wetness were detected within this depth.

The absence of any morphological signs of wetness in the red apedal B horizon at 625 mm is well supported by the zero $AD_{s>0.78}$ values (Table 6.6).

Table 6.6 $AD_{s>0.78}$ for the Inanda (C1) profile during the 4 rain season 1990/91-1993/94

Access tube No.	Depth (mm)	Diag. horizon	90/91 $AD_{s>0.78}$ (Days year ⁻¹)	91/92	92/93	93/94	Mean	Std. dev
C1	125	ah	0	0	0	0	0	0
	625	re	0	0	0	0	0	0
	1375	so	361	352	276	288	319	43
	1875	so	365	365	359	348	357	8
Seasonal rainfall: 1 Oct 30 Sept (mm)			1223	1092	1093	1469		

ah=humic re=red apedal so=saprolite

The zero $AD_{s>0.78}$ values are, however, probably somewhat misleading because neutron water meter readings were generally only taken weekly, and presumably not during rain storms, or even soon afterwards. The zero values nevertheless show that generally any degree of wetness >0.78 S was short lived. It is clear that drainage was rapid.

Neutron access tube C2

The profile is situated in an upper midslope position, with a slope of 19%. The profile was classified as Magwa 1200 and is situated 10 m downslope from C1. During dry months the humic A (125 mm) was much drier than the underlying horizons. Like all the other profiles, this is according to expectation, as the humic A, being the top horizon, undergoes the greatest net water loss due to ET during rain free winter months. This variation decreases in prominence in the deeper horizons (Figure 6.10).

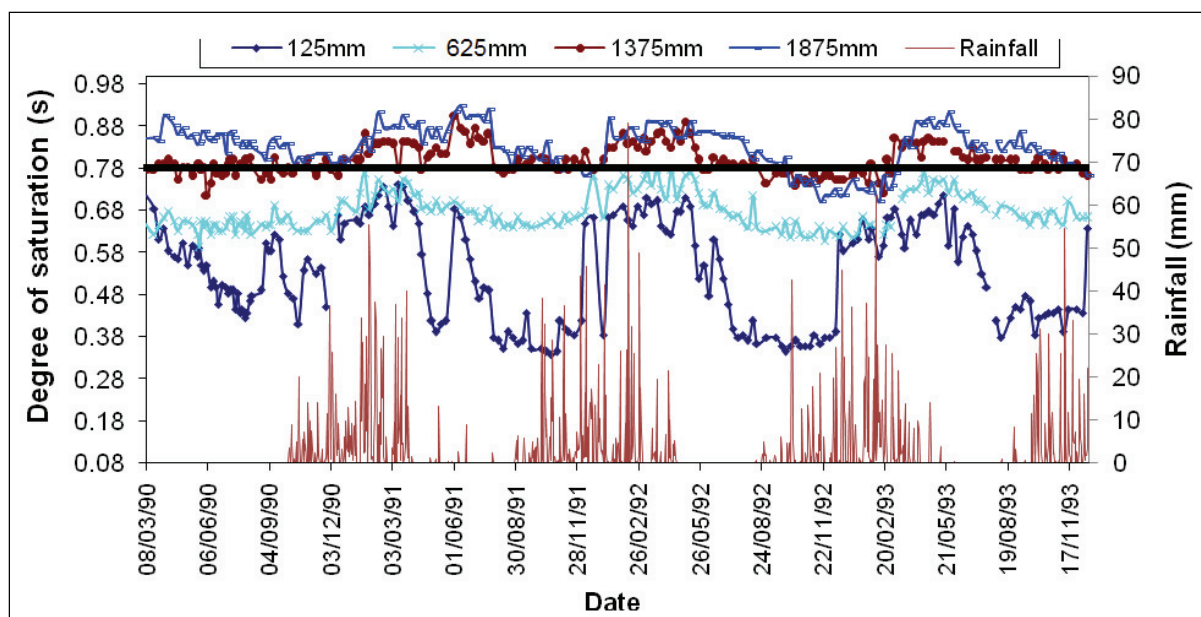


Figure 6.10 Degree of saturation for the Magwa soil profile at C2 for the period March 1990 to November 1993 with associated rainfall.

This profile is saturated above 0.78 S in the upper saprolite at 1375 mm for 242 days year⁻¹ and for 293 day year⁻¹ in the lower saprolite at 1875 mm (Figure 6.10 & Table 6.7). The saprolite was reached at 625 mm depth and no distinct morphological signs of wetness were observed within this depth, showing good agreement with the AD_{s>0.78} values (Table 6.7).

Table 6.7 AD_{s>0.78} for the Magwa (C2) profile during the 3 rain seasons 1990/91-1992/93

Access tube	Depth	Diagnostic	90/91	91/92	92/93	Mean	Std. dev
No.	(mm)	horizon	AD _{s>0.78} (Days year ⁻¹)				
C2	125	ah	0	0	0	0	0
	625	so	0	0	0	0	0
	1375	so	261	292	172	242	51
	1875	so	359	324	196	293	70
Season rainfall:1							
Oct							
30 Sept (mm)			1223	1092	1093		

ah=humic, ye=yellow brown apedal, so=saprolite.

Neutron access tube C3

The profile is situated in an upper midslope position, with a slope of 19%. The profile was classified as Inanda 1200. The relationship between the seasonal trend of rainfall and S values is evident in Figure 6.11 with S values increasing during the rainy season, as expected, and

decreasing during dry winter months. This is most prominent in the A horizon due to water loss by evapotranspiration there.

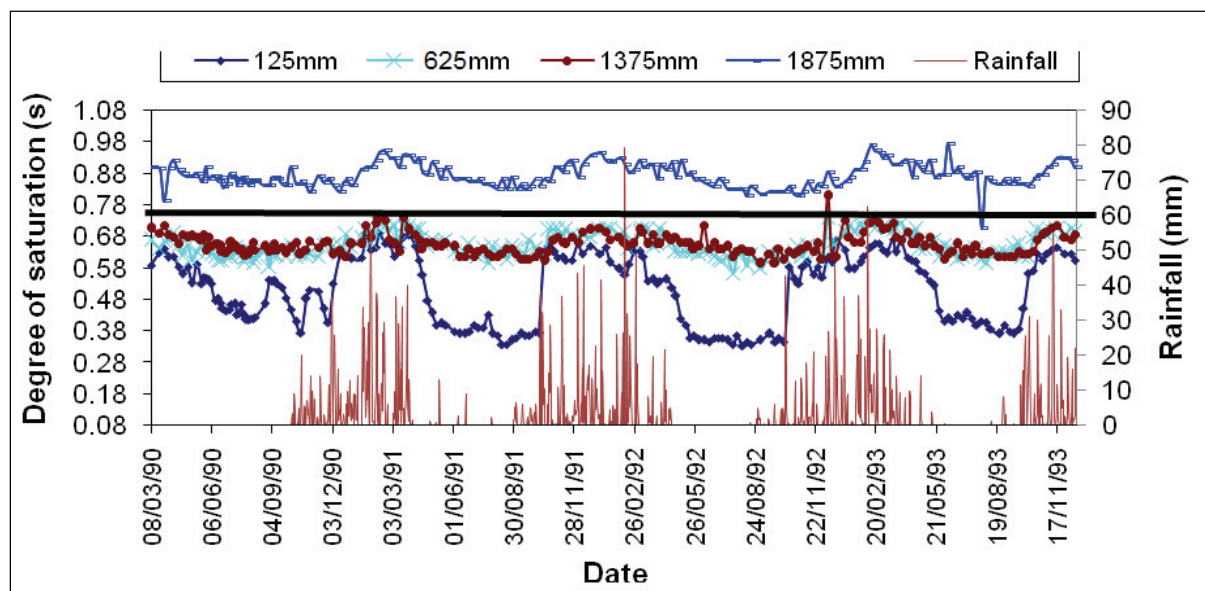


Figure 6.11 Degree of saturation for the Inanda soil profile at C3 for the period March 1990 to November 1993 with associated rainfall.

The mean $AD_{>0.78}$ values increase from a mere 3 days year⁻¹ in the upper saprolite at 1375 mm to 358 day year⁻¹ in the lower saprolite at 1875 mm (Figure 6.11 & Table 6.8). The profile was augered to a depth of 1200 mm with no distinct morphological signs of wetness observed to this depth. As at C1 and C2 the results show good agreement between the morphological features and $AD_{s>0.78}$ values (Table 6.8).

Table 6.8. $AD_{s>0.78}$ for the Inanda (C3) profile during the 3 rain season 1990/91-1992/93

Access tube	Depth	Diagnostic	90/91	91/92	92/93	Mean	Std. dev
No.	(mm)	horizon	$AD_{s>0.78}$ (Days year ⁻¹)				
C3	125	ah	0	0	0	0	0
	625	re	0	0	0	0	0
	1375	so	0	0	9	3	4
	1875	so	362	365	350	358	5
Seasonal rainfall:							
1 Oct-30 Sept							
(mm)			1223	1092	1093		

ah=humic, re=red apedal, so=saprolite.

Neutron access tube C5

The profile is situated in an upper midslope position, much closer to the stream than C1, C2 and C3, with a slope of 19%. The profile was classified as Inanda 1200. As in the other profiles S

values decreased markedly in the A horizon during dry winter months due mainly to water loss by ET, and due to drainage at the two deep measuring depths.

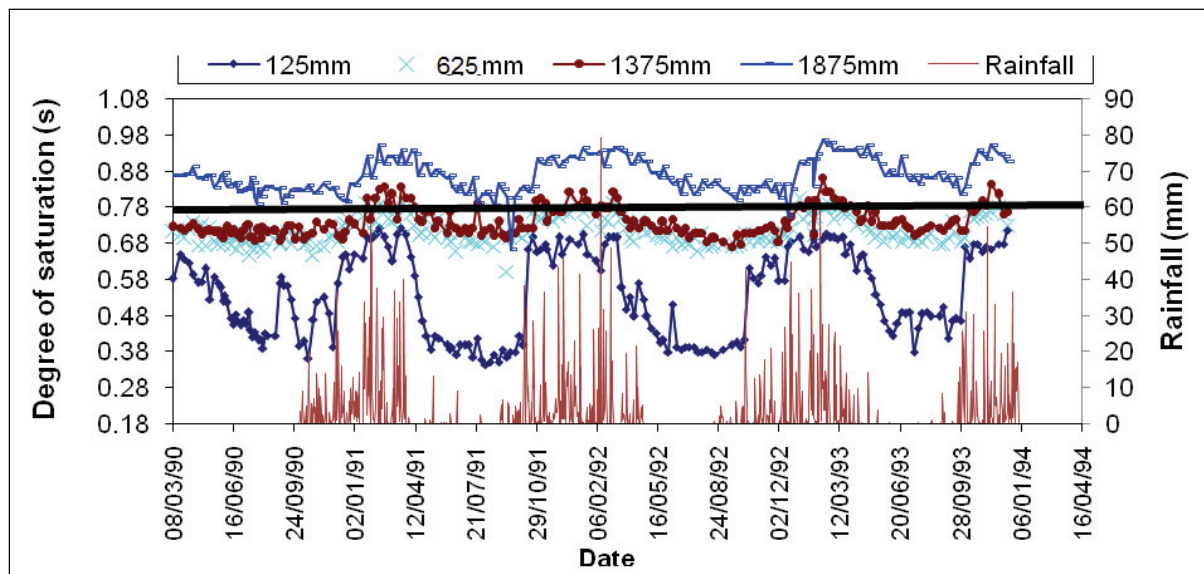


Figure 6.12 Degree of saturation for the Inanda soil profile at C5 for the period March 1990 to November 1993 with associated rainfall.

The mean $AD_{s>0.78}$ values increased from 20 days year⁻¹ in the red apedal B1 at 675 mm to 84 days year⁻¹ in the red apedal B2 horizon at 1375 mm depth and 360 days year⁻¹ in the saprolite at 1875 mm (Figure 6.12 & Table 6.9). Red, grey and black mottles of Fe and Mn were found at 1875 mm depth in the saprolite, caused no doubt by the high $AD_{s>0.78}$ values promoting redox conditions. The high $AD_{s>0.78}$ value of 84 days year⁻¹ in the red apedal B2 horizon at 1375 mm would also be expected to produce redoximorphic conditions. However, this was not the case. The reason for this anomaly is not clear. It may be due to a short residence times and fast flowing water. There are however, other factors that affect redox reactions which may have been operative here.

Table 6.9 $AD_{s>0.78}$ for the Inanda (C5) profile during 3 rain seasons 1990/91-1992/93

Access tube	Depth	Diagnostic	90/91	91/92	92/93	Mean	Std. dev
No.	(mm)	horizon	$AD_{s>0.78}$ (Days year ⁻¹)				
C5C	125	ah	0	0	0	0	0
	625	re	18	23	20	20	2
	1375	re	65	92	94	84	13
	1875	so	362	359	359	360	1
Seasonal rainfall: 1 Oct-30 Sept (mm)			1223	1092	1093		

ah=humic, re=red apedal, so=saprolite.

Neutron access tube C9

The profile is situated in the lower midslope position, with a slope of 18%. The profile was classified as Inanda 1200. $AD_{s>0.78}$ values decrease in the A horizon during dry winter months due mainly to water loss by ET and possibly some drainage.

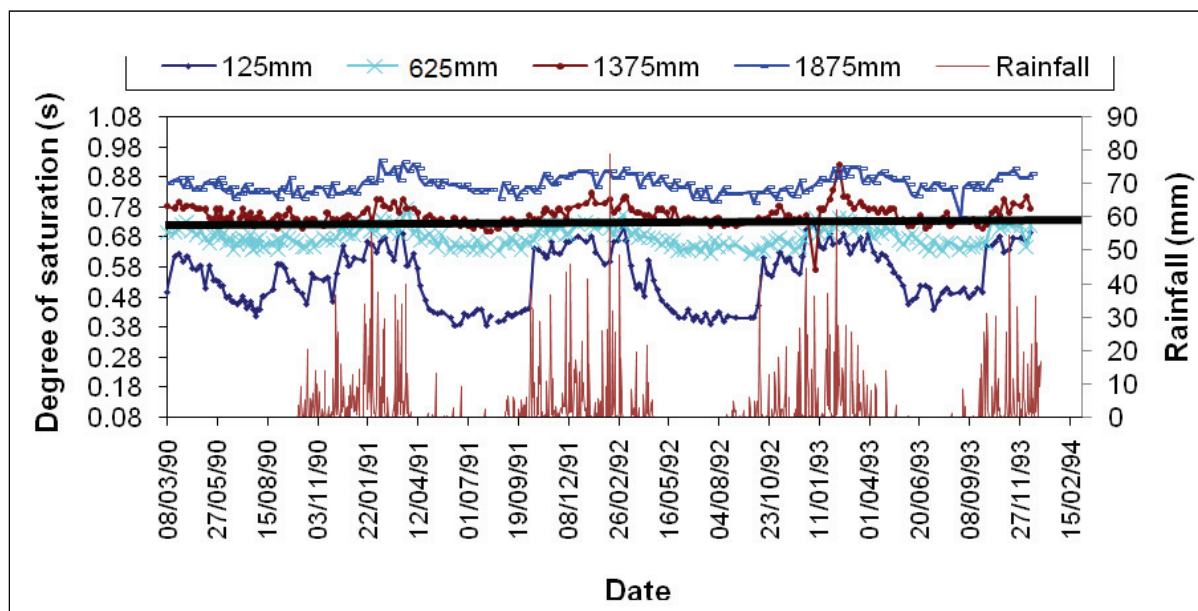


Figure 6.13 Degree of saturation for the Inanda soil profile at C9 for the period March 1990 to November 1993 with associated rainfall.

The mean $AD_{s>0.78}$ values increased from 58 days year⁻¹ in the red apedal B2 to 350 days year⁻¹ in the saprolite (Figure 6.13 & Table 6.10). In this profile, red and black mottles of Fe and Mn were found in the red apedal B2 horizon at 1375 mm, indicating that redox reactions occur to a limited extent, probably only during relatively infrequent periods of continuous high rainfall. Supporting evidence for the validity of this interpretation of the morphological observation is provided by the $AD_{s>0.78}$ values. In the saprolite at 1800 mm in addition to red and black mottles grey mottles were also found, providing morphological evidence for the intense hydromorphy expressed in the very high $AD_{s>0.78}$ values.

Table 6.10 $AD_{>0.78}$ for the Inanda (C9) profile during 3 rain season 1990/91-1992/93

Access tube No.	Depth (mm)	Diagnostic horizon	90/91 $AD_{>0.78}$ (Days year ⁻¹)	91/92	92/93	Mean	Std. dev
C9	125	ah	0	0	0	0	0
	625	re	0	0	0	0	0
	1375	re	34	78	63	58	18
	1875	so	361	347	342	350	8
Seasonal rainfall:1							
Oct-							
30 Sept (mm)			1223	1092	1093		

ah=humic, re=apedal, so=saprolite.

6.4 ESTIMATING THE STORAGE CAPACITY OF THE VADOSE ZONE

It is quite clear that the deep high porosity soils (upper vadose zone), and deep weathered saprolite of the intermediate and lower vadose zones of the catchment make major contributions to streamflow recession during rain free periods due to their significant storage capacity. An attempt is made here to estimate this storage capacity during hydrological year 1994/95. Effective rainfall, streamflow and groundwater data from Everson *et al.* (1998) are used for the period 1/1/95 to 10/5/95. The following water balance equation was solved to determine the storage capacity of the vadose zone;

$$P_{\text{eff}} = Q + G + VS \quad (6.4)$$

Therefore $VS = P_{\text{eff}} - (Q + G)$

Where; P_{eff} = effective rainfall (rainfall – evapotranspiration) (mm)

Q = outflow from the catchment (mm)

G = Groundwater replenishment (mm)

VS = Vadose zone storage (mm)

Table 6.11 Data used to estimate the groundwater storage capacity of Cathedral Peak VI catchment

	Approx. decrease in groundwater levels (mm). 1/1/95-10/5/95	Estimated values			
		Area represented (ha)	^B Volume of storage material ($\text{m}^3 \times 10^4$)	Db of storage material (Mg m^{-3})	Porosity of storage material
^A Borehole Site					^C Volume of drainable water stored ($\text{m}^3 \times 10^4$)
D 01	1500	22.6	33.9	2.0	0.245
D 02	680	22.6	15.4	2.0	0.245
D 05	200	22.5	4.5	2.0	0.245
					13.18

A The locations in the catchment are described by Everson *et al.* (1998).

B Material in which the groundwater was stored.

C This is also the estimated volume of groundwater which is expected to flow out as baseflow during the following dry winter and early spring period

It is worth recalling that the catchment is underlain by an impervious layer of basalt, and no deep water losses occur (Everson *et al.*, 1998). Three boreholes were installed to depths of 22 m, 10.5 m and 5 m at the upper slope (01), midslope (02) and toeslope (03), respectively, to monitor water table levels; derived results from Everson *et al.* (1998) are presented in Table 6.11. An assumption was made that each borehole represents 1/3 (22.6 ha) of the catchment and that the bulk density for the saturated zone is 2.00 Mg m^{-3} .

The measured values of P_{eff} and Q for the period 1/1/1995-10/5/1995 are 401 mm and 150 mm respectively. The value of G from table 6.11 converted to appropriate units is 195 mm. Substituting these values in the water balance equation yields an estimated value of VS (vadose zone storage) of 56 mm.

6.5 HYDRAULIC PROPERTIES OF THE INANDA SOIL

The taking of undisturbed soil samples needed to study hydraulic properties was hampered by the fact that we were denied permission to dig soil pits at any sites in the catchment by the controllers of the Maluti-Drakensberg Transfrontier Project under the Kwazulu-Natal Department of Environmental Affairs. It was nevertheless possible to take a few undisturbed samples. The behaviour of these samples was, in our experience, unprecedented. They shrank irreversibly, to a degree that would have significantly altered the pore size distribution, making them unsuitable for the determination of water retention characteristics and therefore the prediction of the unsaturated hydraulic conductivity curve. The main cause of the shrinking of the samples is evidently due to the high content of the clay mineral allophone in these soils (D. Turner, personal communication, 2010), and also their high organic matter content. Augered soil samples have therefore provided the main information needed to classify the soils and facilitate extrapolation of hydraulic properties from comparable soils in other similar pedological environments. The fact that this is a reasonable procedure accentuates the value of detailed soil profile descriptions, and their accompanying analytical data, as effective holistic pedo-transfer functions.

Fortunately, at an earlier date, Lorentz *et al.* (2004) had studied the hydraulic properties of the A horizon of the Cathedral Peak VI Inanda soil at a representative site. They measured the K_s value, took undisturbed samples for the determination of the water retention curve and processed the data to get the Van Genuchten parameters presented in table 6.12. To represent the B horizon, data obtained by Musto (1994) for a comparable soil horizon in KwaZulu-Natal have been used. They are also presented in table 6.12.

Table 6.12 Appropriate Van Genuchten parameters for the Cathedral Peak VI Inanda soil

Horizon	θ_r (cm ³ /cm ³)	θ_s (cm ³ /cm ³)	m	Ks (mm h ⁻¹)
A ¹	0.420	0.643	0.1883	122
B ²	0.370	0.550	0.3967	130

¹Lorentz *et al.* (2004) ² Musto (1994)

The procedure proposed by Van Genuchten (1980) has been used to employ the parameters in table 6.12 to predict the hydraulic conductivity/water content curves presented in Figure 6.14. The information contained in Figure 6.14 is needed by process hydrologists to refine their hydrological models.

Another important hydrological property of the soils in a catchment is the drained upper limit (DUL). Estimates of this value for the Cathedral Peak VI Inanda soil were made in two ways. Firstly, using the drainage curve for site C7, for the period 31/3/91-3/8/91 presented in Figure 6.17. Based on the shape of the hydrograph which included this period, it was hypothesized that the water that flowed out during the 41 day period 31/3/91-10/5/91 came mainly from the upper and intermediate vadose zones (Table 6.15). Inserting 41 into the equation for C7 in Figure 6.17 yields the predicted water content at the predicted date DUL would have been reached, i.e. 891 mm. It needs to be kept in mind that this value was obtained with grassland vegetation at the site which would have been drawing water by ET throughout the 41 day period. Since we are seeking a DUL estimate for the soil alone, an adjustment needs to be made for the loss by ET. Using the data supplied by Everson *et al.* (1998) ET minus rainfall for the 41 days was calculated to be 51 mm. The predicted 'soil alone' DUL value is therefore 891 + 51 = 942 mm.

The second procedure used to estimate DUL is based on data from appropriate water retention curves. It is reasonable to assume that using the estimated water content of the Inanda soil profile at a suction of 10 kPa (0.1 bar) will provide an acceptable estimate of the water content at the drained upper limit (DUL). Using data presented by Lorentz *et al.* (2004) and Musto (1994) in their publications the appropriate water contents are 0.50 and 0.40 m³ m⁻³ for the A and B horizons, respectively. Weighting these values according to the depths of the A horizon (0-500 mm) and B horizon (500-2000 mm), yields a predicted DUL value of 850 mm. Although somewhat different from the first estimate of 942 mm, it is nevertheless of a similar order. The value of pedotransfer functions is therefore clearly demonstrated. It is clear from numerous publications, e.g. McDonnell *et al.* (2007), Royappen *et al.* (2002), Kutilek (2004) that the soil hydraulic information presented would be useful for hydrologists.

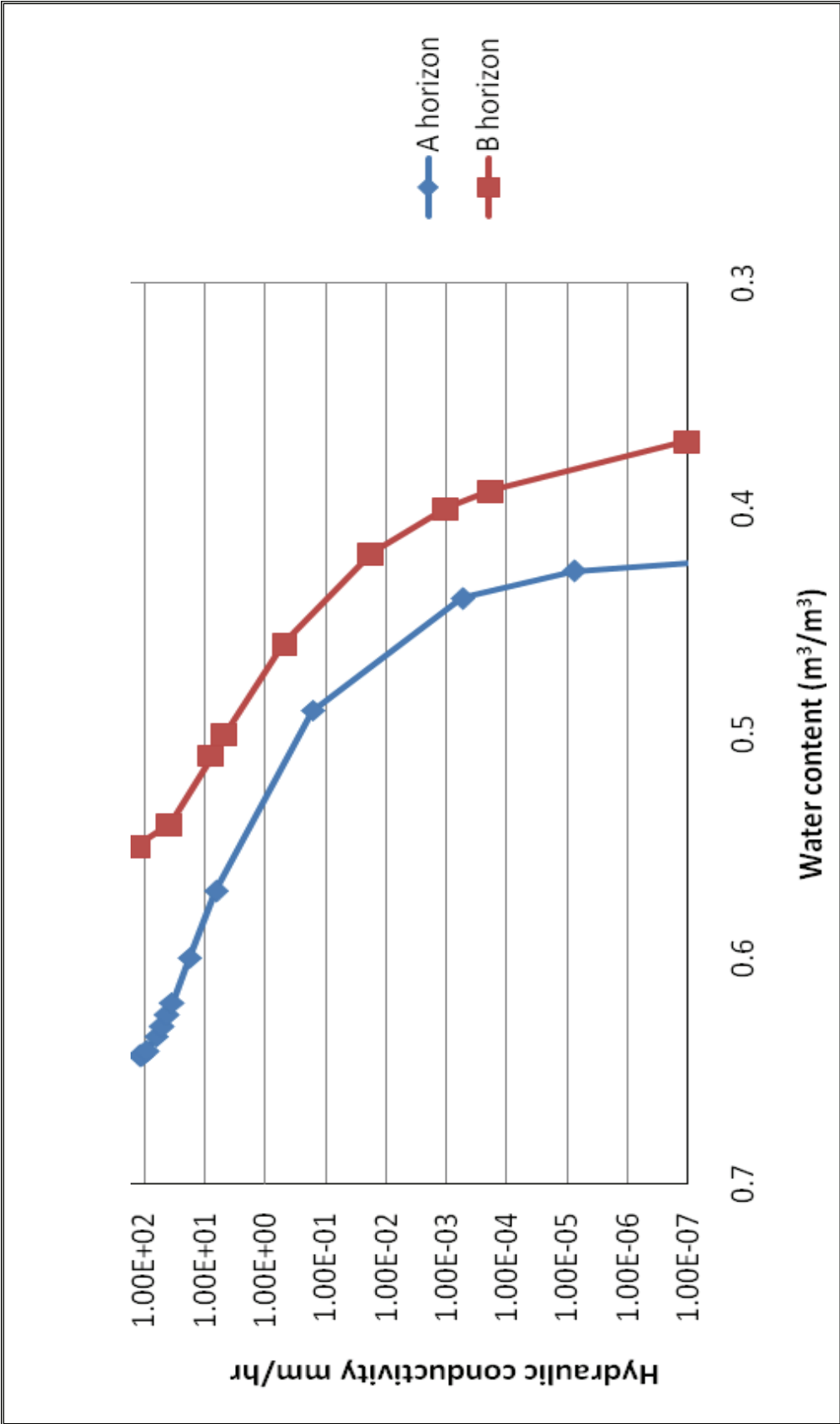


Figure 6.14 Appropriate unsaturated hydraulic conductivity curve for the humic A and red apedal B horizons of Cathedral Peak VI Inanda soil form.

6.6 FACILITATING INTERPRETATION OF THE HYDROGRAPH USING SOIL DRAINAGE CURVES

6.6.1 Introduction

The origin of the streamflow from any catchment can be traced to a number of major sources, viz. overland flow, flow caused by drainage out of the soils (upper and intermediate vadose zones), flow caused by drainage out of the lower vadose zone, and base flow (Hursh & Hoover, 1941; Hursh & Brater, 1941; Kirkby, 1993; Burt & Butcher, 1985; Sanda & Cislerova, 1998; Schulze, 2004; Lin *et al.*, 2006; Ticehurst *et al.*, 2007). In a catchment with deep soils outflow from them between saturation and the drained upper limit makes a major contribution to the rates and volumes of the interflow component of streamflow (Sanda & Cislerova, 1998). Hursh & Hoover (1941) were able to separate an additional component of a storm hydrograph in the form of a channel precipitation factor. When non relevant contributions to streamflow have been removed from the hydrograph, the remainder of the storm discharge may be related to soil profile characteristics with less difficulty (Hursh & Hoover, 1941). Using subsurface trenches, Sanda & Cislerova (1998) related the outflow from the bottom sections of the soil profile to the outflow from the whole watershed for a specific period and found that flow hydrographs had a very similar shape. This is corroborated by Weyman (1975) who reported that the shape of the hydrograph is related to the speed at which the stormflow processes operate and the distance over which water has to be carried to the gauging point. Ultimately it is the variations of soil and topography within the basin which will largely determine travel distance. In an isotropic soil, profile water will be redistributed vertically downwards after infiltration since hydraulic potential will be highest at the ground surface. If not interrupted, this water will continue to percolate through the soil profile and into the underlying parent material until the soil dries to the point where capillary forces are sufficiently strong to hold the water against the pull of gravity (drained upper limit). It is this drainage process that is the focus of this study. In practice, most soils show some form of horizon development with permeability often decreasing down the profile as a result of various factors, or they at least show a marked decrease in permeability at the transition to the underlying parent material (Weyman, 1975). Drainage from the soil profile is thus an important source of recharge for many groundwater systems and a source of lateral subsurface flow if there is an impeding layer in the soil profile limiting vertical drainage or anisotropy between vertical and horizontal hydraulic conductivities (Mosley 1979; Grayson *et al.*, 1997; McGlynn *et al.*, 2002; Mcguire *et al.*, 2005; Sivapalan, 2003). Hensley *et al.* (2000) characterized drainage properties of different soils using drainage curves. This was necessary to quantify the water balance. In a similar way, the soil water balance has been used to quantify streamflow in various catchments

(Everson *et al.* 1998; Zere, 2005). They achieved this by subtracting losses through evapotranspiration and deep drainage or storage from total precipitation. It is therefore hypothesized that reliable soil drainage curves can facilitate the interpretation of the subsurface flow as reflected in the Cathedral Peak VI catchment hydrograph.

6.6.2 Field site and methods

6.6.2.1 Selected profiles/Sites

Five sites were selected in the catchment for representing the almost homogeneous soils. Soil water contents were measured by neutron water meter along a 200 m transect at access tubes placed approximately 20 m apart and to a depth of 2 m (Everson *et al.*, 1998). Approximately weekly soil water content measurements were routinely taken from these sites at 0.25 m depth intervals for four years. This data was collected, published (Everson *et al.*, 1998) and made available for this study. Because of some shortcomings in the original neutron water meter calibration procedure it was found necessary to make appropriate improvements. The improved results were used in this study. Three main soil profiles for constructing drainage curves were used. In cases of missing data for some years, two similar alternative profiles were used. All the soils from these profiles are freely drained soils and are hydrologically representative of the whole catchment. These profiles were identified during the transect soil survey in the catchment and divided by depth, and the area occupied, into three types namely, deep, medium and shallow soils (Table 6.13).

Table 6.13 Estimated areas represented by selected profiles of different depths

Profile name	Area occupied (ha)	Depth (mm)	Type
C7/C9	16	1800	Deep
C6	14	1600	Medium
C5/C5C	12.2	1300	Shallow
Total	42.2		

The soil forms from these measuring sites occupy 42.2 ha out of 67.7 ha catchment (Table 6.13). The remaining 25.5 ha is occupied by rock outcrops (1.4 ha), Champagne soil form (7.7 ha), and Nomanci soil form (16.4 ha). For the portion of the hydrograph on which this study is focused (phases 3 and 4 in Figure 6.16), it is hypothesized that the contributions of the outflow from the upper and intermediate vadose zones of the 25.5 ha during the autumn rainfree period will be minimal. It is expected that the contribution from the shallow Nomanci soils on the steep slopes at the top of the catchment (Figure 6.1) will make a major contribution

to phase 2 (Figure 6.16). A continuous contribution to streamflow is expected to occur via interflow out of the Champagne soils in the lower lying marshy areas and that this contribution will be included in the baseflow component in Figure 6.16.

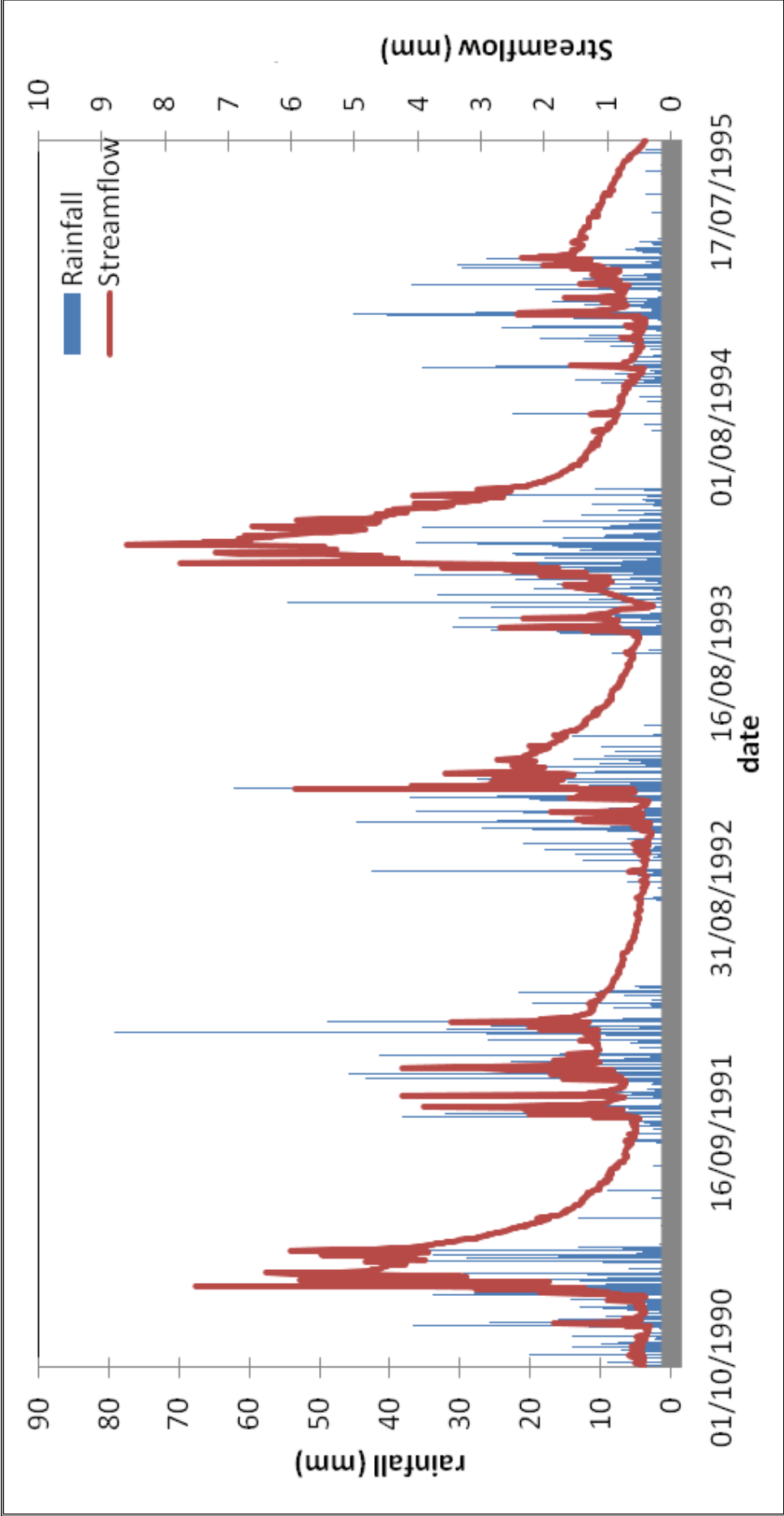


Figure 6.15 Rainfall and streamflow from 1990/91 to 1994/95 for the Cathedral Peak VI catchment (Everson *et al.*, 1998). Rainfree days for each year are also shown.

6.6.2.2 Identifying suitable draining periods

In this study outflow contributions to streamflow, as expressed in the hydrograph, will be subdivided into two portions, the upper vadose zone consisting of the soil to a maximum depth of around 2.0 m, and the lower vadose zone consisting of the remaining portion down to the water table. Although there are portions of the hydrograph which reflect different relative contributions from each of these sources, clear boundaries between them do not exist because the processes are concurrent to some extent. The outflow from the bottom of the soil profile (upper vadose zone) is hypothesized in this study to be an important contributor to streamflow during rainfree periods. Figure 6.15 shows the catchment hydrograph and rainfall patterns over four years as reported by Everson *et al.* (1998). From this diagram, streamflow shows a definite response to rainfall with high peaks visible during rainy seasons and receding streamflow during rain free periods. The increase in streamflow is only apparent in January/February when the water storage capacity of the upper intermediate and lower vadose zones has been recharged. Rainfree periods are shown (Figure 6.15), during which there is no overland flow, and subsurface flow therefore dictates the shape of the hydrograph. These shapes are therefore logically related to the drainage curves of the soils in the catchment. An example for the almost rainfree period 24/3/91-7/10/91 is presented in Figure 6.16 and the hypothetical phases are described in Table 6.15.

6.6.2.3 Determination of drainage curves

A soil profile drainage curve is determined by taking, at appropriate time intervals, soil water measurements from a previously saturated profile until the decrease in soil water content becomes negligible (Hensley *et al.*, 1993). The volumetric water content vs. time data is used to construct a drainage curve for a profile. An exponential equation is used to describe the curve mathematically. The drainage curve equation that fits the drainage pattern of the soil is given by the equation:

$$\theta = x - b(\ln t) \quad (6.5)$$

Where:

θ	=	water content of the soil profile at time t (mm)
x	=	water content at field saturation (mm)
b	=	slope of the drainage curve (mm d^{-1})
t	=	time after saturation (d)

It will be assumed for the Cathedral Peak VI catchment that after each rain season of a hydrological year, soil profiles will be close enough to field saturation for drainage curves to be determined as described above. For each of the almost rain free periods shown in Figure 6.15 a soil drainage curve for each of the profile types described in Table 6.13 was quantified using

equation (4). The relevant drainage curves and equations are presented in Figures 6.19 to 6.22. The equations were used to calculate the amount of water drained over the measuring period and the results are presented in tables during a particular year. The amount recorded as total streamflow (m^3) during selected draining period was summed and baseflow (Table 6.14) subtracted to get the results presented in each table of different years. During soil survey, seepage from the soils into high level channels of the catchment was noticed, hence the subtraction of baseflow (which comes from deep vadose zone) from total streamflow. Drainage quantities from each profile were multiplied by their respective area (Table 6.13) and summed up to give total drained water from the solum over a total area of 42.2 ha. Evapotranspiration (ET) was subtracted from total change in soil water content to give the actual change in soil water content due to drainage. ET was estimated using average monthly values presented by Everson *et al.* (1998). Selected periods generally are rain free days, but a little rainfall was recorded during these periods which could not have contributed to deep drainage. These small rainfalls would have been dissipated by ET, and are therefore subtracted from ET before deducting ET from total change in soil water from the profiles. For rainfall events that sum to slightly more than ET for a particular period, the excess is ignored as it is assumed that the additional water will only serve to temporarily increase the water content of the root zone without making any contribution to deep drainage. For each year (1991-1994), streamflow during the relatively rain free period was compared with the estimated amount of water drained from the soils.

6.6.3 Results and discussion

6.6.3.1 Components of the stream hydrograph

The major components of a streamflow hydrograph are overland flow and subsurface flow from the vadose zone. Excluding baseflow, those portions of the hydrograph in Figure 6.15, which are virtually rain free, represent subsurface flow from the upper and lower vadose zones of the catchment. The solum of the soils (upper vadose zone) in the catchment is assumed to have been filled up with water during the preceding rain period and is starting to drain out on 23/03/91 (Figure 6.16). Different slopes are segmented into specific outflow phases (Table 6.15), and quantities (Figure 6.16). It is hypothesized that specific factors control drainage during each specific outflow phase. This concept was developed on the assumption that a change in slope of the hydrograph reflects a specific change in soil water regime prevailing in a particular part of the catchment at a specific time. In accordance with the detailed hypothesis presented in Table 6.15, phases 3 and 4 are the appropriate ones to relate to drainage curves of the upper vadose zones of the main soils, to determine their contribution to streamflow. The contributions of phase 5 and 6 flows to total streamflow during phases 3-4

for four years are presented in Table 6.14. They were estimated using raw data of streamflow measured daily in the catchment (Everson *et al.* (1998).

Table 6.14 Estimated contributions of phase 5 and 6 streamflows to total streamflow during phases 3 and 4 of the autumn rain free periods during 1991-1994

Autumn period	No. days	Total streamflow during phases 3 & 4 (m ³)	Estimated streamflow during phase 5 & 6 (m ³)
1991	41	77977	53136
1992	41	33249	16721
1993	41	57365	28917
1994	41	52794	31985

Table 6.15 Description of six phases of the hydrograph shown in Figure 6.16, and hypothesis regarding the main flow processes and sources of water

Phase	Average flow rate (m ³ /d)	Dates	Days	Quantity per phase (m ³)	Dominant drainage processes and sources of water
Phase 1	4076	24/3/1991	1	4076	Overland flow; and upslope macropore flow in the topsoil flowing rapidly into the steep high level channels that feed the main stream
Phase 2	3099.50	25/3/1991 to 30/3/1991	6	18597	Permeable subsoils of Lithocutanic B horizons of high lying Nomanci soils draining rapidly into nearby high level channels.
Phase 3	2296.65	31/3/1991 to 16/4/1991	17	39043	Upper vadose zone of Inandas, Magwa and Kranskop draining mainly into nearby high level channels.
Phase 4	1622.25	17/4/1991 to 10/5/1991	24	38934	Drainage from deep subsoils of Inanda, Magwa and Kranskop mainly into nearby high level channels.
Phase 5	857.25	11/5/1991 to 3/8/1991	85	72866	Drainage from the catchment's lower vadose zone mainly into the high level channels plus drainage from Champagne soils in the two riparian zones. Flowing water was seen in these channels during July and September visits to the catchment
Phase 6	438.78	4/8/1991 to 7/10/1991	65	28521	Baseflow from phreatic zone of the whole catchment plus drainage from Champagne soils

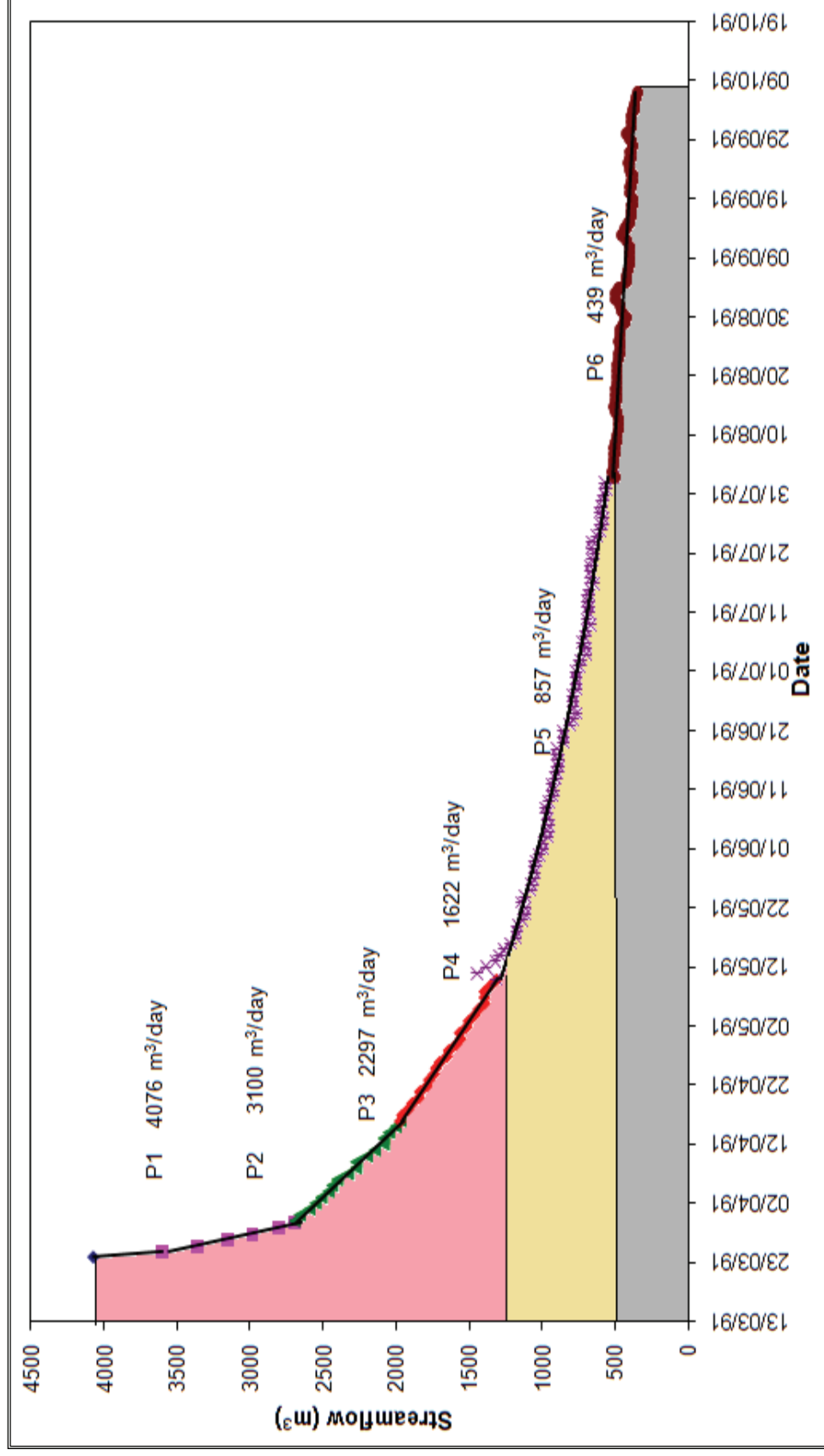


Figure 6.16 The hydrograph for Cathedral Peak VI catchment for the almost rain free period 24/03/91-07/10/91, together with the average flow rates per day during six phases (marked P1 to P6). (Compiled from data of Everson *et al.*, 1998).

6.6.3.2 Soil drainage during the autumn and winter of 1991

Figure 6.17 illustrates drainage curves at NWM access sites C5, C6 and C7 for the period 31/03/91 to 03/08/91. This period represents phases 3 (ending day 17), 4 (ending day 41), and 5 described in Table 6.15. The drainage period has been subdivided into two sections with vertical lines. The first one on the left represents phases 3 and 4. The logarithmic equations in Figure 6.17 describe each drainage curve. They are used to estimate the change in water content (i.e. amount lost by drainage and ET) at day 41, ending phases 3 and 4. Table 6.16 shows the results of change in water contents at each NWM access site, and also streamflow for the selected period of phases 3 and 4. Total change in water content presented here is a result of the vertical downward movement of water with ET subtracted for the period. A noticeable fact is that each drainage curve has an almost negligible slope during phase 5. Most of that change in water content is due to ET, since DUL has evidently been reached. For example, for profile C7 in 1991 the soil water content at the end of 41 days (end of phases 3 & 4) is estimated to be 891 mm. After 120 days (end of phase 5), the water content is estimated to be 856 mm, predicting a change in soil water content of 35 mm. For the phase 5 period of 79 days ET was estimate to be 52 mm, providing supporting evidence for the assumption that all the water loss from the profile during phase 5 was due to ET.

During phases 3 and 4, which lasted for 41 days, the total change in soil water content from all sites representing the 42.2 ha portion of 67.7 ha catchment was estimated at 41625 m³ of which 21564 m³ was estimated as lost by evapotranspiration. The actual change in soil water content due to drainage is therefore estimated at 20061 m³. During this 41 day period outflow from the lower vadose zone and baseflow, described as phase 5 and phase 6 type flows in Table 6.15, would also have been occurring. The data in Figure 6.16 show that these flow rates amounted to 857 and 439 m³/day, respectively, giving an estimated total of 53136 m³ over the 41 day period. To obtain a more reliable estimate of the contribution of upper vadose zone drainage (Figure 6.17) to total streamflow during the 41 day period, based on the hydrograph, 53136 m³ needs therefore to be subtracted from the total streamflow of 77977 m³ during that period (Table 6.16), giving a value of 24841 m³. The similarity of this estimate to the one obtained via the drainage curves, i.e. 20061 m³, indicates that the procedures used are reasonably reliable.

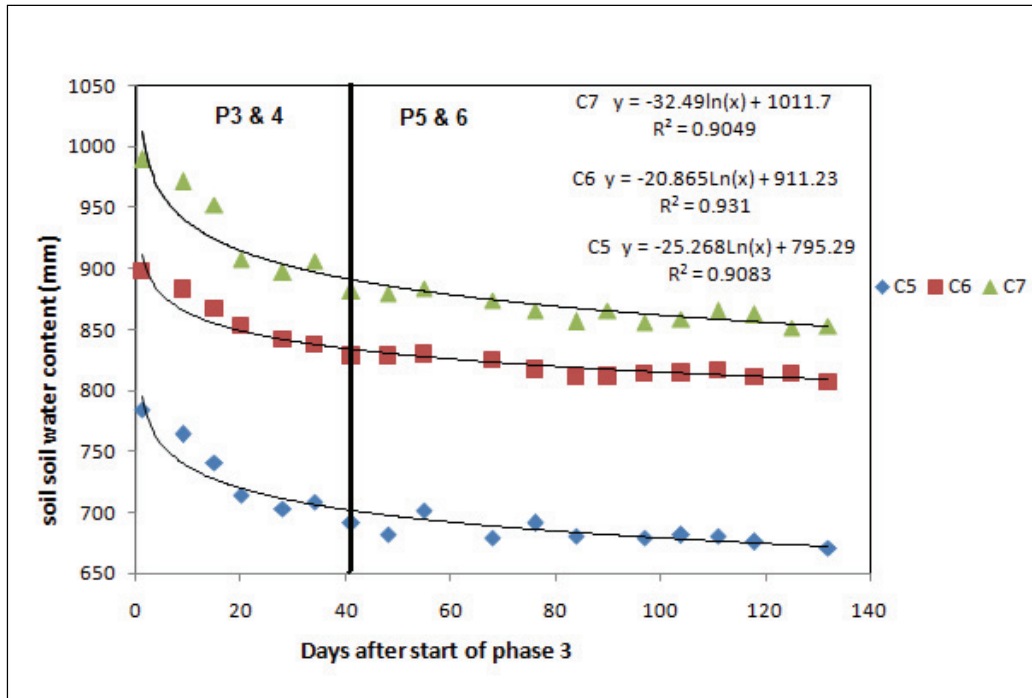


Figure 6.17 Drainage curves for C5, C6, & C7 during 31/03/91 to 03/08/91. P3, P4, P5 and P6 are phases described in Table 6.15.

Table 6.16 Estimated changes in soil water contents of C7, C6, C5 drainage curves and their relationship to streamflow during 31/3/1991 to 10/5/1991 (Phases 3 and 4 from Table 6.15)

NWM site	^A θ at day 1 (mm)	^B θ at day 41 (mm)	Δ profile θ(mm)	m ³ ha	16 ha	14 ha	12.2 ha
C7	1011.7	891	120.7	1207	19312		
C6	911.23	834	77.2	772		10808	
C5	795.29	701	94.3	943			11505
Estimated total Δ θ from 42.2 ha(m ³)				41625			
^C ET – rainfall (m ³)				21564			
Estimated actual Δ θ from the upper vadose zone				20061			
^C Measured total streamflow during the 41 days of phases 3 and 4 (m ³) (Table 6.14)				77977			
Estimated combined contribution to total streamflow during the 41 days from the lower vadose zone and baseflow (m ³)				53136			
Estimate, based on the hydrograph, of the contribution of the upper vadose zone to total streamflow during the 41 day period (m ³)				24841			

^A It is assumed that the soils were close to field saturation (fsat) after the preceding heavy rain.

^B Calculated using the relevant equations in Figure 6.17

^C Obtained from data of Everson *et al.* (1998)

6.6.3.3 Soil drainage during the autumn and winter of 1992

The estimated total soil contribution to streamflow during 1992 is 39048 m³ (Table 6.17). Streamflow for the same period (31/3/92 to 10/5/92) is 33249 m³. It is not possible that the contribution from the soil drainage can exceed streamflow for the same period. This is because all processes contributing to streamflow, including baseflow, are doing so concurrently. The contribution from the soil solum cannot therefore be sole contributor. The baseflow for this year is considerably lower than for the other years (Table 6.14). This might suggest that the water content of the lower vadose zone was low and that the soil water drainage has been draining into this zone, rather into the streamflow directly. This result exposes a shortcoming in the procedure used in this study.

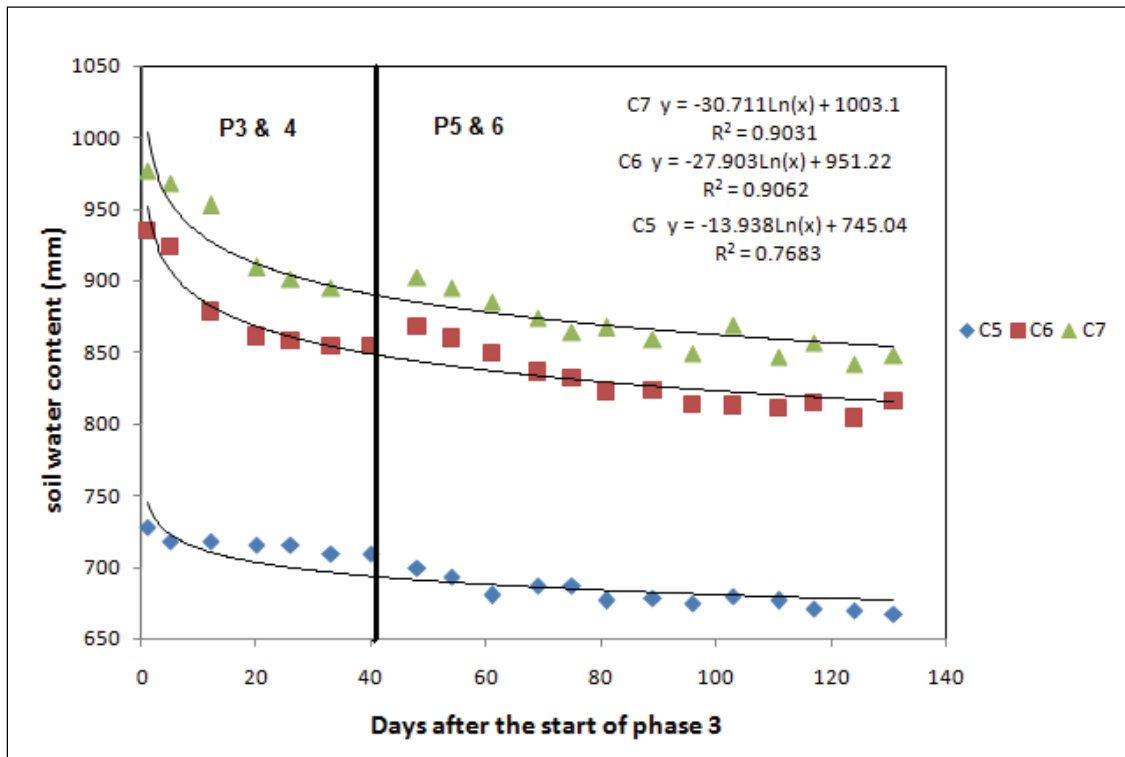


Figure 6.18 Drainage curves for C7, C6 & C5 during 20/03/92 to 02/08/92.

Table 6.17 Estimated changes in soil water contents of C7, C6, C5 drainage curves and their relationship to streamflow during 31/3/1992 to 10/5/1992 (Phases 3 and 4 from Table 6.15)

NWM site	^A θ at day 1 (mm)	^B θ at day 41 (mm)	Δ profile θ(mm)	m ³ ha	16 ha	14 ha	12.2 ha
C7	1003.1	889	114.1	1141	18256		
C6	951.22	848	103.22	1032		14448	
C5	745.04	693	52.04	520			6344
Estimated total Δ θ from 42.2 ha(m ³)							39048
^C ET – rainfall (m ³)							0
Estimated actual Δ θ from the upper vadose zone							39048
^C Measured total streamflow during the 41 days of phases 3 and 4 (m ³) (Table 6.14)							33249
Estimated combined contribution to total streamflow during the 41 days from the lower vadose zone and baseflow (m ³)							16721
Estimate, based on the hydrograph, of the contribution of the upper vadose zone to total streamflow during the 41 day period (m ³)							16528

^A It is assumed that the soils were close to field saturation (fsat) after the preceding heavy rain.

^B Calculated using the relevant equations in Figure 6.18

^C Obtained from data of Everson *et al.* (1998)

6.6.3.4 Soil drainage during the autumn and winter of 1993

The estimated actual soil contribution from soil drainage curves to streamflow during 1993 for the phases 3 and 4 is 29967 m³. The estimation from upper vadose zone using hydrograph data to streamflow is 28448 m³. The soil drainage curve estimation procedure seems therefore to be reasonably reliable for this year.

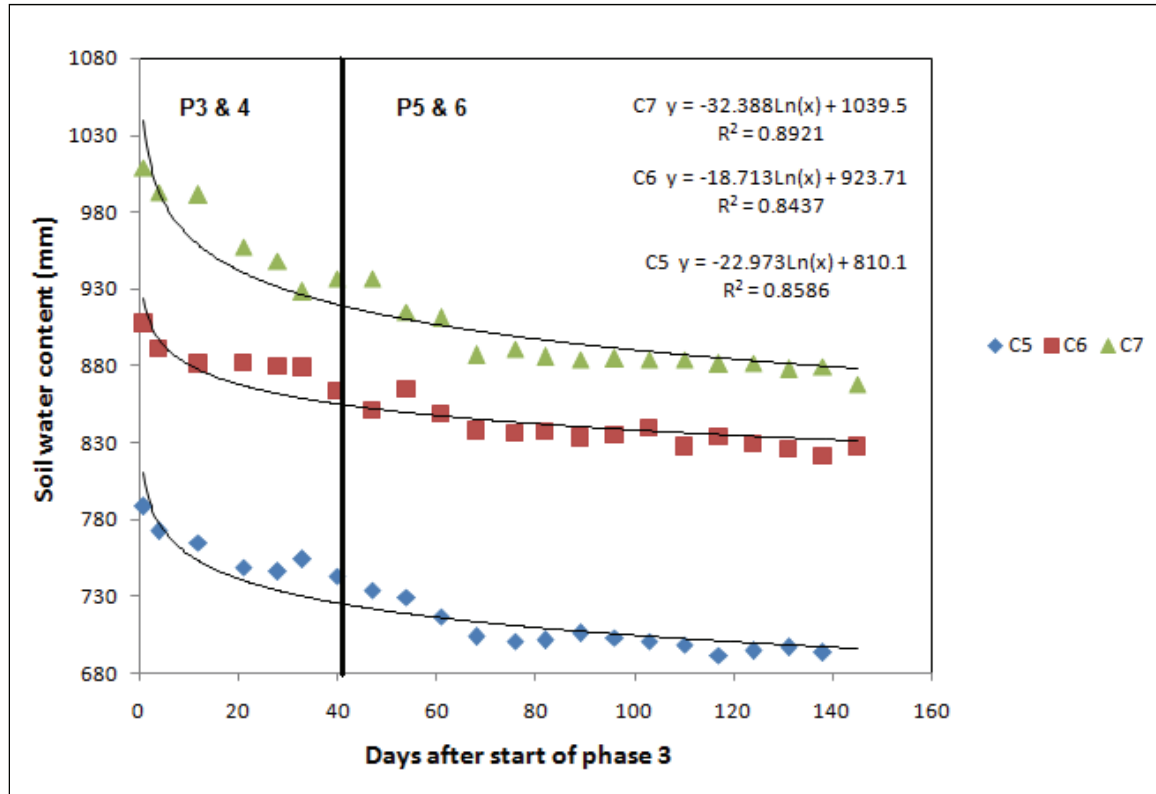


Figure 6.19 Drainage curves for C7, C6 & C5 during 23/03/93 to 09/08/93.

Table 6.18 Estimated changes in soil water contents of C7, C6, C5 drainage curves and their relationship to streamflow during 23/3/1993 to 3/5/1993 (Phases 3 and 4 from Table 6.15)

NWM site	^A θ at day 1 (mm)	^B θ at day 41 (mm)	Δ profile θ(mm)	m ³ ha	16 ha	14 ha	12.2 ha
C7	1039.5	919	120.5	1205	19280		
C6	923.7	854	69.7	697		9758	
C5	810.1	725	85.1	851			10382

Estimated total Δ θ from 42.2 ha(m ³)	39420
^C ET – rainfall (m ³)	9453
Estimated actual Δ θ from the upper vadose zone	29967
^C Measured total streamflow during the 41 days of phases 3 and 4 (m ³) (Table 6.14)	57365
Estimated combined contribution to total streamflow during the 41 days from the lower vadose zone and baseflow (m ³)	28917
Estimate, based on the hydrograph, of the contribution of the upper vadose zone to total streamflow during the 41 day period (m ³)	28448

^A It is assumed that the soils were close to field saturation (fsat) after the preceding heavy rain.

^B Calculated using the relevant equations in Figure 6.19

^C Obtained from data of Everson *et al.* (1998)

6.6.3.5 Soil drainage during the autumn and winter of 1994

The selected C7 and C5 profiles used in previous years were monitored from 1991 to 1993 only, and could therefore not be used in this year. Alternate C9 and C5C sites were therefore used. The estimation of the soil drainage contribution to streamflow during phases 3 and 4 is 15703 m³ (Table 6.19). Estimations using hydrograph data yielded a slightly higher value of 20809 m³. This is however satisfactory given the complexity governing flow of water in catchment hydrology.

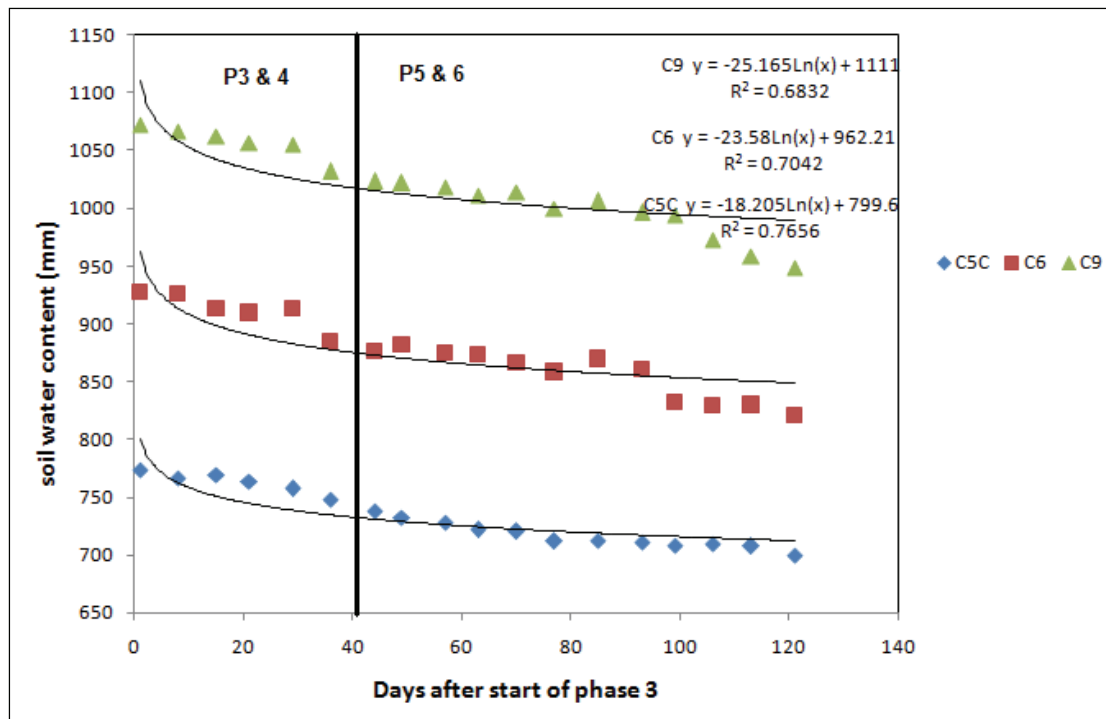


Figure 6.20 Drainage curves for C9, C6 & C5C during 30/04/94 to 30/07/94.

Table 6.19 Estimated changes in soil water contents of C9, C6, C5C drainage curves and their relationship to streamflow during 30/4/1994 to 09/6/1994 (Phases 3 and 4 from Table 6.15)

NWM site	^A θ at day 1 (mm)	^B θ at day 41 (mm)	Δ profile θ(mm)	m ³ ha	16 ha	14 ha	12.2 ha
C9	1111	1018	93	930	14880		
C6	962.2	895	67.2	672		9408	
C5C	799.6	748	51.6	516			6295
Estimated total Δ θ from 42.2 ha(m ³)				30583			
^C ET – rainfall (m ³)				14880			
Estimated actual Δ θ from the upper vadose zone				15703			
^C Measured total streamflow during the 41 days of phases 3 and 4 (m ³) (Table 6.14)				52794			
Estimated combined contribution to total streamflow during the 41 days from the lower vadose zone and baseflow (m ³)				31985			
Estimate, based on the hydrograph, of the contribution of the upper vadose zone to total streamflow during the 41 day period (m ³)				20809			

^A It is assumed that the soils were close to field saturation (fsat) after the preceding heavy rain.

^B Calculated using the relevant equations in Figure 6.20

^C Obtained from data of Everson *et al.* (1998)

6.6.4 Conclusions

The application of hydropedology in hydrological research has been demonstrated in this chapter by:

Conducting a hydropedological soil survey of the catchment; identifying the main hillslopes and their pedosequences; describing and classifying the soils and taking and analysing undisturbed and disturbed samples for chemical and physical properties, and correlating them with morphological features; formulating conceptual flowpaths in the main hillslopes.

- Using the soil water content measurements by hydrologists to describe soil water regimes of the catchment soils. A good agreement between soil water regime and profile morphology was achieved by using a symbol $AD_{s>0.78}$.
- Estimating the contribution of drainage from the soil solum (upper vadose zone) to streamflow. The estimations were similar to estimations done using measured data of streamflow obtained by subdividing the hydrograph for rainfree periods into appropriate portions. Results showed that the soil drainage curve estimation procedure was reasonably reliable.
- Appropriate data was used to obtain an estimated Kh curve and DUL values for the main soil in the catchment, i.e. deep Inanda. The procedure used serves to highlight the value of pedotransfer function in hydropedology.
- Estimating the groundwater storage capacity of the catchment.

Chapter 7 **HYDROPEDOLOGICAL ASPECTS OF THE TWO STREAMS CATCHMENT**

7.1 INTRODUCTION

Knowledge of the hydrology of South African soils is important in the study of hillslope hydrology, an important component of hydrology. General aspects of this subject have been well discussed in Chapter 5. Specific aspects of the Two Streams catchment related to hydrology were studied in detail in an earlier Water Research Commission funded project by Everson *et al.* (2006). The project title was “Can effective management of riparian zone vegetation significantly reduce the cost of catchment management and enable greater productivity of land resources”.

7.1.1 Location and Extent

The Two Streams catchment is situated on the Mistle-Canema Estate of Mondi Forests in the Seven Oaks district, approximately 70 km from Pietermaritzburg, between latitudes 29°12'23.3"S and 29°12'42.8"S and longitudes 30°39'10"E and 30°39'16"E. It is 73.3 ha in extent; the elevation ranges from 1071 m above sea level at the weir to 1170 m above sea level at the highest point; the terrain generally has a slope of about 8% grading to 2% in the riparian zone; land use comprises mainly of a wattle plantation and a small area of sugarcane (Everson *et al.*, 2006).

7.1.2 Climate

The Two Streams catchment lies in the summer rainfall zone of South Africa where summers are wet and humid and the winters are dry and cold. The annual rainfall for the catchment ranges from 800 mm to 1280 mm Everson *et al.* (2006). Relevant long-term mean monthly climate data for the region was extracted from the Agrohydrological and Climatological Atlas (Schulze, 1997) and is presented in Table 7.1. The data shows that the climate is sub-humid during the summer months.

Table 7.1 Monthly climatic data for the region (Schulze, 1997)

Monthly variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual total/ mean
T-Max (°C)	21	20	19	18	17	15	13	17	21	22	23	22	19.0
T-Min (°C)	13	14	13	11	8	6	6	8	10	12	14	13	10.7
T-mean	17	17	16	15	13	11	10	13	16	17	19	18	14.9
Rain (mm)	118	103	103	44	20	11	10	20	48	81	107	123	788
A-pan (mm)	190	170	150	125	105	95	105	125	145	150	160	180	1700
Aridity index	0.62	0.61	0.69	0.35	0.19	0.12	0.10	0.16	0.33	0.54	0.67	0.68	0,46

7.1.3 Land type information

The catchment is located in land type Bb107. The main soils present in this land type are recorded in tabular form in the inventory presented here as Table 7.2. The land type covers 6130 ha. The topography is characterized by gentle slopes, ranging from 2-25% with TMU3 dominant and estimated to occupy 70% of the landscape. The climate zone is 1452S. Regarding soil distribution patterns, the moist climate plays a major role. High leaching conditions are prominent promoting the genesis of dystrophic soils. The main soil forms and the estimated percentages of the total area that they occupy are: Longlands (24.8%); Mispah (20%); Cartref (18.1%); Clovelly (13.3%); Hutton (11.3%) Glenrosa (7.0%) and Avalon (2.6%). These soils all occupy TMUs 1 and 3; on TMU 5, estimated to occupy about 1% of the landscape, Katspruit is the dominant soil. The geology consists mainly of sandstone of the Natal Group with small areas of dolerite.

7.1.4 Catchment water balance

Everson *et al.* (2006) present the following valuable water balance information about the catchment (Table 7.3). An alternative procedure for calculating the mean water balance using the data in table 7.3 is described by Everson *et al.* (2006) as follows: “all terms except P depend on soil moisture level and distribution which is generally not measured, the problem being overcome by assuming the system to be stationary in the mean. If the integration interval is a full year and expected values are substituted, the change of storage is negligible and the average annual water balance equation is as follows: $P - E_a = Q$ (mm year^{-1})”. Following this procedure and using the mean values for the six seasons presented in Table 7.3, and solving for E_a (since Everson *et al.*, 2006 found it difficult to provide a measurement for this parameter), yields the following results: 944.0 (mean P) $- 34.0$ (mean Q) = 910 (mean E_a) mm year^{-1} .

Table 7.2 Soil and terrain form inventory of land type data Bb107

LAND TYPE / LANDTIP : Bb107									
CLIMATE ZONE KLIEMATSTONE : 1422S									
Area / Oppervlakte : 6130 ha									
Estimated area unavailable for agriculture									
Bernaamde oppervlakte onbeskikbaar vir landbou : 40 ha									
Terrain uni	Terreineenheid	1	3	5					
% of land type % van landtipe		27	70	3					
Area Oppervlakte (ha)		1655	4201	184					
Slope / Helling (%)		2 - 15	3 - 25	3 - 20					
Slope length Hellinglengte (m)		50 - 300	100 - 900	1 - 10					
Slope shape Hellingvorm		Y	Y X	X Z					
MB0, MB1 (ha)		861	3433	74					
MB2 - MB4 (ha)		794	858	110					
Soil series or land classes									
Grondseries of landklasse	Depth Diepte (mm)	MB	ha	%	ha	%	Total Totaal ha	Clay content % Klei-inhoud %	Texture Tekstuur
Albany Lo22	400-700	0	232	14	1287	30	1519	24.8	15-35
Mispah M610	100-350	3	579	35	644	15	1223	20.0	5-35
Carrief C621	500-800	0	248	15	858	20	1106	18.1	6-15
Outsdale Cv16	500-1200	0	298	18	515	12	813	13.3	20-35
Hutton Hu16	800-1200	0	50	3	644	15	693	11.3	20-35
Platt Gs14, Trevanian Gs17	150-400	3	215	13	215	5	430	7.0	10-30
Leksand Av24	700-1000	0	33	2	129	3	162	2.6	6-15
Katspruit Ka10	300-600	0					64	1.1	15-35
Jozini Oa36	1000-1200	0					9	0.2	15-35
Stream beds/Stroombeddings		4					110	60	1.8

Terrain type / Terrein tipe : C2

Terrain form skets/Terrain vormskets



For an explanation of this table consult LAND TYPE INVENTORY (table of contents)
 Ter verduideliking van hierdie tabel kyk LAND TYPE - INVENTARIS (inhoudsopgawe)

Geology: Mainly sandstone of the Natal Group with small areas of dolerite.

Geologie: Hoofsaaklik sandsteen van die Groep Natal met klein oppervlakte van doleriet.

Table 7.3 Components of the water balance equation measured in the Two Streams catchment (1999/2000 to 2004/2006).

Year	P	-	Q	-	SS	=	Ea	% of P	Rr
1999/2000	1071.0	-	15.2	-	(+104.5)	=	951.3	88.8	0.014
2000/2001	897.0	-	26.6	-	(+77.3)	=	793.1	88.4	0.030
2001/2002	1170.9	-	46.1	-	(+4.2)	=	1120.7	95.7	0.039
2002/2003	659.1	-	6.7	-	(-52.5)	=	704.9	106.9	0.010
2003/2004	727.1	-	17.8	-	(+8.5)	=	700.7	96.4	0.024
2004/2005	1139.2	-	91.8	-	(+9.5)	=	1037.9	91.1	0.080
Mean	944.0	-	34.0	-	25.3	=	884.7	94.5	0.033

P = precipitation; Ea = estimated evaporation; SS = soil storage; Q = measured streamflow

Although this 'second approximation' Ea value is slightly higher than the 885 mm value in Table 7.3 it can only be considered to be a better value if it is certain that there was no leakage out of the base of the catchment. Information in this connection is not available at present.

7.2 SOIL SURVEY

The procedure used was in line with what is described in Chapter 3. Six profiles were dug in the catchment and described in detail, sampled and the soil analysed. Strategically sited auger traverses were conducted and the soils classified and GPS readings taken at each observation site. More detail is available on CD as Appendices. A computer software programme 3D Mapper was employed to facilitate the soil survey. The topography, sequence and extent of the different soil types were used to differentiate between different kinds of hillslopes and to select those considered to be modal. 3dMapper software was used to determine topographical attributes of the modal hillslopes and conceptual flowpaths were then developed.

7.3 RESULTS AND DISCUSSION

7.3.1 Soil survey

The main relevant information obtained during the soil survey is presented in Table 7.4. The characteristics of the soils are presented in the form of the profile descriptions, analytical data, bulk densities and location of observation points. More detail is available on CD as Appendices. Griffin soil dominates the catchment (Table 7.4). It is a well drained soil. The solum rests on a yellowish hard saprolite. Griffin has formed on gentle to moderately steep slopes. Hutton soil is well drained and deep. It is the next most dominant soil. The solum rests on a highly weathered light grey soft and fluffy saprolite. It is found on sloping TMU 3 positions. Clovelly soil is also well drained, deep. It occupies the south facing fairly steep midslope of the catchment. Pinedene soil is moderately well drained internally and poorly drained externally. There are many high chroma mottles in the lower part of yellow brown apedal B horizon of this soil as a result of periodic saturation from the underlying hydromorphic horizon. This soil occupies lower concave footslopes. It covers a small part of the catchment. Oakleaf is a well drained and moderately deep soil and occupies convex, gentle to steep slopes. The solum grades into sandstone saprolite. Katspruit is a poorly drained shallow soil that occupies the main wetland 2.8 ha strip of the catchment. The average bulk densities range from around 1.1 Mg m^{-3} in the B horizon of the Hutton soil to 1.49 Mg m^{-3} in the G horizon of the Katspruit soil (Table 7.4).

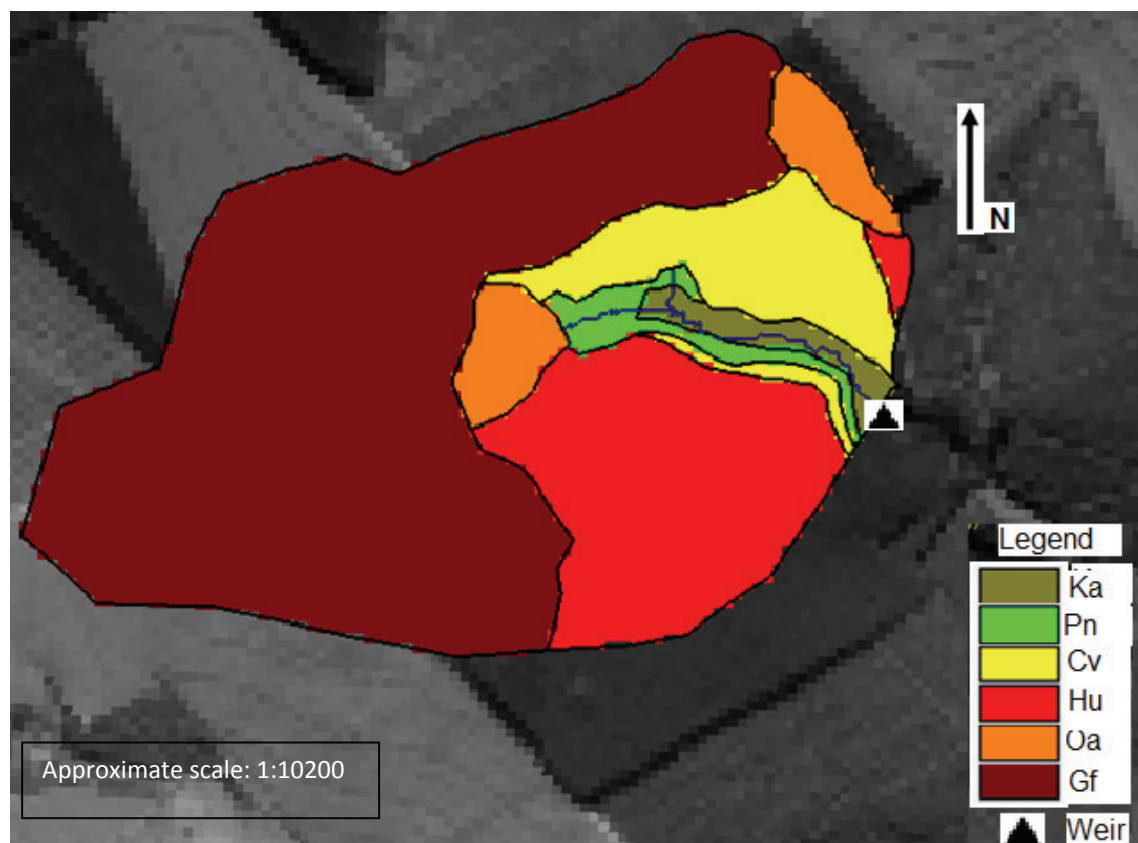


Figure 7.1 Generalised soil map of the Two Streams catchment.

Table 7.4 The different soils in the Two Streams catchment; their extent, depths and bulk densities

Soil form	Area (ha)	% of catchment	Horizons	Average horizon depth (mm)	Average soil depth (mm)	Bulk densities (Mg. m ⁻³)
Clovelly	7.9	10.8	Orthic Yellow brown apedal	0-350 350-1200	1750	1.24 1.16
Griffin	39.2	53.5	Saprolite Orthic Yellow brown apedal	1200-1750 0-250 250-500	1750	1.35 1.24 1.16
Hutton	17.5	23.9	Red apedal Saprolite Orthic	500-1250 1250-1750 0-300	1800	1.08 1.35 1.24
Katspruit	2.8	3.8	Red apedal Saprolite Orthic	300-1200 1200-1800 0-300	600	1.08 1.35 1.24
Oakleaf	4.8	6.5	G horizon Orthic	300-600 0-300	1600	1.49 1.24
Pinedene	1.1	1.5	Neocutanic Saprolite Orthic	850-550 550-1600 0-300	1400	1.2 1.35 1.24
Catchment size	73.3	100	Yellow brown apedal Unspecified material with signs of wetness	300-800 800-1400		1.16 1.49

7.3.2 Hydropedological aspects

7.3.2.1 Hydrological soil types

A hydrological soil type map was created from the generalised soil map. Three hydrological soil types were identified and delineated. They are deep recharge soils, interflow soils, and saturation excess responsive soils. Their location is shown in Figure 7.2 and coverage in Table 7.5.

Table 7.5 Hydrological soil types in the Two Streams catchment.

Soil type	Area (ha)	% of area	Average depth (mm)
Recharge	69.4	94.7	1766
Responsive	2.8	3.8	600
Interflow	1.1	1.5	1400
Total catchment size	73.3	100	

Deep recharge soils

A large part of the catchment is dominated by recharge soils (Figure 7.2). These are deep, medium textured soils, and well drained with no signs of wetness within the observed depths. Griffin, Hutton and Clovelly are the main soils. The wattle and sugar plantations facilitate the infiltration process and impede overland flow especially when the rainfall intensity is moderate or low. Excess water drains through the soils, out of the reach of ET, into the saprolite. This water recharges the lower vadose zone, regional water tables and other soils downslope. These soils are the main contributors to baseflow and to interflow in soils at the footslopes. They cover 95% of the total catchment (Table 7.5).

Interflow soils

Interflow soils of the Pinedene form in this catchment from a conduit through which water pass to reach the wetland in the valley bottom. Signs of wetness identified in these soils are an indication of a flow at the soil/water table interface. Their location is such that they have fluctuating water tables which are recharged from upslope soils. They drain laterally within the solum into the wetland of the riparian zone.

Saturation excess responsive soils

The permanent water table in the streambed has facilitated the formation of Katspruit soils in this position. The Katspruit soils are saturated for long periods. Infiltration is therefore impeded during significant rains and overland flow becomes active. Because of this the runoff response from the saturated zones is expected to be very rapid after the start of a storm, and also ends relatively abruptly. The soils are therefore called saturation excess responsive soils.

7.3.2.2 Hillslope hydrology

Hillslope 1

Hillslope 1 covers 24.9 ha (34%) of the catchment. The average length of the hillslope from the top of the catchment to the stream is about 490 m, with an average slope of around 8%. Conceptual subsurface flow paths based on the topographical and soil type features are presented in Figure 7.3. A significant fraction of the rain falling on the hillslope infiltrates vertically (arrow 1) through the solum and saprolite to the relatively permeable and cracked bedrock to charge the ground water systems (arrow 2). This water contributes to baseflow which raises the watertable in the riparian zone to near the surface (arrow 3). Some water also flows laterally through the solum, some possibly through macropores near the surface, (arrow 4) to feed the riparian zone. Because of water being of primary importance in soil genesis, Clovelly soil has tended to form in the direction of increasing wetness on the lower slopes, while Hutton has formed in the drier upslope positions. At the footslope water flows laterally within the soil solum, mainly in the (on) horizon of Pinedene, then exits into the stream.

Hillslope 2

Hillslope 2 covers 22 ha (30%) of the catchment. The length of the hillslope is about 403 m, with an average slope of around 12%. Conceptual subsurface flow paths, based on the topographical and soil type aspects are presented in Figure 7.4. Some water flows through the soil vertically (arrow 1) in the recharge soil to recharge the water table through the permeable and cracked bedrock and then exits the catchment as baseflow (arrow 2). Some of the water moves laterally at the soil/saprolite interface (arrow 3) as well as within the solum through macropores (arrow 4) toward the riparian zone.

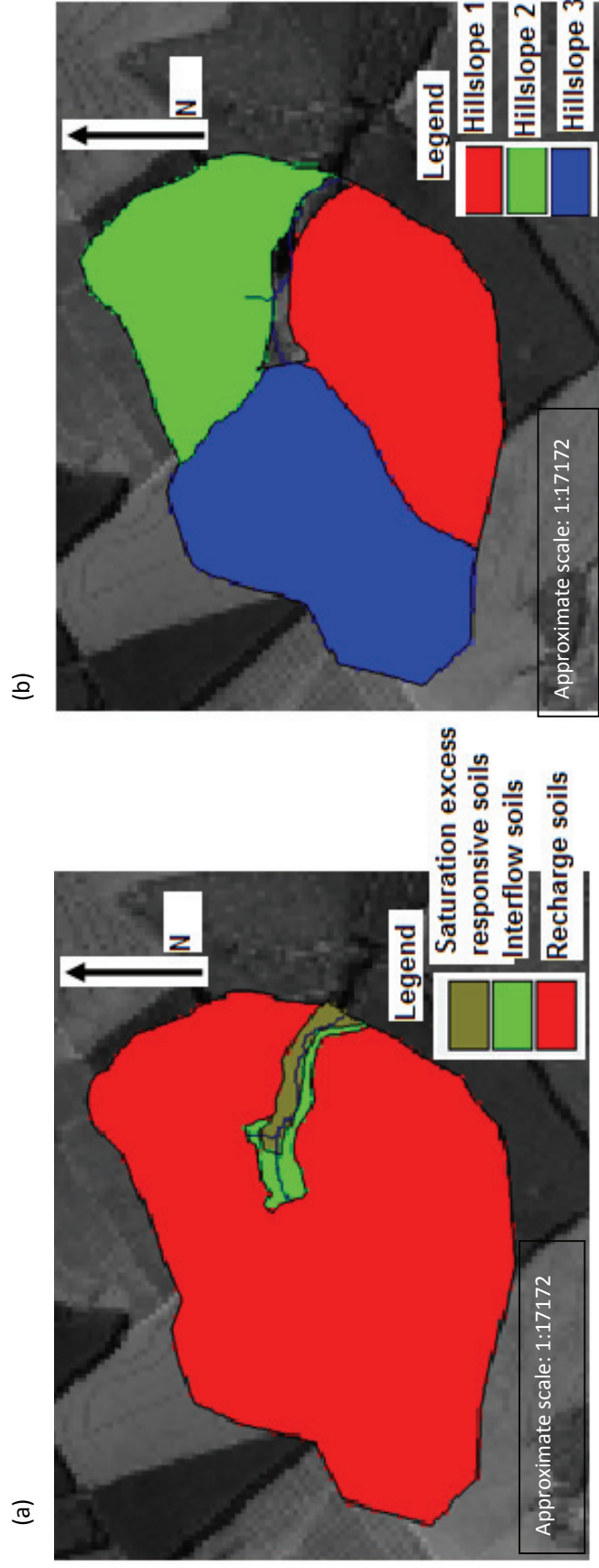


Figure 7.2 Hydrological soil types (a) and hillslopes (b) in the Two Streams catchment.

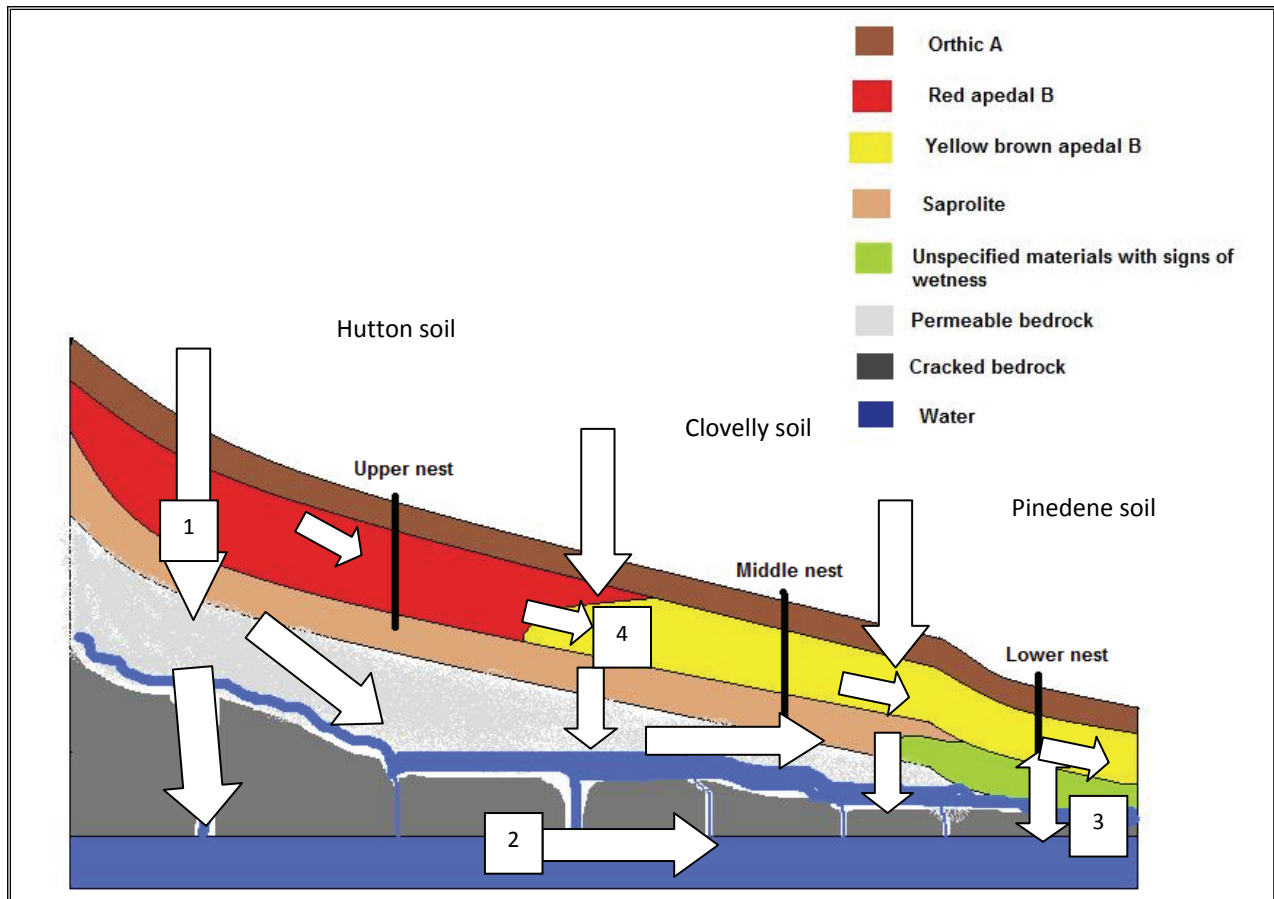


Figure 7.3 Conceptual flow paths of hillslope 1 in the Two Streams catchment. Location of the 'watermark' soil water measurement nests used in section 7.3.2.3 are shown on the hillslope.

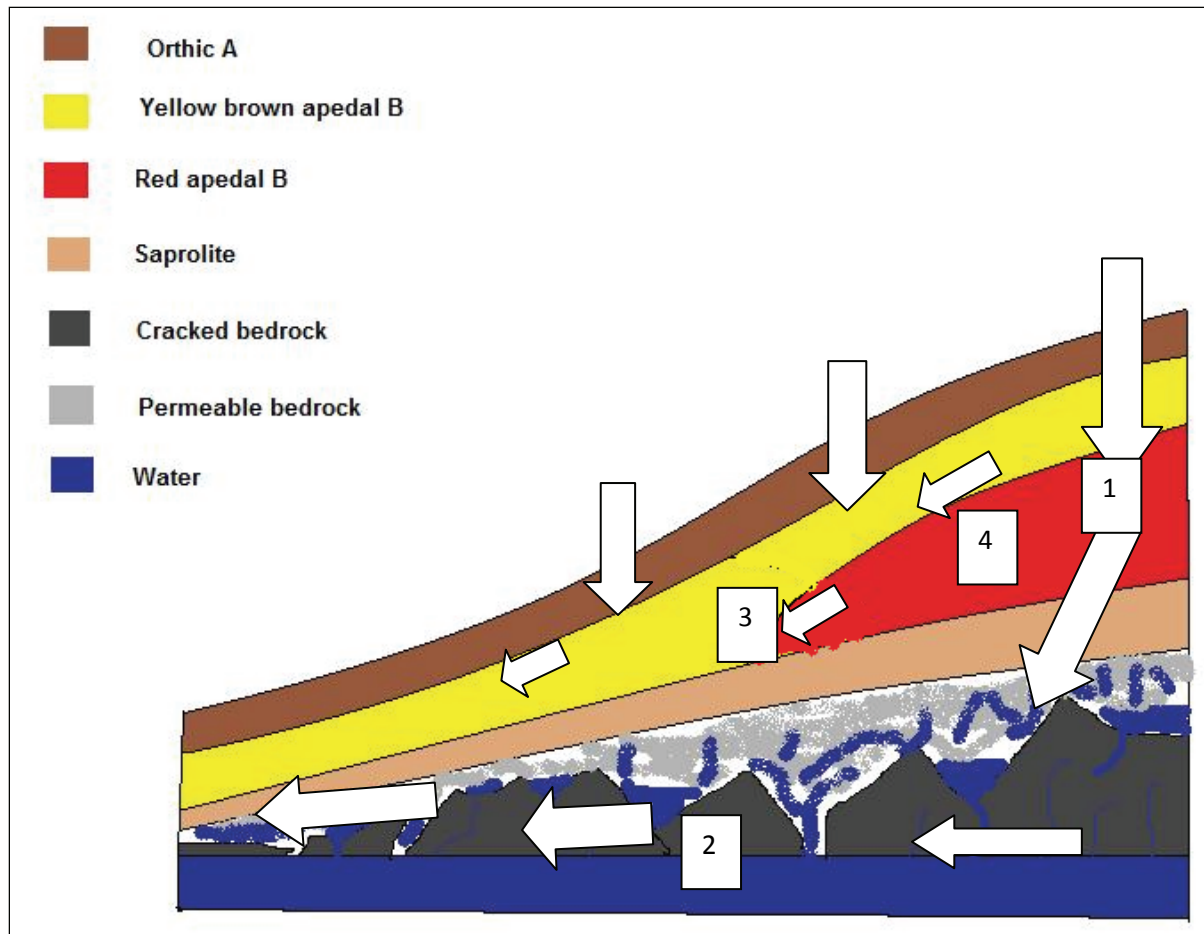


Figure 7.4 Conceptual flow paths of hillslope 2 in the Two Streams catchment.

Hillslope 3

Hillslope 3 covers 26.4 ha (36%) of the catchment. The length of the hillslope is about 804 m, with an average slope of around 4.5%. Recharge soils are dominant and cover 25.3 ha (95%) while interflow soils cover 1.1 ha (5%). Conceptual flow paths based on topographical and soil type aspects are presented in Figure 7.5. Some water flows through the soil vertically (arrow 1) to recharge the water table and exit the catchment as baseflow (arrow 2). Some of the water moves laterally (arrow 5) in the solum and its accumulation at the footslope (arrow 4) has promoted the genesis of the on horizon of the interflow Pinedene soil located there.

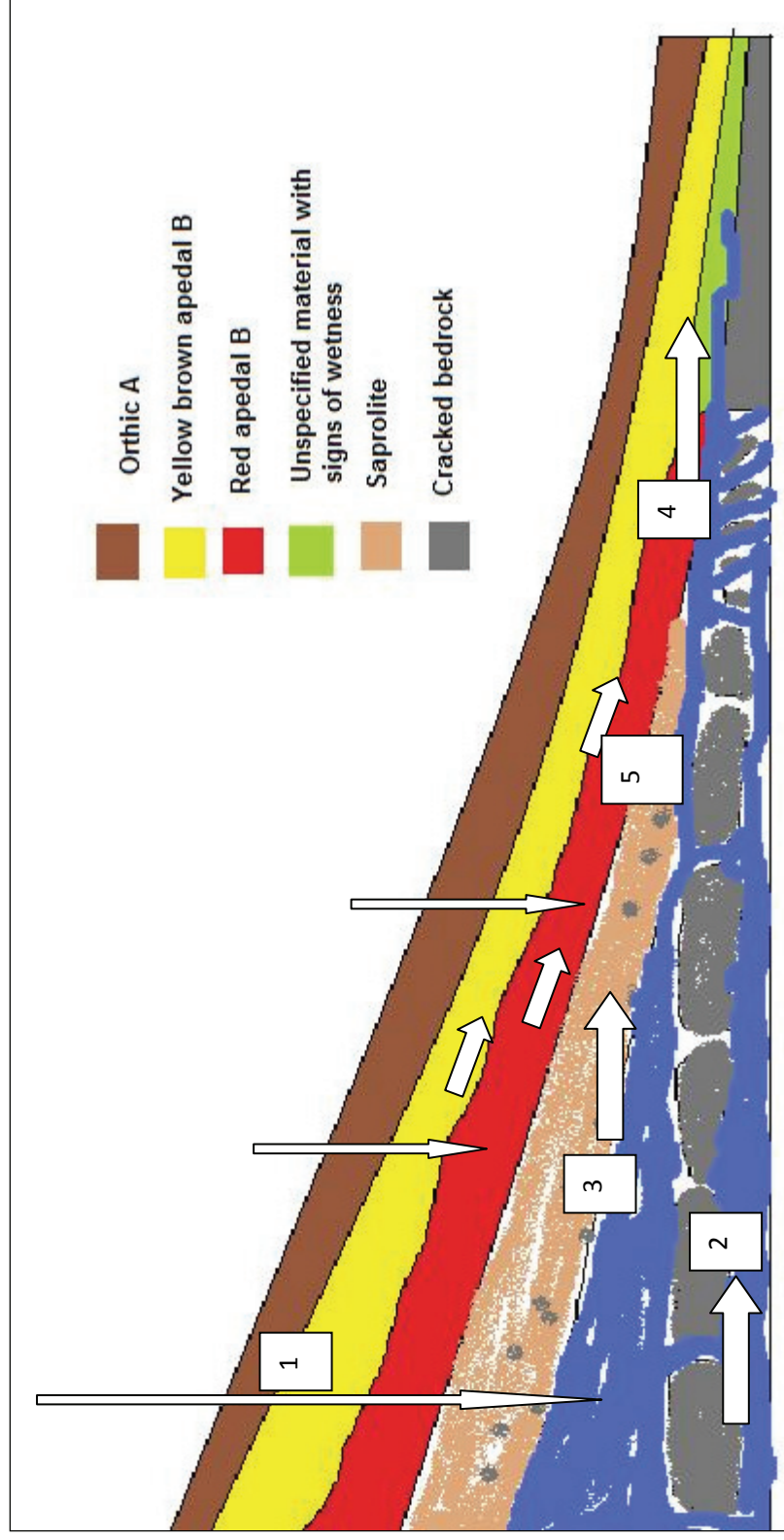


Figure 7.5 Conceptual flow paths of hillslope 3 in the Two Streams catchment

7.3.2.3 Soil water measurements related to the lateral flow of water in the solum of the soils in hillslope no.1 (arrow 4 in Figure 7.3)

The instrumented hillslope transect showing the location of three ‘watermark’ sensor nests is presented in Figure 7.3. The basic data is from Everson *et al.* (2006). Soil water potentials were measured continuously at 0.40 m, 0.80 m, 1.2 m and 2.0 m depths at the three nests in Hutton, Clovelly and Pinedene soils respectively (Figure 7.3). Based on the results of the soil survey, the given measuring depths can be related to diagnostic horizons, respectively, as follows: in the Hutton soil, ot, re, re, so; in the Clovelly soil, ot, ye, ye, so; in the Pinedene soil, ot, ye, on, on. The annotations in Figure 7.6 are according to this convention. Soil water potential results at the three nests over the period 9/11/04-5/9/05, as measured by Everson *et al.* (2006), are presented in Figure 7.6. Negative values on the graphs indicate unsaturated conditions and the greater the negative value of hydraulic head, the drier the soil. Conversely, the greater the positive value of hydraulic head, the wetter the soil. The results show that the deeper layers of all the profiles are wetter than the shallow layers (first two) which have been dried out by the vegetation roots extracting water for ET during the virtually rain-free autumn and winter recording period. Although ET losses over the whole hillslope would have been similar over this period the soil profiles are shown to progressively become significantly wetter downslope. For example at the end of the winter the hydraulic head values (m) at the 1.2 m measuring depth are approximately -17, -12 and -7, at the upper, middle and lower nests, respectively. The logical conclusion is that there must have been a certain amount of downslope interflow in the red apedal and yellow brown apedal horizons. In the long-term this has caused an accumulation of water at the toeslope to form the hydromorphic (on) horizon in the Pinedene soil.

The hydrological process described can be further illuminated by plotting the water potential measurements for each depth, for each nest, together on one graph. The results in Figure 7.7 show that during this dry season, diagnostic A horizons at 400 mm in the upper and middle nests dry out more than the same horizon at the lower nest. The A horizon in the lower nest remains wetter long after any rainfall, probably assisted by capillary rise from deep wetter layers. The drying at all nests of surface layers reflects the evapotranspiration demands near the surface. This pattern is repeated for the 0.8 m, 1.2 m and 2 m depths, i.e. Figures 7.8 to 7.10, respectively. These results confirm clearly the conclusion regarding lateral movement downslope in the red apedal and yellow brown apedal B horizons to ‘feed’ the Pinedene soil in the riparian zone.

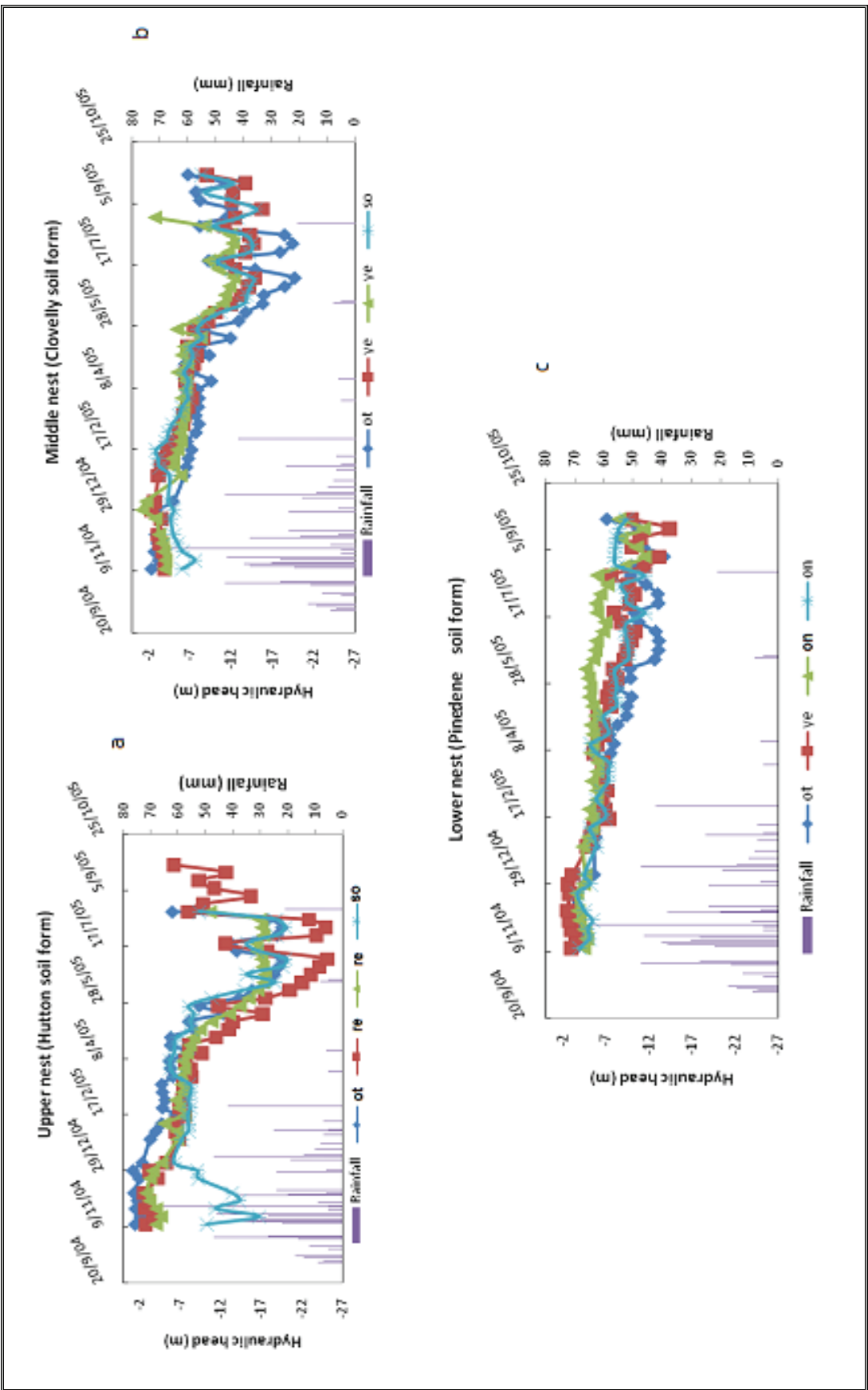


Figure 7.6 Soil water potential measurements at the three sites, i.e. (upper nest (a), the middle nest (b) and the lower nest (c)), shown in Figure 7.3.

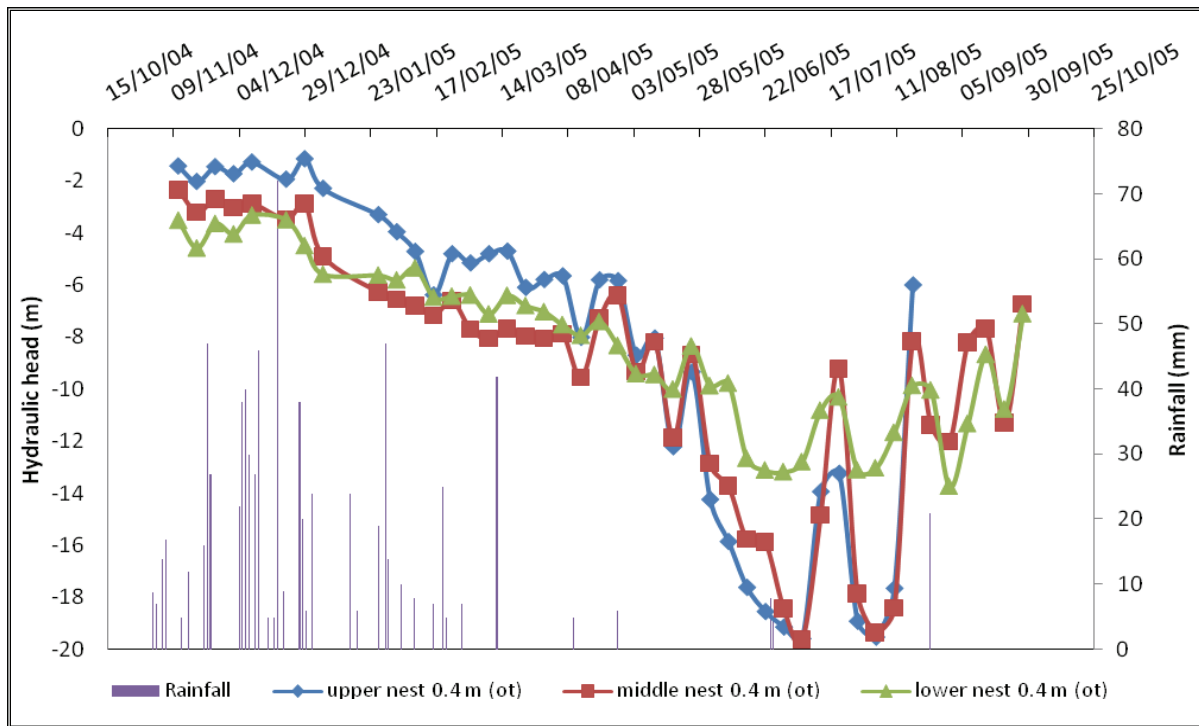


Figure 7.7 The trend in hydraulic potential at 0.40 m depth at the three nests.

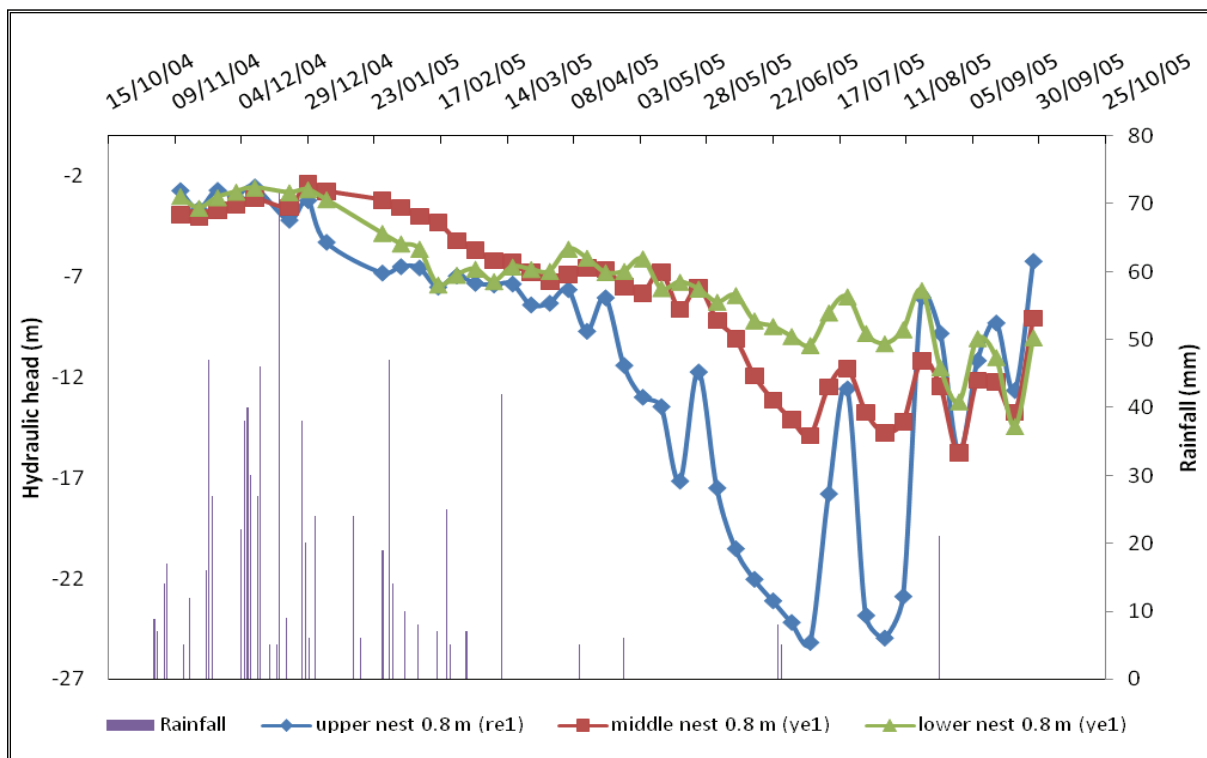


Figure 7.8 The trend in hydraulic potential at 0.80 m depth at the three nests.

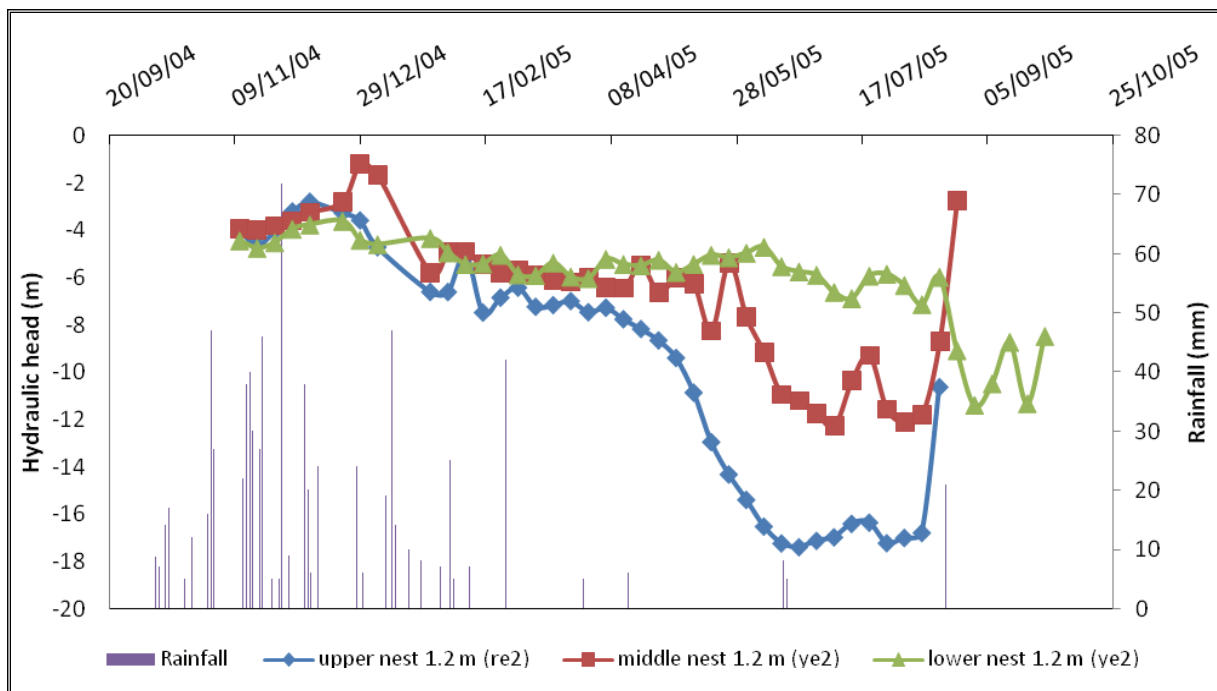


Figure 7.9 The trend in hydraulic potential at 1.2 m depth at the three nests.

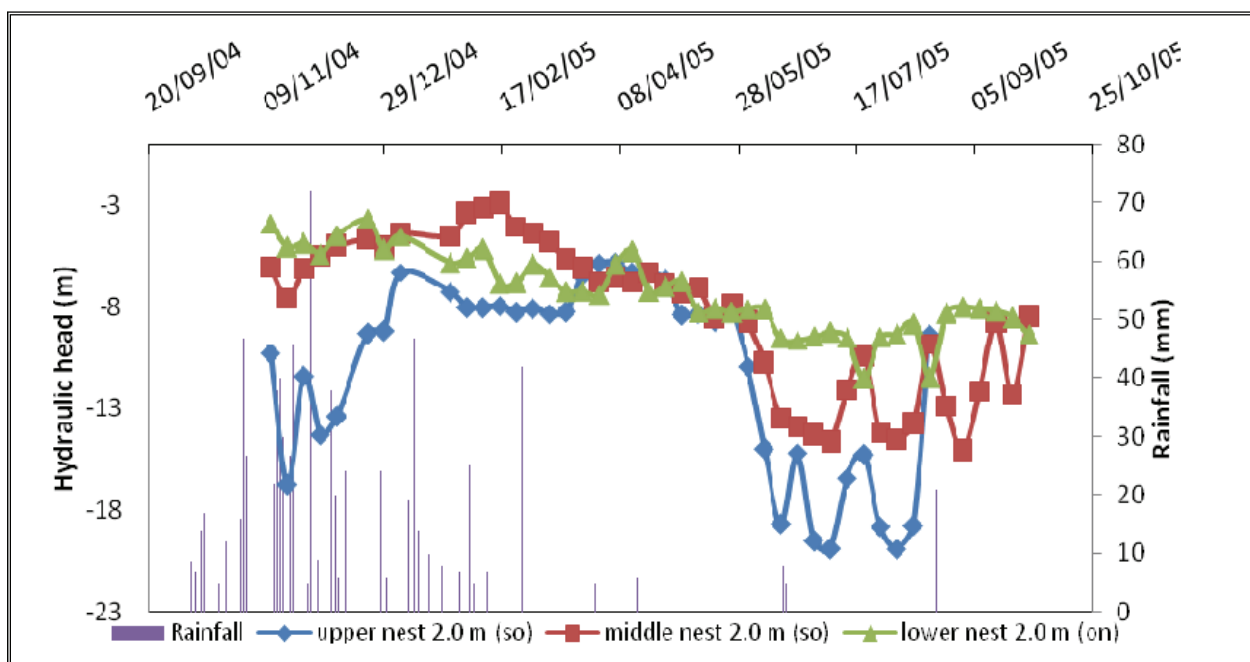


Figure 7.10 The trend in hydraulic potential at 2.0 m depth at the three nests.

7.3.2.4 An attempt to quantify the contribution from the surrounding hillslopes to total catchment streamflow

Procedure

A number of simplifying assumptions will be made in order to formulate and test a preliminary hypothesis regarding the way in which water flows out of the hillslopes to feed the stream. They are that:

- a. all the slopes exhibit the same hydrological behaviour as hillslope 1 depicted in Figure 7.3;
- b. the catchment is rectangular in shape with the stream in the middle, with the dimensions as shown in figure 7.12, giving the correct area, i.e. 73.3 ha;
- c. the generic hillslope consists of terrain morphological unit (TMU 3), with slope 8% and length 485 m, consisting of a top half mainly Hutton and Griffin soils and a lower half mainly Clovelly soils, and a very narrow TMU 4 with mainly Pinedene soil;
- d. all the water from the upper vadose zone of the hillslope discharges into the streambed via the unspecified material with signs of wetness (on) horizon of the Pn soils; the depth of this horizon is 1 m; the *Kh* curve for this horizon is the one shown in Figure 7.13 which has been determined from the water retention curve data for the relevant horizon reported by Everson *et al.* (2006).

The hydrological behaviour of the catchment will be studied over the period 27/03/2005-27/07/2005. The hydrograph for this period is presented in Figure 7.11 (Data supplied by Everson, personal communication, 2007). Soil water measurements (Everson *et al.*, 2006) are available for more than two years (2004 & 2005) at the 3 measuring nests (Figure 7.3) situated in the representative soils of the catchment. The procedure adopted was to select a portion of the hydrograph not influenced by overland flow, i.e. the rainfree period 27/3/2005-27/7/2005, and to relate this flow to interflow from the hillslopes surrounding the stream. For this catchment, Griffin, Hutton and Clovelly soils occupying the hillslopes on terrain morphological unit 3 are classified as recharge soils. The Pinedene soil occupying terrain morphological unit 4 is classified as interflow. The underlying horizon to the yellow brown apedal B in this soil is unspecified materials with signs of wetness (on). The redoximorphic features of this horizon are a good indication that there is a consistent inflow of water from the upslope recharge soils into

it. Clear evidence for this process is presented in section 7.3.2.3. Since we have assumed that all the water from the hillslope discharges into the streambed via the (on) horizon in the Pinedene soils, the Kh curve for this horizon (Figure 7.13) was determined from the water retention curve data reported by Everson *et al.* (2006) using the following equations of Van Genuchten (1980);

$$Kh = K_s * Se^{\frac{1}{2}} \left[1 - \left(1 - Se^{\frac{1}{m}} \right)^m \right]^2 \quad Se = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right) \quad (7.1)$$

Where;

K_s = saturated hydraulic conductivity (mm h^{-1}) (from Everson *et al.*, 2006)

Se = effective saturation ($\text{m}^3 \text{m}^{-3}$)

θ = water content ($\text{m}^3 \text{m}^{-3}$)

θ_s = Saturated water content ($\text{m}^3 \text{m}^{-3}$) (determine from bulk density data of Everson *et al.*, 2006)

θ_r = residual water content ($\text{m}^3 \text{m}^{-3}$) (assumed to be at the estimated value that θ would have at the drained upper limit taken as equivalent to θ at the matric suction value of 100 cm)

m = 0.4959 (determined using the procedure described by Van Genuchten (1980) and the water retention data provided by Everson *et al.*, 2006)

Results and discussion

The streamflow presented in Figure 7.11 represents a rain free period following a period with much rain, leaving the soil in the landscape fairly full of water. Since rainfall is negligible during the measuring period, the source of all the water in the stream must be from interflow out of the hillslope soils plus baseflow, amounting at the end of the period to approximately $30 \text{ m}^3 \text{day}^{-1}$ (Figure 7.11). The latter flow will be assumed to be coming from groundwater and the lower vadose zone. The latter is mainly well weathered sandstone in this catchment. Judging by the borehole data presented by Everson *et al.* (2006) it is expected that the contribution from groundwater would have been relatively small.

With regard to assumption (d), Everson *et al.* (2006) provide information (their Figure 4.22) about the water content of the riparian zone during the period of our study. The results show that the soil profile remains permanently saturated at a depth of 2.0 m, close to saturation at 1.2 m, and with lower and variable water content in the shallower layers. It is not possible with this limited information to make a reliable prediction of the outflow rate from the (on) horizon.

It is, however, clear that the horizon would have been very wet throughout the period of our study. Figure 7.13 shows that at a degree of saturation of around 0.7 the predicted hydraulic conductivity would be around 1 mm h^{-1} . It is useful to consider some possible scenarios. If one assumes the (on) horizon to be 1 m deep along both sides of the streambed its total area would be 1512 m^2 . Assuming a reasonable K value of 1 mm h^{-1} the flux would amount to $1 \times 10^{-3} \times 1512 \times 24 \text{ m}^3$ per day or $36.3 \text{ m}^3 \text{ d}^{-1}$. This is very similar to the streamflow during the last part of the study period (Figure 7.11), i.e. around $30 \text{ m}^3 \text{ d}^{-1}$.

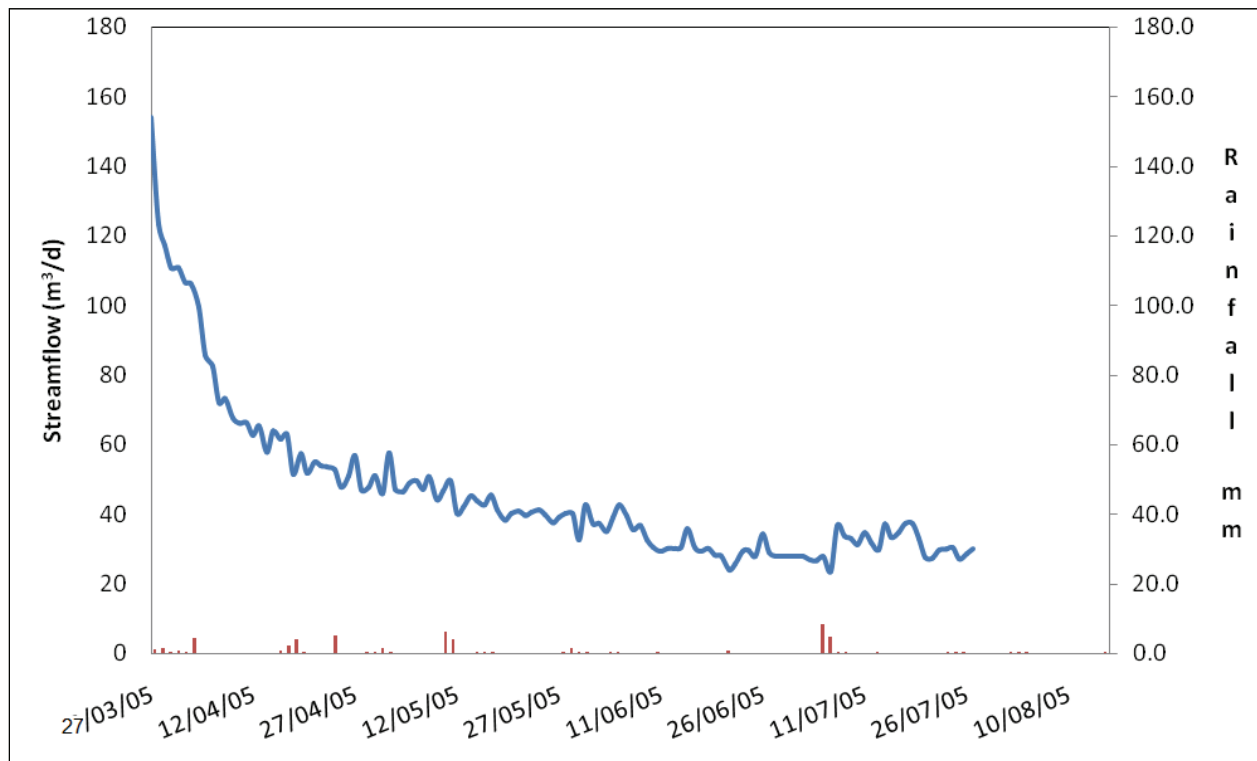


Figure 7.11. Streamflow and rainfall for the almost rainfree period 27/3/2005-27/7/2005 in the Two Streams catchment.

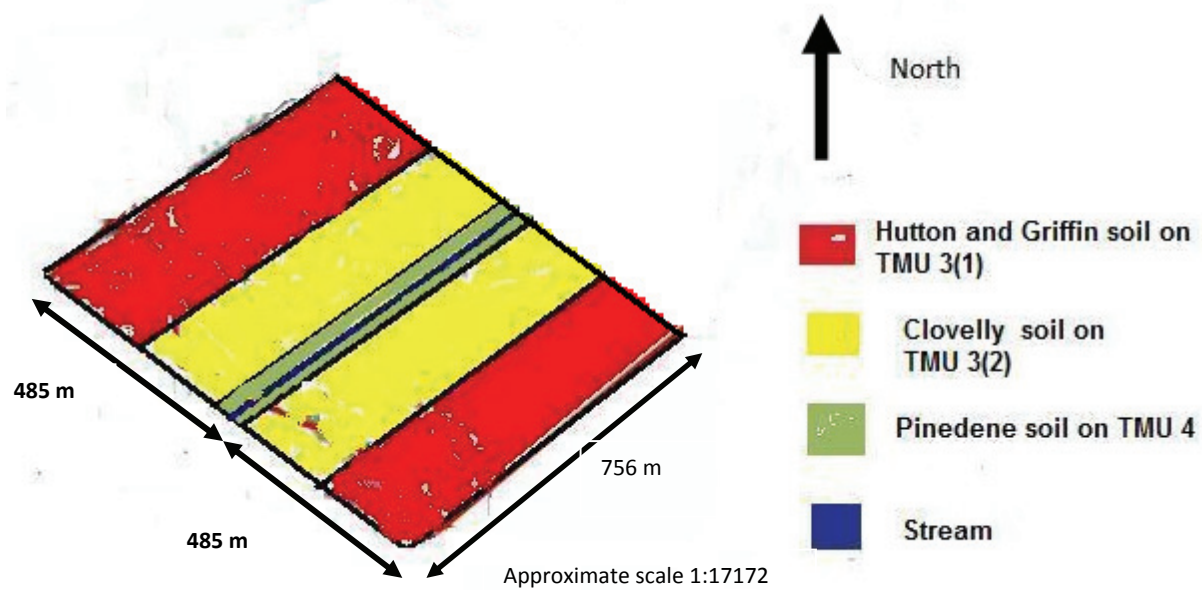


Figure 7.12 The assumed rectangular shape and dimensions of the catchment with the stream in the middle, bounded on both sides by the typical hillslope shown in Figure 7.3.

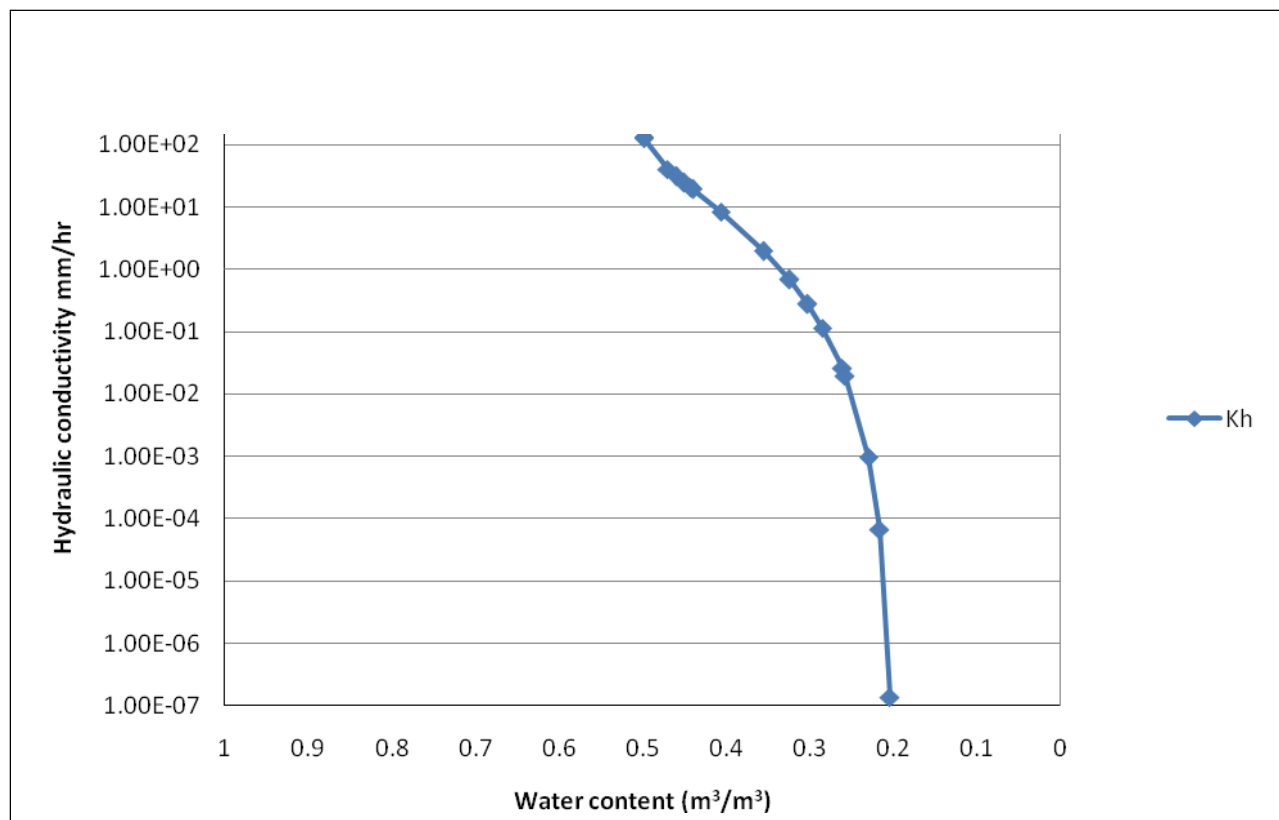


Figure 7.13 A predicted hydraulic conductivity curve for the (on) horizon of the Pinedene soil.

Another way of estimating the contribution of interflow from the upper vadose zone of the hillslopes to streamflow is via the decrease in water content of the hillslopes over a specified rain free period. The water lost from TMU 3₁ and TMU 3₂ (Figure 7.12) estimated for the period 7/6/2005-27/6/2005 is presented in Table 7.6. The results presented by Everson *et al.* (2006) in their Figure 4.12 (page 43) show that at the 'north facing slope upper nest' (water mark sensor) the hydraulic potential at 1.2 m and 2.0 m depth both show very small decreases in water content (θ) during the 20 day period 7/6/05 to 27/6/05. In contrast θ decreases relatively rapidly during this period at the 0.4 m and 0.8 m depths, presumably due to ET losses. Since grass was evidently the only vegetation present at this time water extraction for ET is expected to be negligible below about 900 mm. It is therefore a reasonable first approximation assumption to consider, as a contribution to streamflow, the water losses during the 20 day period out of a 1 m depth of soil (i.e. between 1 m and 2 m) from that part of the hillslope represented by this 'upper nest', presumably mainly Hutton and Griffin soils (Figure 7.12). The results in Figure 4.12 (page 43) of Everson *et al.* (2006) for the middle nest are different. They show considerable water content decreases over the named 20 day period at both 1.2 m and 2.0 m. This difference is understandable as water will have been draining out of this hillslope since the start of the dry period on 27/3/05 (Figure 7.11). Downslope movement of this water will have dried out the higher lying soils earlier than those on the midslope. The soil depth from which water is being lost during the 20 day period from the lower part of the hillslope is therefore more than from the upper portion. It will be assumed that this soil depth is 2 m (for the lower part of the hillslope in Figure 7.12).

Table 7.6 Estimated amount of water which would have drained during 7/6/2005-27/6/2005 from the northern and southern slopes of the Two Streams catchment as presented in Figure 7.12

TMU	$\theta(\text{m}^3/\text{m}^3)^*$ 7/6/2005	$\theta(\text{m}^3/\text{m}^3)$ 27/6/05	$\Delta \theta$	Area (ha)	Depth (m)	Volume of soil (m^3)	Water lost (m^3)
3 ⁽¹⁾	0.2188	0.2130	0.0058	36.658	1	366580	2126
3 ⁽²⁾	0.2307	0.2225	0.0082	36.658	2	733160	6012
Estimated water loss from the hillslopes							8138
Measured streamflow (m^3) during this period							601

3⁽¹⁾ upper TMU 3. 3⁽²⁾ lower TMU 3

*using unpublished data from Everson (personal communication, 2009)

The estimated water loss from the hillslopes during the 20 day period (8138 m^3) due to drainage is far more than the 601 m^3 of streamflow during this period. The previous estimated rate at which the water could flow through the on horizon into the stream now needs to be considered. The result was 36.3 $\text{m}^3 \text{d}^{-1}$. This estimate therefore predicts that over a 20 day period only 726 m^3 of the hillslope water would have been able to flow into the streambed. The

rest would remain stored temporarily in the hydromorphic Pinedene and Katspruit soils of the riparian zone and slowly flow out into the stream. During the following 107 day period 27/6/2005-12/10/2005 streamflow amounted to 2978 m³. Since there were no rainfall events during this period that could have had a significant influence on streamflow, it is reasonable to assume that this low flow was provided to a large extent by outflow from the hillslopes, i.e. part of the estimated 8138 m³ recorded in Table 7.6. This outflow would presumably have continued for a considerable period at a similar rate until the soils had become recharged by the summer rainfall.

7.4 CONCLUSION

The value of the following potential contributions by hydropedologists has been demonstrated:

- a) soil survey information focusing on hillslopes;
- b) the definition of conceptual flow paths, and the role of different hydrological soil types;
- c) detailed water content measurements on representative hillslopes in important diagnostic horizons, which made it possible to estimate the contribution of hillslope drainage water to streamflow;
- d) the use of water retention curves and Ks values of important diagnostic horizons and the prediction of the Kh curve (using the Van Genuchten (1980) procedure) which would be useful for hydrological modelling.

To be of maximum value to hydrologists for predictions in ungauged basins the long-term aim of hydropedologists needs to include being able to relate soil profile morphology to soil profile hydrology in a reliable way. The results of this study provide some evidence that this should be possible to at least a reasonable extent. The need for considerable improvements in this approach will become possible in the future.

Chapter 8 **HYDROPEDOLOGICAL ASPECTS OF THE CRAIGIEBURN CATCHMENT**

8.1 STUDY AREA AND METHODOLOGY

8.1.1 Catchment description

The Craigieburn-Manalana sub-catchment is located at the headwaters of the Sand River, approximately 300 km East-North-East of Tshwane (Pretoria) adjacent to the village of Craigieburn (Figure 8.1). This is one of many such headwater catchments containing riparian wetlands situated within a dry sub-humid belt on the periphery of the South African semi-arid low-veld savannah at the foothills of the Klein Drakensberg Escarpment. The Sand River is unusual in that its entire catchment is situated within this lowveld complex; meanwhile most other north-eastern South African river systems have their origins on the high altitude grasslands (highveld).

The relief of this sub-catchment is relatively steep with an average 13% interfluvial slope, whilst its altitude ranges from 744 m.a.s.l. at the highest point along the watershed to 654 m.a.s.l. at its confluence with Motlamogasana stream. The sub-catchment lies within a granitic geological zone and is underlain by medium to coarse grained porphyritic biotite granite, a dolerite dyke intersects this on its northern flank. The Manalana catchment is 2.61 km² of which 2.5 km² and 0.11 km² (or 95.6% and 4.4%) make up the area of interfluvial and wetland respectively. Rainfall is strongly seasonal in the Sand River catchment occurring during the summer months October to March. An MAP of 1075 mm a⁻¹ (1904-2000) for this area has been derived from the nearest long-term dataset at the Wales rain gauge, approximately 2.3 km away, although the Craigieburn-Manalana sub-catchment probably receives somewhat less than this since it is not in such close proximity to the Klein Drakensberg Escarpment.

Vegetation within the catchment is characterized by grassy shrubland communities on the interfluvial areas to communities more suited to permanently flooded conditions within the wetlands (e.g. *Phragmites mauritianus*). Land use within the catchment comprises densely populated rural housing with dry crop smallholdings (e.g. maize), there is also a dense network of roads and pathways as well as heavy grazing by cattle and goats. Within the wetland there is a high density of plots with raised bed and furrow systems, cultivated predominantly with another regional staple, madumbe (*Colocasia esculenta*).

Instrumentation was installed during the latter half of the 2005 dry season (August-October) in order to determine the hydrological processes within the wetland catchment at the commencement of the first rains October-November. Hydrological monitoring stations with automated soil moisture tensiometers and shallow groundwater observation wells were installed along three transects that ran perpendicular to the longitudinal orientation of the catchment. In addition manual groundwater observation wells were replicated but at different depths at the wetland monitoring stations in order to account for possible water table stratification (see Figure 8.2). Further manual groundwater observation wells were installed at other relevant positions within the wetland (Riddell *et al.*, 2007).

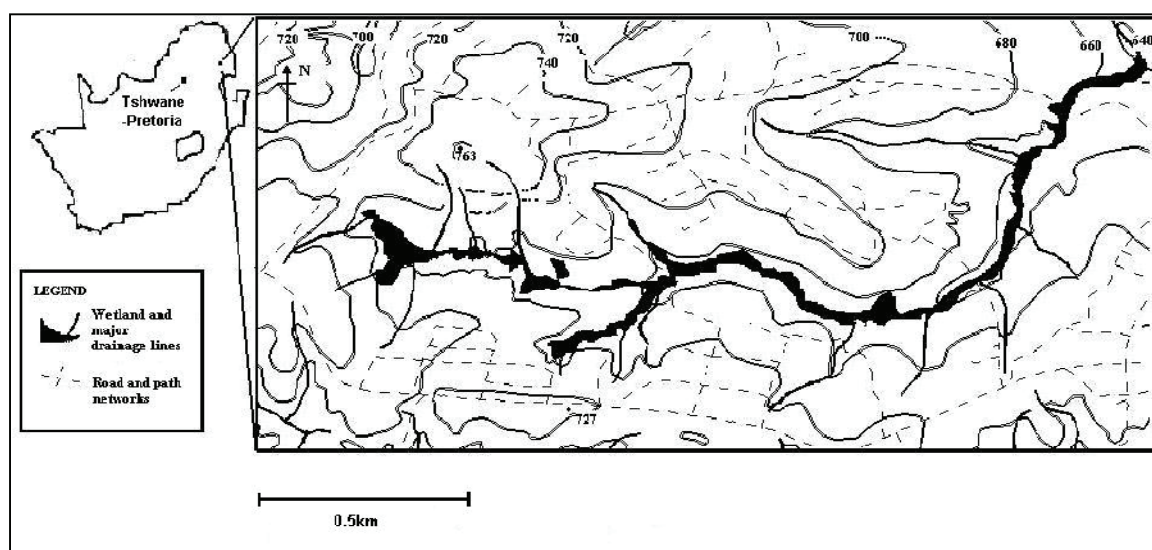


Figure 8.1 1:15000 relief map of the Craigieburn-Manalana catchment and its location within South Africa (Riddell *et al.*, 2007).

8.1.2 Field procedure

Profiles were opened at hydrometric observation stations. These profiles were described and analysed. Some of the observation stations are presented in Figure 8.2. Representative transects selected visually in the field were also surveyed. Observations were made by hand auger. Observations were made as deep as possible. The distance between auger observations varied between 50 and 100 m depending on changes in topographical features. The soils were classified using S. A. Soil Taxonomy (Soil Classification Working Group, 1991). Features with hydrological significance were recorded.



Figure 8.2 Location of some of the hydrometric observation stations (Riddell *et al.*, 2007).

8.2 DATA PRESENTED TO HYDROLOGISTS

A summary of the soil data of Craigieburn catchment given to the hydrologists are presented in the following sections. For the modelling results see Chapter 10.

8.2.1 Land Type data

The information obtained during the soil survey is presented in Table 8.2 as well as Figure 8.3.

Table 8.1 Soil forms, coverage, average and weighted average depths as well as clay contents of the soils of Land Type Ab41

Soil form	Coverage (%)	Depth (mm)	Weighted depth average depth (mm)	Average clay (%)
Hu	61	675	411.75	43.75
Gs	16.5	400	66	27.5
Cf	7.3	700	51.1	16
Hu	5.5	600	33	26.25
Es	4.5	450	20.25	30.3
Cv	1.5	825	12.375	17.25
Lo	1.3	750	9.75	22
Oa	1	1150	11.5	30
Stream	1.5			

The average depth according to Land Type Ab41 is 616 mm and the average clay content is 36%.

8.2.2 Soil survey data

Table 8.2 The different soil forms their extent, depths and bulk densities of the Craigieburn catchment

Soil form	Area (ha)	% of catchment	Horizons	Average horizon depth (mm)	Average soil form depth (mm)	Bulk densities (Mg m ⁻³)	Weighted average bulk densities (Mg m ⁻³)
Ms	12.9	51.0	ot	300	300	1.42	1.42
Gs	2.76	10.9	ot	300	900	1.42	1.55
			li	600		1.61	
Oa	6.56	26.0	ot	300	1430	1.42	1.49
			ne	1130		1.51	
Du	0.32	1.3	ot	300	1700	1.42	1.58
			al	1400		1.61	
Ka	0.6	2.4	ot	300	1487	1.42	1.70
			gh	1187		1.77	
Kd	2.13	8.4	ot	300	1837	1.42	1.66
			gs	350		1.47	
			gh	1187		1.77	

The weighted average soil depth of the Craigieburn catchment is 835 mm and the weighted average bulk density is 1.48 Mg.m⁻³

Table 8.3 Particle size distribution of different horizons in the Craigieburn catchment

Horizon	CoSa	MeSa	FiSa	vFiSa	CoSi	FiSi	Cl
ot	24.9	14.9	11	8.2	10	10.7	18.9
so	18.5	9.7	9.5	10.3	6	16	28
ne	16.7	13.3	10.2	8.3	9.1	11.4	32
al	22.3	17	10.1	7.4	7.3	9.6	26
G	10.7	11.3	10.3	8.4	10	9	39.5
E	25	17.6	11.5	5	8	8	24
Average	19.7	14.0	10.4	7.9	8.4	10.8	28.1

8.2.3 Hillslopes

A soil map was created (Figure 8.3a) and from the soil map a hydrological soil type map (Figure 8.3b), based on the response of the various soil forms. The sequence and extent of the various soil types served as basis for delineating hillslopes with different expected hydrological behaviour (Figure 8.3c). Three different hillslopes (1 to 3) were identified based on the presence, extent and the sequence of different hydrological soil types along the hillslopes (Figure 8.4). The depths of the various soil types are presented in Table 8.4 and a summary of the attributes of the hillslopes in Table 8.5.

Table 8.4 Average depth of hydrological soil types in the Craigieburn catchment

Soil type	Average soil depth (mm)
Recharge	1015
Interflow (A/B)	1837
Interflow (soil/bedrock)	900
Responsive	1594

Table 8.5 Attributes of the dominant hillslopes in the Craigieburn catchment

Hillslope	% of catchment	% Recharge	% Interflow	% Responsive
1	40	70	29	1
2	24	90	0	10
3	36	72	16	13

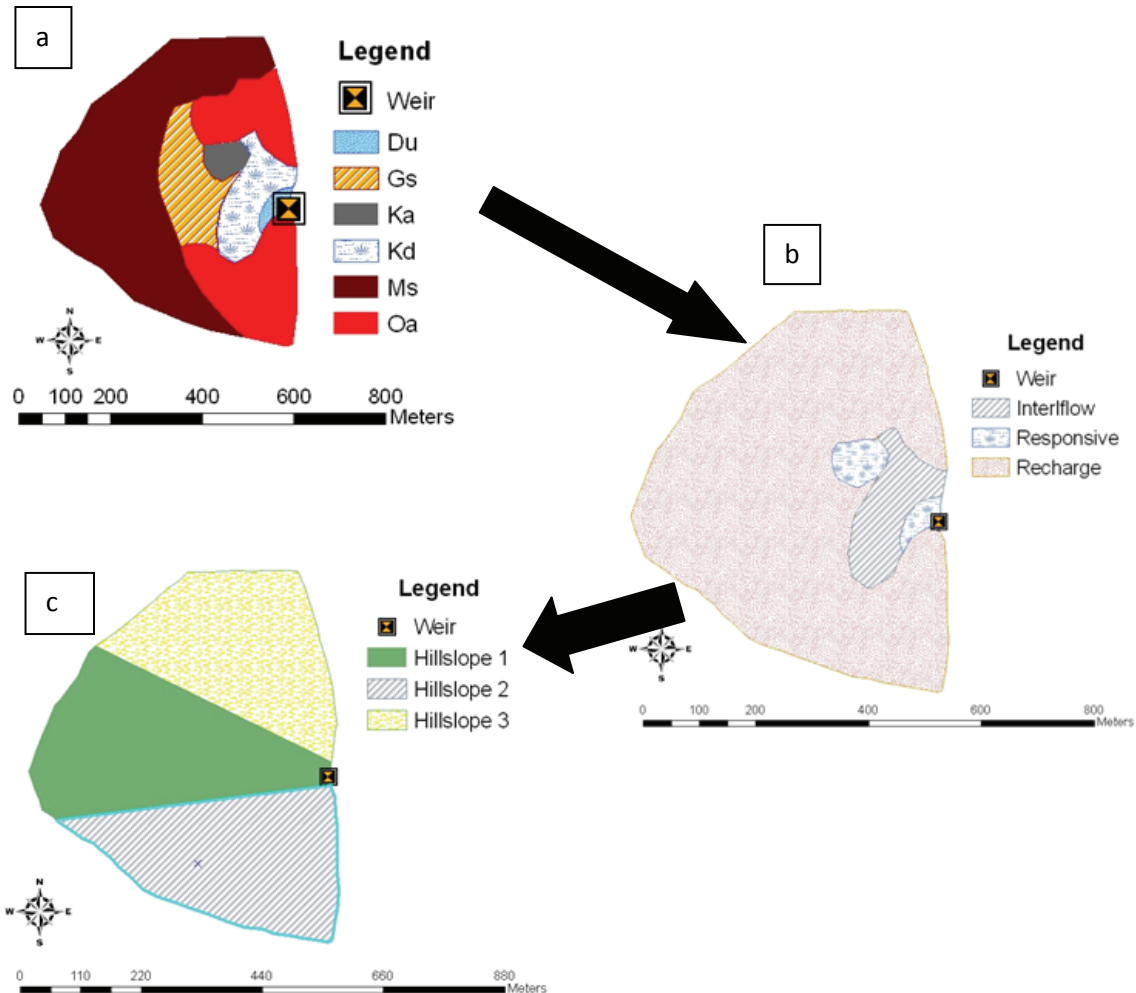


Figure 8.3 Soil map (a), hydrological soil types (b) and dominant hillslopes (c) in the Craigieburn catchment.

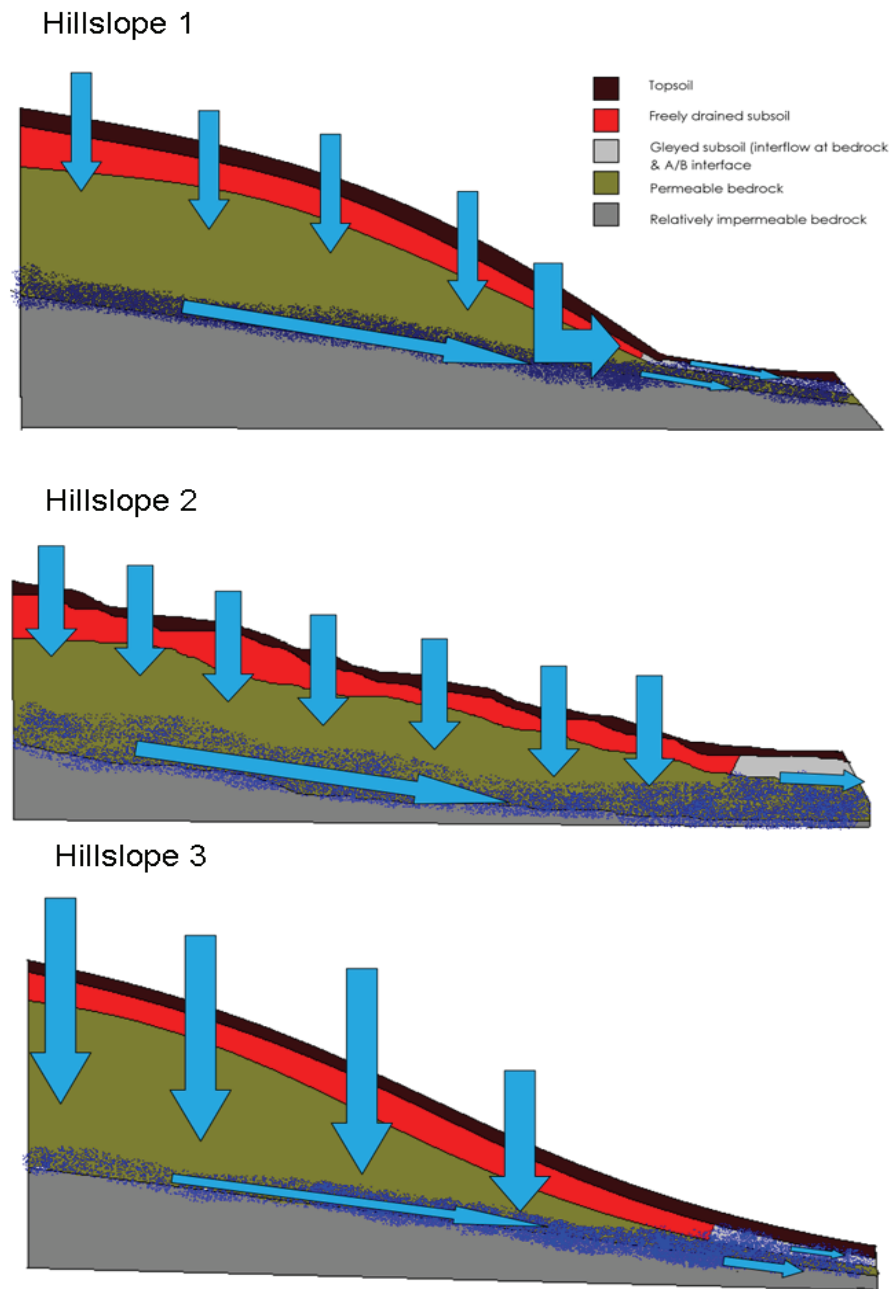


Figure 8.4 Dominant hillslope processes of the various hillslopes in Craigieburn catchment.

Chapter 9 **HYDROPEDOLOGICAL ASPECTS OF THE BEDFORD CATCHMENT**

9.1 STUDY AREA AND METHODOLOGY

Three sub-catchments (B3, B4 and B5) of the Bedford catchment in the Eastern Cape (Figure 9.1) were surveyed for soil distribution and related features for hydropedological purposes. The Bedford catchment is drained by the eNyara River and covers about 670 km². The areas of B3, B4 and B5 are 40.3, 31.1 and 17.7 km² 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 mixture of grass, bush and trees and is classified as Grasslands with False Thornveld in the valley bottom. Land use is restricted grazing by cattle; sheep and a limited amount of game. These catchments are representative of large semi-arid areas in South Africa (Hughes & 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 (Hughes & Sami, 1993).

The parent material form part of the Middleton Formation and consists of horizontally bedded sandstone and shales, some area are however underlain by Koonap and Balfour Formations. Together these three Formations make up the Adelaide Sub-Group of the Beaufort Group of sediments in the Karoo Sequence. The majority of this region has relatively low relief and gentle slopes (Hughes & Sami, 1993).

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. These transects and others selected visually in the field were surveyed. Approximately 240 observations were made on 30 transects. Observations were made as deep as possible. 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 classified in accordance with Soil Classification: A taxonomic system for South Africa (Soil Classification Working Group, 1991).

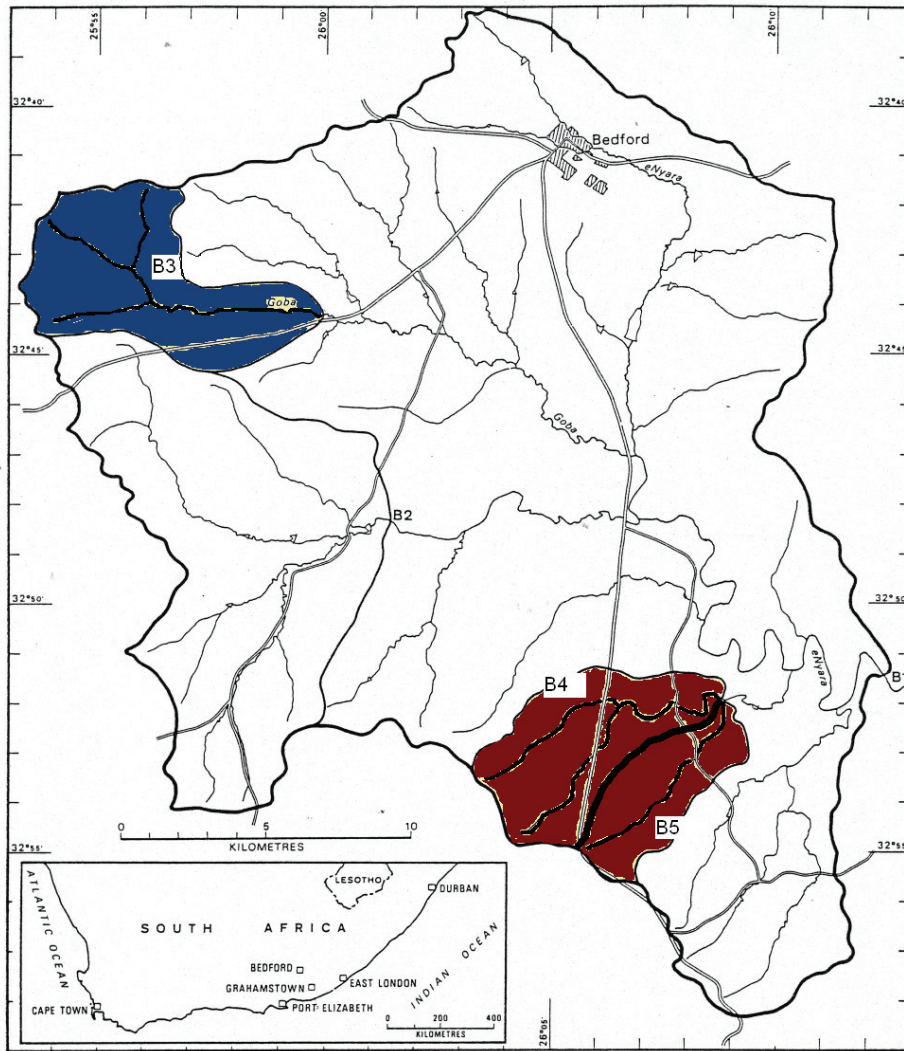


Figure 9.1 Location of the surveyed catchments (Hughes & Sami, 1993).

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.

A weighted mean bulk density (D_b) value for the profile was calculated and used to determine an estimated mean P_o value of the whole soil profile in order to calculate the storage capacity of the catchments. 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. The D_b values were determined on undisturbed core samples from the horizons taken during the field survey.

9.2 RESULTS AND DISCUSSION

The genesis and behaviour of soil is interactive and both a product of the impact of the climate on the geological parent material. This product, soil, is manipulated by the topography. In the Bedford catchment vegetation play a minor role. Soil features (especially depth and texture), supported by topographical, geological and vegetation features related to the soil type, reflect the hydrological behaviour of soils. The pedosequence (soil distribution pattern) therefore reveals how the hillslope responds hydrologically. The contribution of all types of hillslopes determines the catchments response but because the Bedford catchments have characteristic hillslopes they are expected to respond typically.

9.2.1 Soil distribution pattern

The soil distribution pattern of catchment B4 and catchment B5 is the same but differs from that of B3. Therefore catchments B4 and B5 are considered as one catchment (B4 & B5). The dominant soil forms on different terrain morphological units (TMUs) and the relative coverage in catchments B3 and B4 & B5 differ (Figures 9.2 and 9.3).

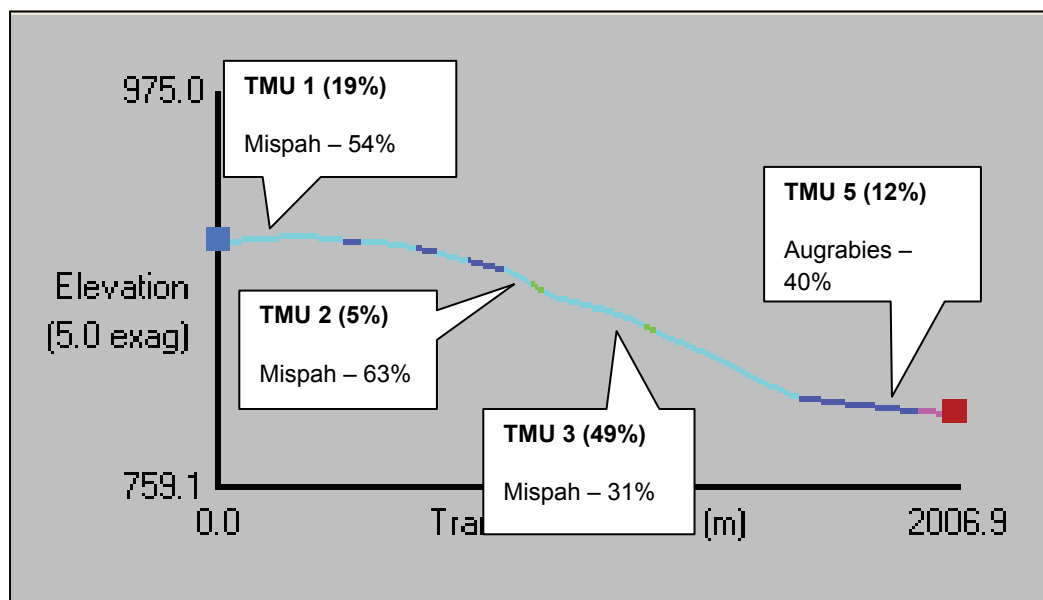


Figure 9.2 Distribution of the dominant soil forms and their coverage on different TMUs along a typical hillslope in B3.

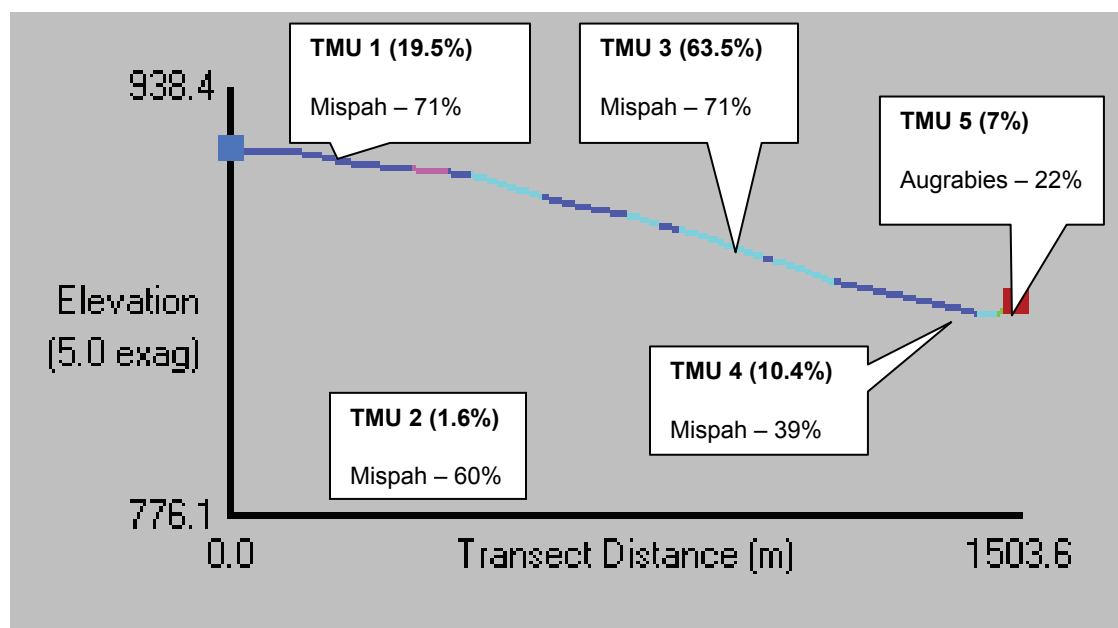


Figure 9.3 Distribution of the dominant soil forms and their coverage on different TMUs along a typical hillslope in B4 & B5.

In catchment B3 Mispah (orthic A horizon/ hard rock) soils dominate on TMU 1 and 2, but on the TMU 3 position soils of the Glenrosa (orthic A horizon/ lithocutanic B horizon) form is dominant (Figure 9.2). This position covers almost half of the catchment. In the lower positions (TMU 4 and 5) soils with well developed B horizons prevails. Almost the entire valley bottom is covered by soils of the Augrabies (orthic A horizon/ neocarbonate B horizon) soil form, with carbonates present in the B horizon.

In catchments B4 & B5 Mispah soils are dominant on TMU 1, 2, 3 and 4 (Figure 9.3). The backslope (TMU 3) covers the greatest area of this catchment (63.5%). Development of B horizons in the form of pedocutanic and neocarbonate were observed in the TMU 5 positions of this catchment.

The degree of physical weathering of the parent rock, visible as cracks, varies between the catchments. An increased degree of physical, and to varying degree chemical weathering, results in soils of the Glenrosa form to dominate in catchment B3 (Figure 9.2 and 9.4). The rock parent rock in B4 & B5 are rarely cracked and impermeable and as a result the soils of the shallow Mispah form are dominant (Figure 9.3 and 9.5). A field test showed that water did not infiltrate the fine hair cracks present on the surface. The lithocutanic B horizon consists of soil mixed with weathered parent material. Although the soil fraction is subdominant the cracks in the lithocutanic B horizon serve as a flowpath for deep drainage water as the underlying rock is fractured. The cracks serve as channels for preference flow for flowing water recharging the phreatic zone of cracked rocks in the hillslope.



Figure 9.4 Soil present in the fissures of the physically weathered rock; typical of the lithocutanic B horizons of catchment B3.

In catchments B4 & B5 water was observed exiting from the shallow soil of the Mispah form in small streams during a rainfall event (Figure 9.5). In the veld water was also exiting the soil at the surface resulting in saturated excess overland flow. The implication is that 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. The sensitivity of a waterlogged soil to erode and overland flow from return flow, 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 9.5).



Figure 9.5 Return flow visible after rain from Mispah soils (B5).

The presence of trees in B3 might be an indication of the existence of cracks in the rock serving as a reservoir of water that is available to deep tree roots and 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 9.6). This is supported by the observation in this catchment of rapid recharge of the regional water table as the water levels of boreholes increase immediately after rain and water flowing into boreholes could be heard, implicating that recharge of the regional water table is from a local origin (Hughes and Sami, 1993).



Figure 9.6 Shrubs and trees growing in the bare rock with cracks near catchment B3. The cracks hold water lower down to support the trees.

In catchment B3 mottled sub-soils on TMU 5 close to the streambed implies 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 interflow addition. The topographical relationship implies that interflow in the hillslope through the fractured bedrock is a more likely explanation for the intermitted water table and development of these signs of periodic subsoil saturation.

According to land type data soils of the Cartref form (orthic A / E / lithocutanic B horizon) occur more frequently in B3 than B4 & B5 (Land Type Survey Staff, 2002). These catchments may not be truly representative of the land types as this could not be confirmed in the survey. Very few soils of the Cartref form were observed. However, 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 a perched water table on the B horizon and interflow.

In B3 the valley bottom is a large, 5 m deep, alluvial body of soils of the Augrabies form. The absence of flowpaths of preference flow indicates that this soil body rather serves as a store 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.

9.2.2 Soil depth and water storage

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. In the Bedford catchments the degree of cracking are correlated to soil depth. The soils in the Bedford catchments are generally shallow, with an average of 215 mm for the selected catchments. There was however a difference between the average depths of B3 (450 mm) compared to B4 & B5 (190 mm). The depth of various soil forms, the area covered, bulk densities and porosity are presented in Table 9.1 for B3 and in Table 9.2 for B4 & B5.

Table 9.1 Description of selected “weighted average” characteristics of observed soil profiles in catchment B3

Soil form	% of catchment	Horizon	Depth (mm)	D _b (mg.m ⁻³)	Weighted mean D _b (mg.m ⁻³)	Po (%)	Po (mm)
Sw/Va	22	ot	200	1.39	1.52	42.6	383
		vp	800	1.56			
		so/uw	900	1.56			
Gs	30	ot	200	1.39	1.50	43.4	174
		li	400	1.60			
Ms	29	ot	200	1.39	1.39	47.5	95
Oa	8	ot	200	1.39	1.35	49.1	1080
		ne	2200	1.34			
Ag	8	ot	200	1.39	1.35	49.1	638
		nc	1300	1.34			
R	3						

Table 9.2 Description of selected “weighted average” characteristics of observed soil profiles in catchment B4 & B5

Soil form	% of catchment	Horizon	Depth (mm)	D _b (mg.m ⁻³)	Weighted mean D _b (mg.m ⁻³)	Po (%)	Po (mm)
Sw/Va	8	ot	300	1.39	1.49	43.88	307
		vp	600	1.56			
		so/uw	700	1.56			
Gs	18	ot	150	1.39	1.52	42.59	170
		li	250	1.60			
Ms	60	ot	200	1.39	1.39	47.5	95
Oa	4	ot	300	1.39	1.36	48.63	340
		ne	700	1.34			
Ag	2	ot	200	1.39	1.36	48.68	243
		nc	500	1.34			
R	8						

The average porosity of B3 is 301.5 mm compared to 130.6 mm of B4 & B5 (Tables 9.1 and 9.2). Although the area of B3 is smaller (40.7 km²) than that of B4 & B5 (49.4 km²), it can store almost twice the volume of water (12.5 × 10⁶ m³ compared to 6.7 × 10⁶ m³; calculated from the average porosity). This facilitates more water infiltration, greater water holding capacity, a greater drainable porosity, a greater volume of water contained at saturation and at drained upper limit. It results in more interflow on the A/B horizon boundary and/or the soil/rock interface, 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, phreatic and regional water tables. The deeper soils on TMUs 4 and 5 of all these catchments are expected to increase these effects. This effect of deeper soils in TMUs 4 and 5 will also be more pronounced in B3 than in B4 & B5.

Thickness of the soil is an important factor determining the flowpaths and 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 surface runoff will play a more dominant role due to saturation excess, especially on the steeper slopes of the TMU 3s. More surface runoff is associated with a shorter residence time and high peak flow volumes.

Deeper Glenrosa soils and shallow Mispah soils alternate down the hillslopes in catchments B3, B4 & B5 to form a stepwise terrain profile (down slope) 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 in vegetation due to the variation in water, profile extractable water impacting on vegetation vitality.

The individual sedimentary layers (shelves) vary in hardness resulting in a corrugated planform (horizontal) curvature. Reddish coloured Mispah soils occur on the ridges and slightly deeper grey coloured 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 flow diagonally downslope from the shallow Mispahs 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 streaks in the landscape three weeks after the rain (Figure 9.7). More water will be stored and tend to move down the slope in the corrugated channels.



Figure 9.7 The influence of variation in soil depth is visible as downslope green streaks where the soils are deeper.

9.2.3 Distribution of lime in the soils and landscape

The solubility of lime (CaCO_3) in water makes it an important indicator of the preferred flowpaths in a hillslope in arid and dry semi-arid environments. Lime released by weathering dissolves and move down slope with leaching water. As water evaporates under a large evaporative demand the lime concentrates and precipitates where the water evaporates and the concentration exceeds the solubility product. The absence of lime from soils on TMU 1 and the upper part of TMU 3 and its presence in the sub-soils of lower lying soils on TMUs 3, 4 and 5 of all the catchments implies a redistribution of lime after being released by chemical weathering. It further implies that redistribution depends on the leaching factor and periodic

presence of flow paths in the soils. 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 length and gradient, and profile and planform slope shape). Leaching of lime is effective in the higher lying soils in spite of the impermeable rock in B4 & B5 implying interflow on the bedrock. However, lime accumulation in the subsoils of lower lying calcareous Augrabies form in the TMU 4 and 5 positions soils implies significant interflow of water enriched in CaCO_3 . It further implies that leaching is often limited by the ratio of precipitation to evaporative demand and 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 & B5. This is an indication of storage of small volumes of CaCO_3 rich water rather than the cracks being conduits for phreatic water. This observation supports the supposition that phreatic water tables do exist in the lower landscape, but do not play a significant role in hillslope behaviour of B4 & B5.

The occurrence of calcareous soils indicates the presence of a phreatic water table in arid climates. The water table is probably transient in nature and only occurs in the wettest time of the rainy season of wetter years. The water table is presumably also the cause of mottles in the deep subsoil of B3 indicating a wetter condition in the TMU 5 position than is the case in B4 & B5. Calcareous character was also more prominent in the alluvial body of catchment B3. CaCO_3 precipitates occurred in macro pores (both interpedal pores of pedocutanic B horizons and root channels of neocarbonate B horizons) implying a much larger storage capacity in the deep soils and possible return flow from the hillslope fractured rock.

9.3 CONCEPTUAL MODELS OF HYDROLOGICAL BEHAVIOUR

The hillslope hydrology of the catchments differs. Shallow Mispah soils and impermeable underlying bedrock are the dominant governing factors of flowpaths in catchments B4 & B5 (Figure 9.8). These factors favour overland flow (1) as saturation excess water are added to infiltration excess water and adds to peak flow which implies short residence times. Infiltrated water flow 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 down slope. Water storage occurs as an infrequent water table (4) in TMU 5 as indicated by the presence of lime.

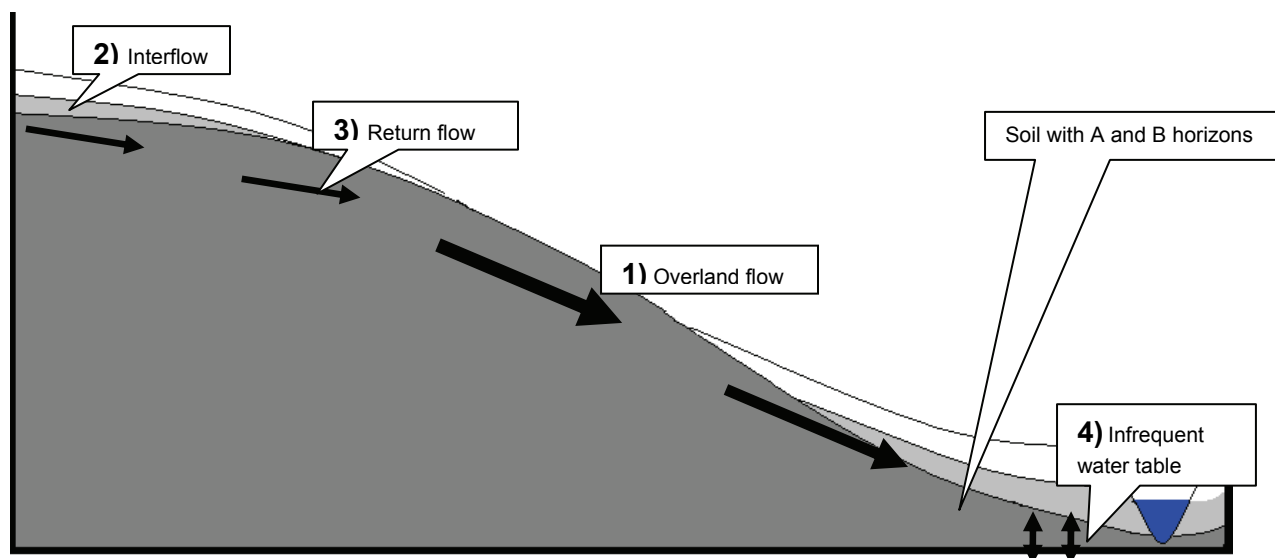


Figure 9.8 Conceptual hillslope hydrological behaviour in catchments B4 & B5.

Deeper Glenrosa soils and permeable bedrock are the dominant factors governing flowpaths in catchment B3 (Figure 9.9). These factors favour bedrock flow (1) recharging the regional water table (2) and phreatic water tables (3) in the lower hillslope. Indication of flow at the A/B horizon interface (4) indicates some activity in B3. This implies longer residence times in the hillslopes. A more active phreatic water table (5) are expected. The latter is indicated by the presence of more lime and mottles as indications of periodic redox conditions.

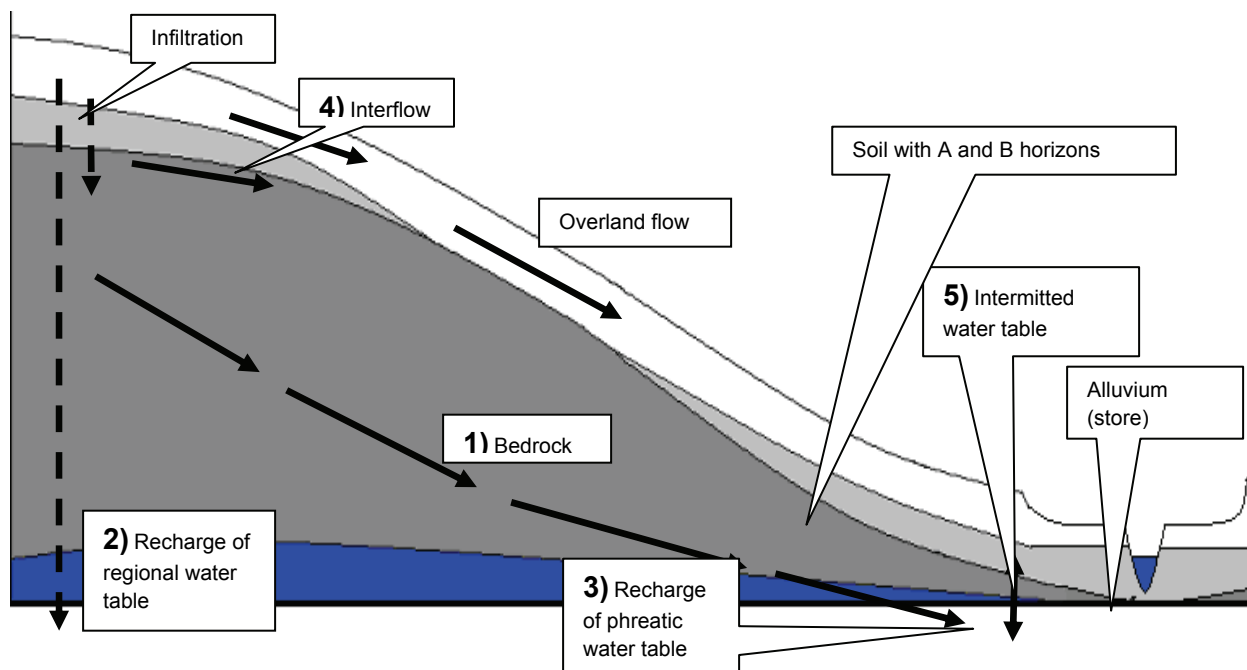


Figure 9.9 Conceptual hillslope hydrological behaviour of catchment B3.

These conceptual models of the hydrological behaviour of the hillslopes of catchments B3 and B4 & B5 is in harmony with the results of Hughes and Sami (1993) and field observations (personal communication Hughes, 2007). An important element of the flow paths is that there may be a significant difference in the direction of flow in the soils of B4 & B5 and B3. This knowledge implies that the direction in which soil samples are taken for saturated hydraulic conductivity measurements should be according to the main flow direction rather than vertical.

9.4 SOIL DATA FOR HYDROLOGISTS

A brief summary of the data supplied to the hydrologists are presented in Table 9.3. More detail is available on CD as Appendices.

Table 9.3 Summary of the two different levels of inputs for the different catchments used by the Pitman and VTI model

	Characteristic	B3	B4&5
Level 1	Soil texture	SaCl	SaLm
	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%
Level 2	Soil texture	SaClLm	SaLm
	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%

9.5 CONCLUSIONS

Soil indicators and their links with bedrock and topographical characteristics reveal 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. Incorporation of this kind of soil information into hydrological models may contribute to improved prediction of the hydrological behaviour of hillslopes and catchments. Although interpretations of soil properties as indicators of hillslope hydrology can play a role in understanding the hydrology of gauged catchments, they may be much more valuable in predictions of the hydrological behaviour of ungauged catchments.

Soil properties serving as indicators of hillslope hydrology are commonly observed and often recorded in soil surveys yet neglected for interpretation. A mind shift in this regard may change soil surveys to include more and different observations and enhance the role soil survey data can be turned into information useful in environmental issues.

Chapter 10 **HYDROLOGICAL MODELLING RESULTS**

10.1 INTRODUCTION

The gap between experimentalist and modellers poses one of the greatest challenges in hydrological modelling. Modellers normally rely on small scale physical descriptors to describe a hillslope scale water balance, while the experimentalist proposes a conceptual model of hillslope hydrological behaviour based on observations, measurements and experience, but unfortunately modellers usually do not incorporate the experimentalist's knowledge into the model structure (Sivapalan 2003a; Sivapalan 2003b; Weiler & McDonnell, 2004; McDonnell *et al.*, 2007; Tromp – van Meerveld & Weiler, 2008). On the other hand experimentalists have focussed on the documentation of the unconventional behaviour of new hillslopes instead of the systematic examination of first order controls of hillslope hydrological behaviour, without intercomparisons to obtain common process behaviours (Weiler *et al.*, 2004).

Interpreted soil survey data was presented to hydrological modellers from CSIR, University of KwaZulu-Natal and Rhodes University to incorporate into hydrological models: ACRU, Pitman, VTI, SWAT and WAVES. Streamflow and soil water contents were simulated and compared to simulations using "original soil inputs" (normally Land Type data, Land Type Survey Staff, 2002) and measured outflows and water contents.

In this paper results from the modellers are scrutinized by the experimentalists (UFS). The aim was to narrow the gap between the modellers and experimentalists through enhanced interaction and proposed amendments on the application of soil survey data in the hydrological models for different catchments.

It is important to note that this chapter is written from the experimentalist's viewpoint, assuming that the soil data presented to the modeller is correct and unsatisfactory simulations are caused by incompetence of the hydrological model.

10.2 BEDFORD CATCHMENTS

Records of historical measured outflow from the Bedford catchments were lost due to computer hardware failure at Rhodes university some years ago, therefore parameter exploration and sensitivity using a 'best guess' time series estimate were used as the basis for the assessment. The appropriateness of the soil data for the model would thus be judged by its

ability to produce identifiable, hydrologically plausible parameters. More detail is available on CD as Appendices.

10.2.1 Results from the Pitman 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 10.1. 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 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 (Figure 10.1). For example the model predicts that a similar monthly outflow of $0.5 \times 10^6 \text{ m}^3$ 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.

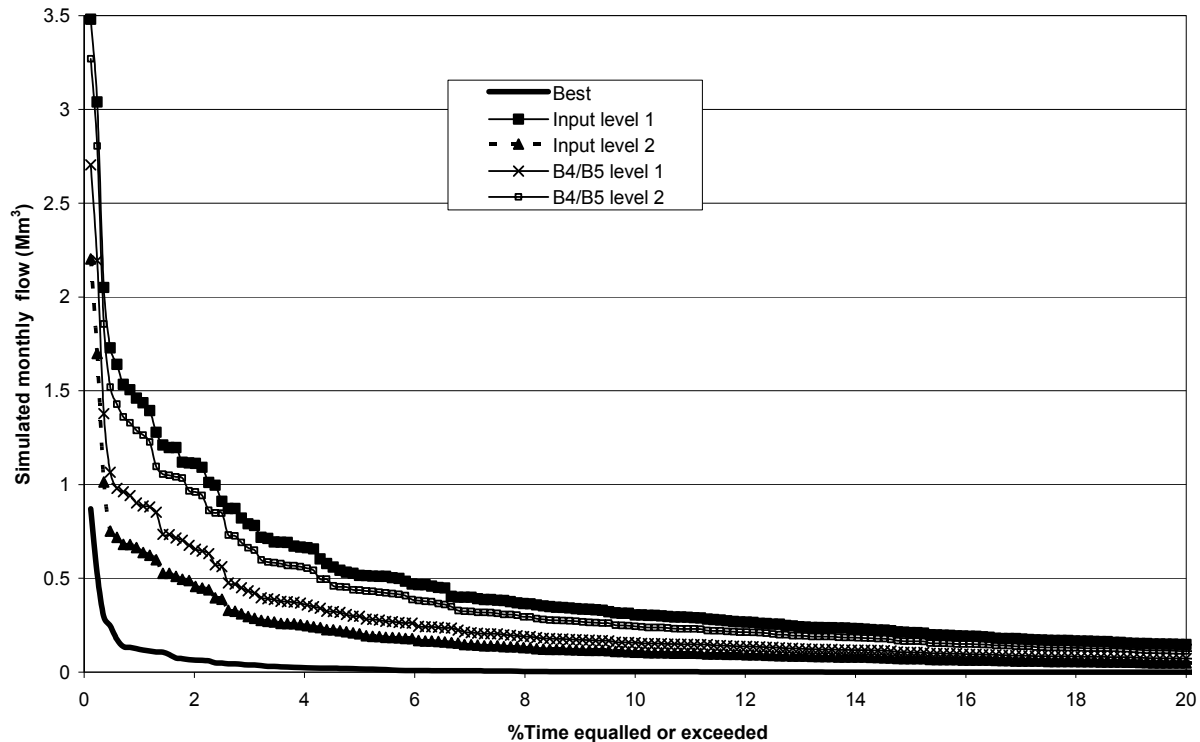


Figure 10.1 Flow duration simulations for catchment B3 using different types of input levels. The first two levels of input refer to those for catchment B3 (After Kapangaziwiri, personal communication, 2008).

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 $0.5 \times 10^6 \text{ m}^3$ 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 outflows 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% 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. 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%. 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 9.12 include the storativity of the subsurface layers (5%), which explains the very low simulated outflow. The influence of the storativity is magnified in Figure 9.13, where the low storativity of catchment B4&5 (1%) resulted in much higher simulated streamflow compared to catchment B3.

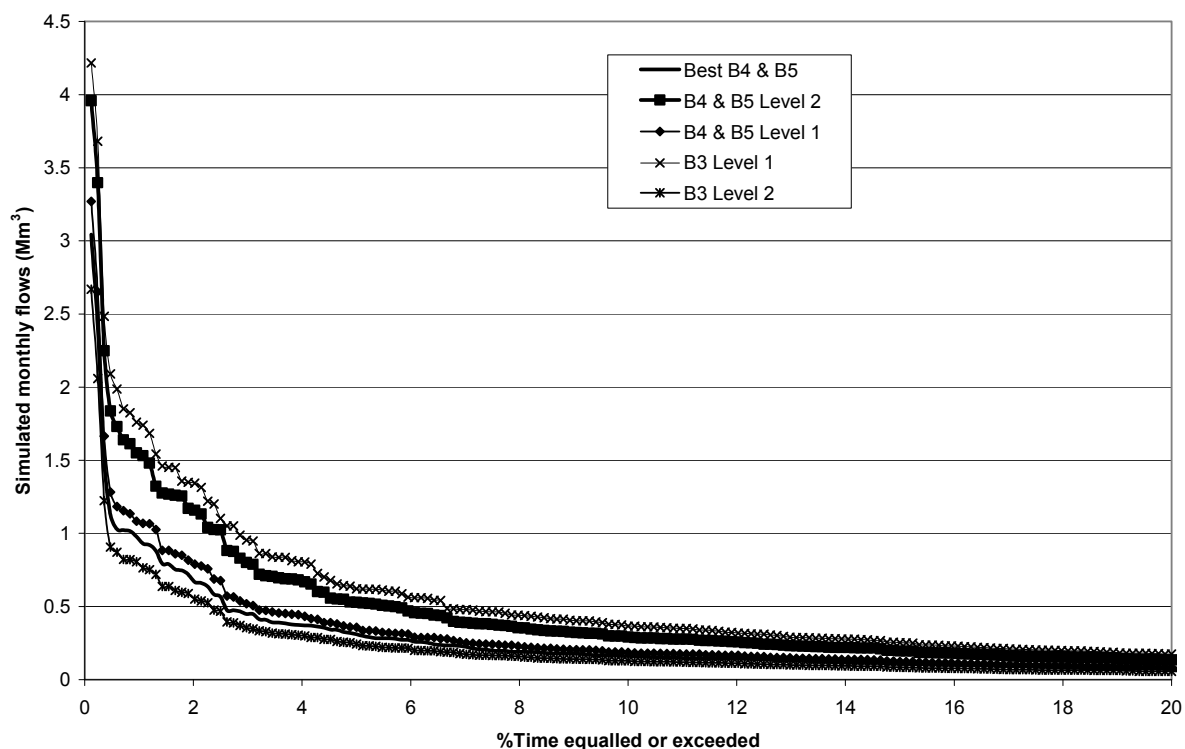


Figure.10.2 Flow duration curves for catchment B4&5 using different soil input levels for different catchments (After Kapangaziwiri, personal communication, 2008).

The results presented in Figure 10.2 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.

10.2.2 Results from the VTI model

Only sub-catchment B3 was used for this exercise since there was no existing setup for B4 and B5 and no flow data were recorded for these catchments. The model was run four times with changes made to soil related parameters (Figure 10.3). The “original” run used parameters calibrated during a few short term events in an earlier project in B3 between 1988 and 1993.

During the following 3 runs, the hydraulic conductivity, infiltration rates and texture classes were adjusted according to the soil survey results while the rest of the parameters remained constant. The adjustments are presented in Table 10.1 and results of the various runs in Figure 10.3.

Table 10.1 Original and soil survey parameters of the VTI model

Parameter	Original (calibrated) parameters	Soil survey parameters
Hydraulic conductivity	5.1-6.3 (mm.h ⁻¹)	11.4 (mm.h ⁻¹)
Infiltration rate	8.9 (mm.h ⁻¹)	1.73 (mm.h ⁻¹)
Texture class and % coverage of catchment	SaCl (100%)	LmS/SLm (5%) SClLm/SiLm/Lm (45%) SaCl/CLm/SiCLm (50%)

It is clear that the most significant change in simulated flow is caused by a decrease in the final infiltration rate (from 8.9 to 1.73 mm.h⁻¹) (Figure 10.3). Far more runoff, as well as more frequent runoff is generated due to infiltration excess and overland flow. This accentuates the importance of accurately quantifying this parameter. Infiltration measurements over a wide range of soil and vegetation types on various locations in the catchment should be conducted.

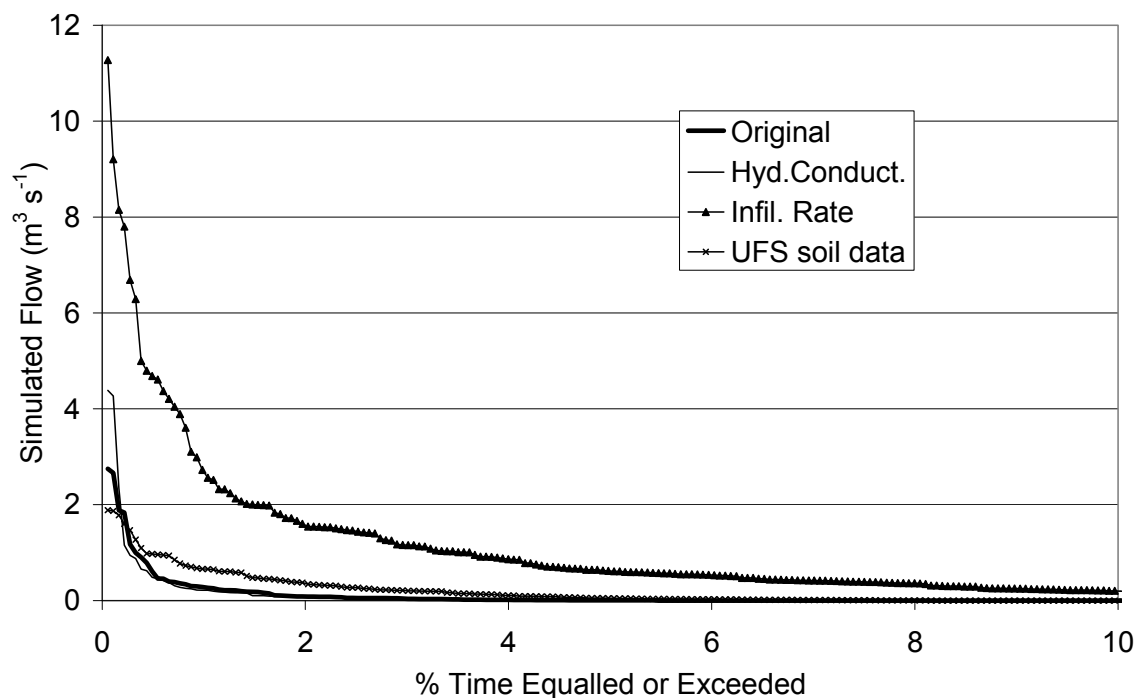


Figure 10.3 Duration curves showing the results of the VTI model runs in B3.

Increased hydraulic conductivity resulted in no substantial changes in the shape of the flow duration curve. Peak flows during a single events did however increased, which may be

attributed to an increase in the contribution of interflow to streamflow due to higher hydraulic conductivities.

The last run, termed, “UFS soil data” used the texture class distributions obtained from the soil survey (Table 10.1) and hydraulic conductivity and infiltration rates estimated by the model. Using this texture distribution resulted in an increase in the infiltration rate (6.6 mm.h^{-1}) and a decrease in the hydraulic conductivity (4.0 mm.h^{-1}). These parameters resulted in simulated flows very similar to the original calibrated setup with slightly higher outflows because of the lower infiltration rate.

10.3 TWO STREAMS CATCHMENT

A detailed soil survey of Two Streams catchment was given together with other essential soil qualities (texture, bulk density, etc.) to the hydrologists to improve their hydrological modelling. Three models were run to evaluate the influence of advance soil data on the simulated streamflow and soil water content in this catchment. The models used were WAVES, SWAT and ACRU. More detail is available on CD as Appendices.

10.3.1 ACRU model simulations

10.3.1.1 Comparison between observed and simulated streamflows using original soil data

The streamflow simulations using ACRU show that the accumulated streamflow over time is underestimated when using the original soil data (Figure 10.4). During the period of measurement from January 2000 to December 2008 the measured accumulated streamflow is 400 mm, while the simulated total streamflow using the original soils is 375 mm. The simulation tracks the actual closely until the end of 2004 when the catchment was clearfelled. From late 2004 to early 2007 the model consistently overestimates the streamflow. However from 2007 to December 2008 the model consistently underestimates the streamflow. An explanation for this may be that during the fallow period, the model is underestimating total evaporation and when the catchment is planted up with wattle we are overestimating total evaporation resulting in reduced streamflow estimates. This apparent divergence between simulations and observed data together with a change in the conditions of the catchment provide an excellent opportunity to verify model performance. It also shows that good model performance under a specific landcover does not necessarily ensure good performance under different landcover scenarios.

10.3.1.2 Comparison between observed and simulated streamflows using new soils data

The streamflow simulations using ACURU with the new soils data which reflect changes in soil type, soil depth and soil texture show that the accumulated streamflow over time is consistently oversimulated by the model when compared to the observed accumulated flows (Figure 10.4). During the period of measurement from January 2000 to December 2008 the measured accumulated streamflow is 400 mm, while the simulated total streamflow using the new soils data is 525 mm. The model consistently oversimulates streamflow during the simulation period January 2000 to December 2008, even during periods of significant landuse change, e.g. clearfelling during 2003 and replanting in 2006.

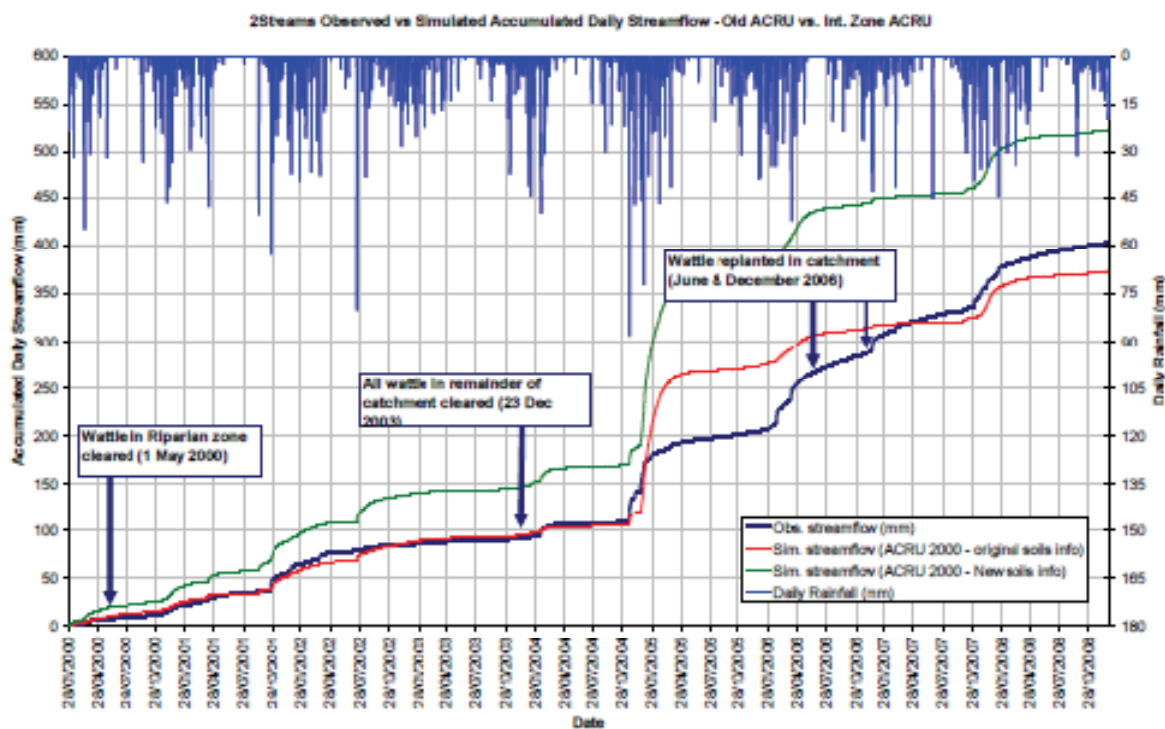


Figure 10.4 Time series of accumulated daily observed streamflow totals (mm) from Two Streams from January 2000 to December 2008 using ACURU version 3.31 and the new Intermediate Zone ACURU. Periods of significant land use change are indicated.

A comparison of simulated soil water using the original soil data and the new soils data with the ACURU model is illustrated in Figure 10.4 for the period 2001 to 2008. Both estimates of model soil water do follow a very similar trend for this period. However during 2003 and 2004 the soil water profile estimated using the new soils information reduced in volume when compared to the original soil data simulation, illustrating a larger difference between the two plots. Actual values of soil profile water content have been included from September 2007 to December 2008 providing a validation period of 16 months when comparing with the model output. The

CS616 probes were used for the actual measurements, since they provided the longest deep soil profile data set at the site, down to 2.4 m. The actual total profile water content ranged from a minimum of 517 mm at the end of the long winter period (October 2008) to 681 mm of water in midsummer (December 2007), after approximately 300 mm of summer rainfall since the beginning of October 2007.

A comparison of the actual and the modelled total profile water contents over the 16 month is illustrated in Figure 10.5. At the start of this period, both ACRU simulations were very similar (approximately 480 mm) compared to actual total profile water content (547 mm). For both

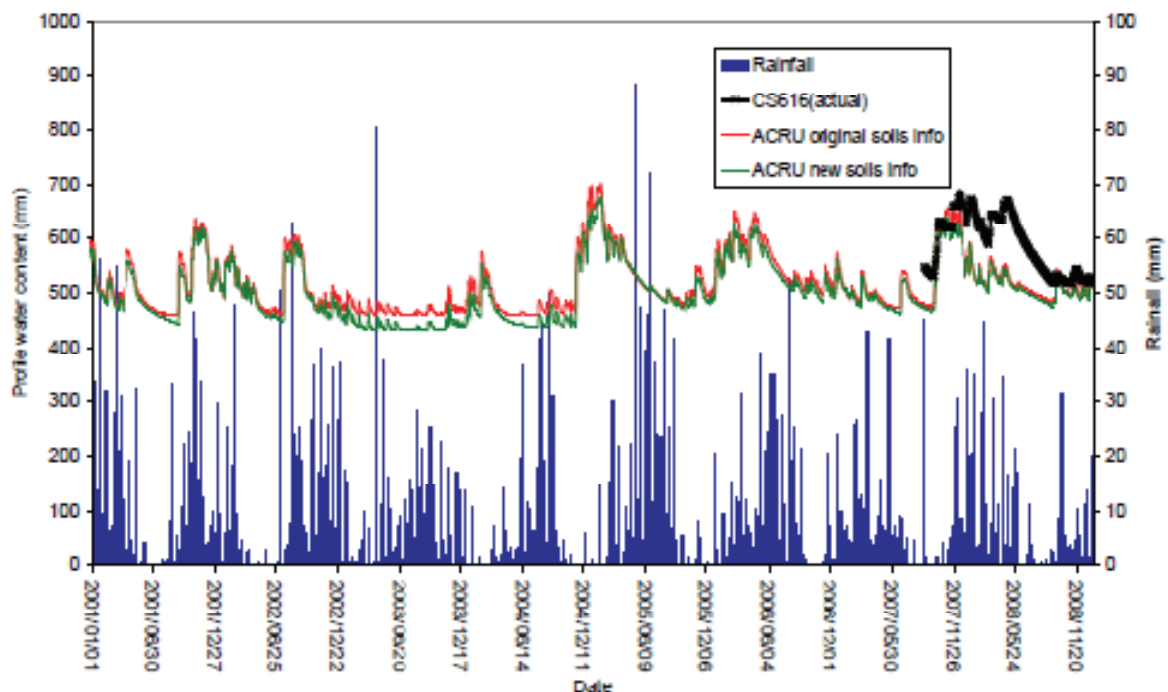


Figure 10.5 Time series of simulated profile soil water (mm) from Two Streams from January 2000 to December 2008.

ACRU model simulations only small responses to the large rainfall events occurred. The ACRU model initially responded well to the first summer rains in October 2007, but then showed a gradual decrease in values when the actual values were increasing in late December 2007. The ACRU model generally underestimated soil water during this simulation period when compared to actual soil water profile measurements (Figure 10.6).

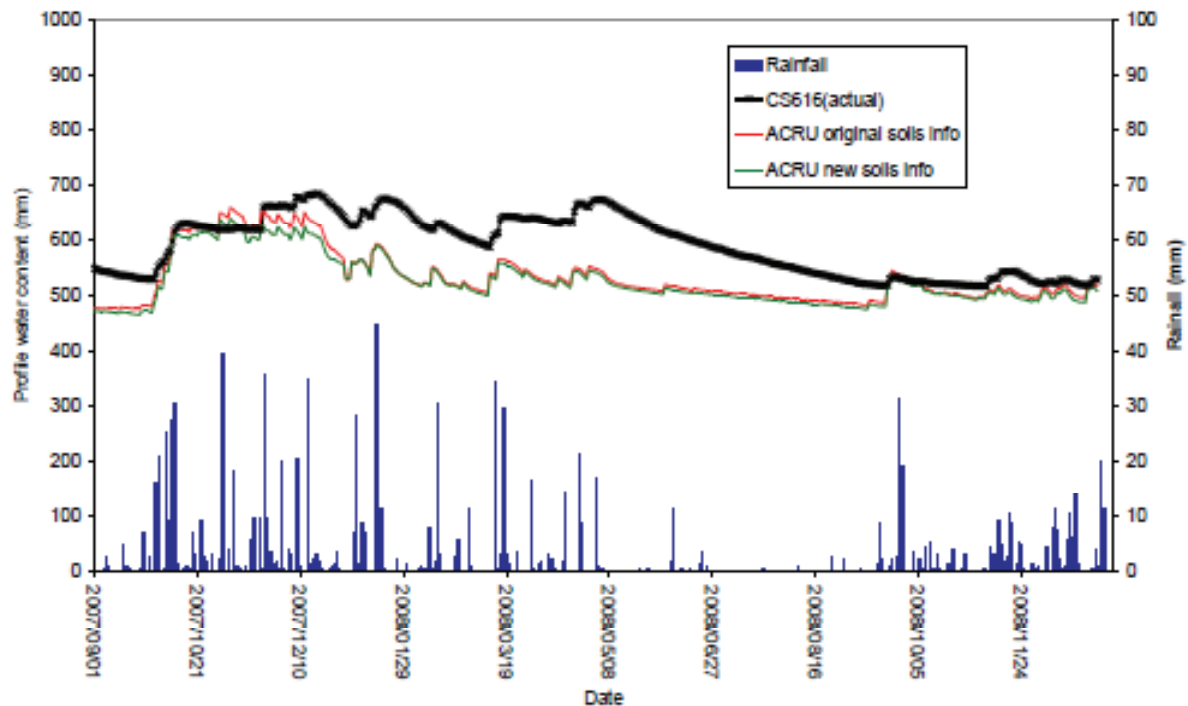


Figure 10.6 Time series of simulated profile soil water (mm) from Two Streams for September 2007 to December 2008.

Discrepancies between the modelled and simulated soil water demonstrates the value of actual long-term soil water data from deep profiles for improving model development and modelled components of the hydrological water balance.

10.3.2 SWAT model simulations

10.3.2.1 Comparison between observed and simulated streamflows using original soil data

Modelled streamflows are consistently overestimated when compared to observed data until replanting of the catchment in December 2006 (Figure 10.7). From December 2006 to December 2008 streamflow is underestimated by the SWAT model, as the wattle plantation continues to grow in the catchment. An 8% deviation between modelled and observed accumulated streamflow totals exists at the end of the simulation period. In general there is good agreement between modelled and simulated accumulated streamflows when using the original soil data.

10.3.2.2 Comparison between observed and simulated streamflows using new soil data

The streamflow simulations using SWAT 2000 with the new soils data which reflect changes from a 2-layer to 4-layer dominant soil type shows that the accumulated streamflow over time is consistently overestimated by the model when compared to the observed accumulated flows (Figure 10.7). During the period of measurement from January 2000 to December 2008 the measured accumulated streamflow is 400 mm, while the simulated total streamflow using the new soils data is 600 mm (50% deviation in total accumulated flows). In general there is poor agreement between SWAT model simulations using the new soil data and the observed streamflow totals for this period.

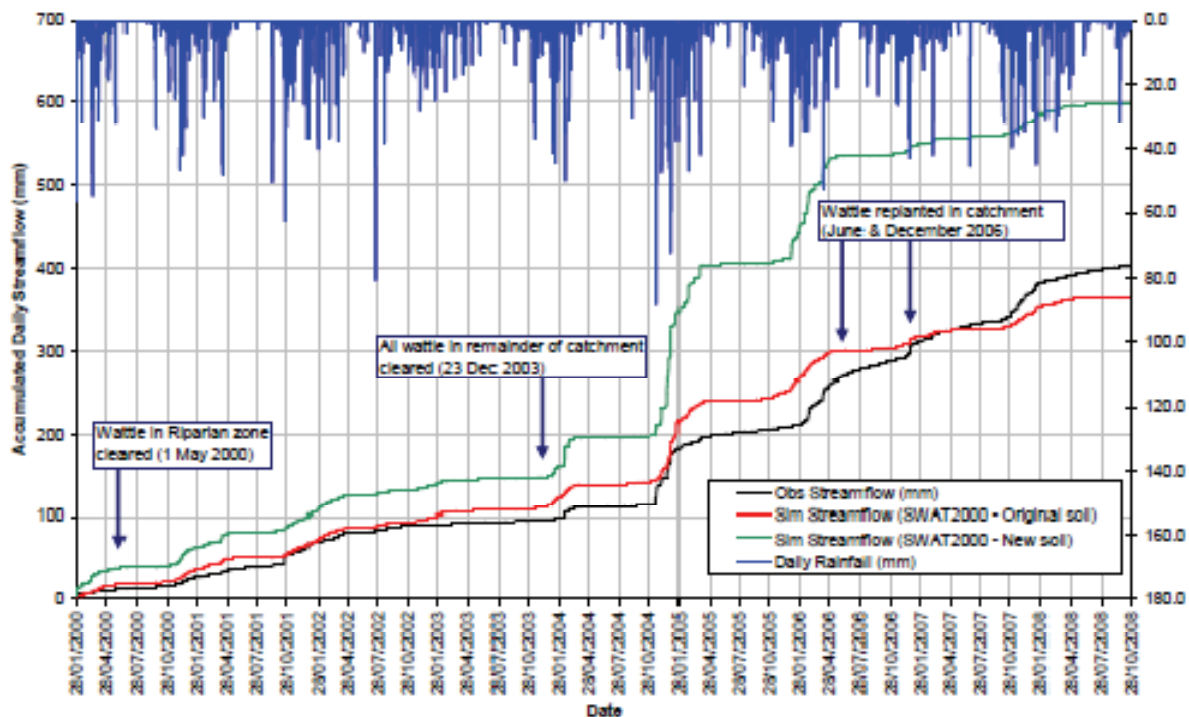


Figure 10.7 Time series of accumulated daily observed streamflow totals (mm) from Two Streams from January 2000 to December 2008 using SWAT 2000. Periods of significant land use change are indicated.

A comparison of the actual and the modelled total profile water contents using SWAT 2000, for the period September 2007 to December 2008 is illustrated in Figure 10.8. There is very poor agreement between actual total profile water content measurements and simulated soil water content using the original and new soil data. The model consistently underestimates soil water from the start of the simulation. From the start of the simulation both SWAT model estimates are very similar, responding to rainfall events but estimating too small soil water volumes. Due to very poor model performance, difference components of the water balance were checked against measured datasets to identify possible source of errors. Simulated daily total

evaporation patterns for 2006 and 2007 (on average 1.5-2 mm/day during dry season and 4-5 mm/day during wet season where compared with total daily evaporation obtained using Large Aperture Scintillometer (on average 2 mm/day during dry season and 6-7 mm/day during wet season) (Clulow, 2008). Other model checks included increasing soils depths and increasing infiltration of soils which did not change the model outputs significantly. Discussions with the SWAT model developers are underway in order to understand why the model performed poorly for the Two Streams catchment.

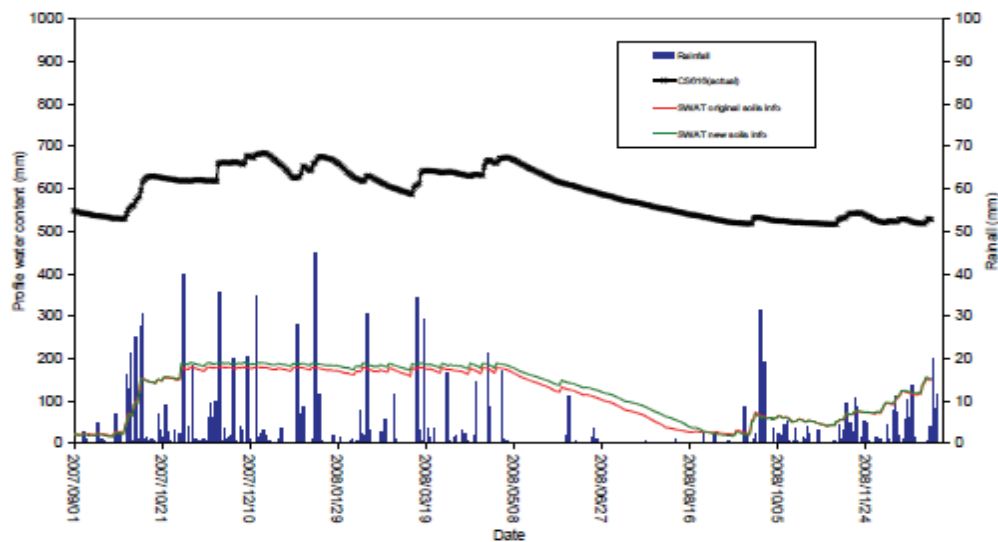


Figure 10.8 Time series of simulated profile soil water (mm) from Two Streams for September 2007 to December 2008 using SWAT 2000.

10.3.3 WAVES model simulations

A comparison of the two model simulations and the actual measured data is shown in Figure 10.9 For ease of comparison, the soil water contents (both modelled and actual) are presented as the total profile water content which integrates the top 2.4 m of the soil profile by converting the volumetric water content into a depth equivalent of water in mm. It is interesting to note that the two model simulations follow the exact same trends but predict the profile soil water differently. For the baseline simulation, using the original soils data, the actual and the modelled total profile water contents were very similar. In this simulation the WAVES model showed fairly good agreement to the trends in the actual total profile water content. However, for the second simulation where the soil textural information was changed, the model consistently underestimates the total profile water content at 2.4 m.

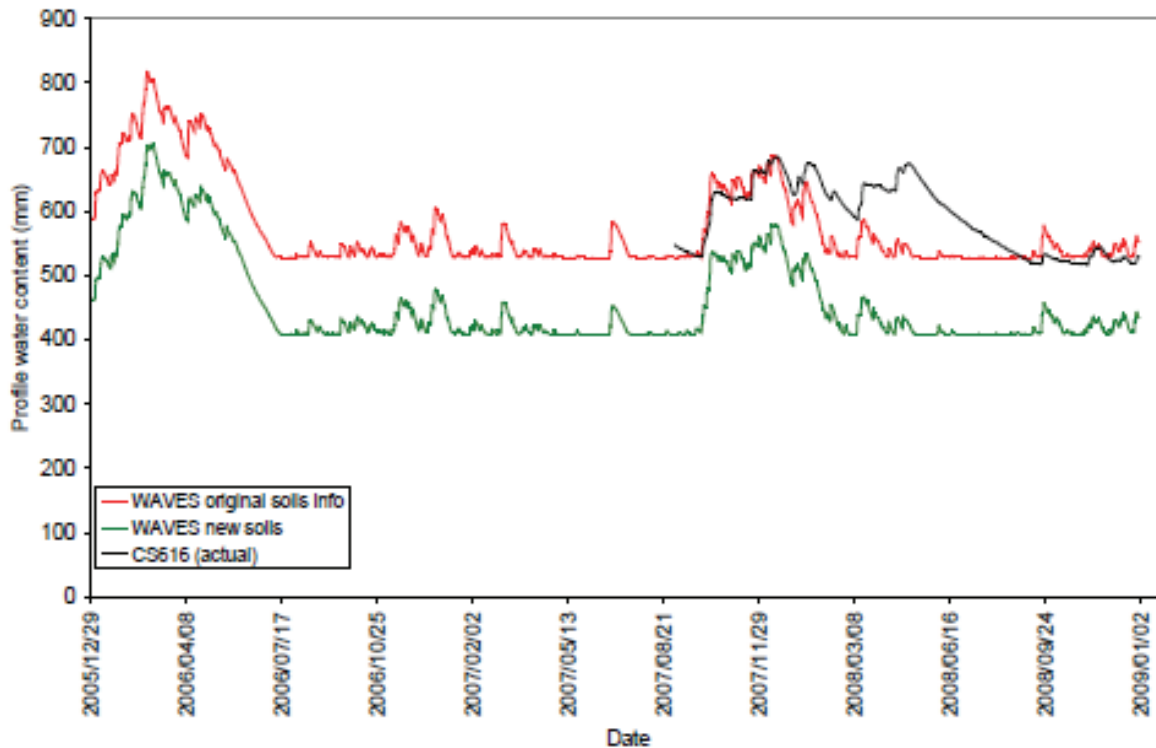


Figure 10.9 Time series of simulated profile soil water (mm) to a depth of 2.4 m from Two Streams for January 2006 to December 2008 using WAVES.

In the WAVES model configuration, there are a number of vegetation parameters available to accurately describe the characteristics of the crop which can have a significant impact on the soil profile water content. The most significant of these was found to be leaf/stem ratio, maximum assimilation rate, respiration and leaf mortality (Clulow *et al.*, 2009). Unfortunately, although this provides the user with the ability to more accurately represent the actual crop growth, many of the parameters then require estimation as they are not known for all species. Therefore the model performance may also be improved through better estimates of the WAVES model crop growth parameters for *Acacia mearnsii* at this site.

10.3.4 Comments on the modelling results of the Two Streams catchment

In general, soils provided by this project did not improve any modelling exercise according to the results above. There could be reasons for this but a general inference from these results is that proper communication and information about specific model parameters related to soil information should be established. There were some gaps picked up in some soil information used in modelling exercises discussed above. This are discussed below for each model used.

10.3.4.1 SWAT model

This model overestimated streamflow by almost 50%. Some soil information provided by this project was misquoted in SWAT model parameters. For instance, there was a consistent exaggeration of sand percentage in the four horizons (layers) of Griffins soil form information. Misquotation was as follows, layer 1 (assumed to be A horizon) is 54.90%, instead of 53.3%, layer 2 (assumed to be B1 horizon) is 57% instead of 52.7%, layer 3 (assumed to be B2 horizon) is 56.10% instead of 54.8%, layer 4 (assumed to be the saprolite) is 53% instead of 51.6% (More detail is available on CD as Appendices). It is not clear whether this was done deliberately or not, depending on the requirements of the model in question. The depths of the layers (horizons) of Griffins soil forms were also incorrect in the subsoil horizons, e.g. layer 2 (B1 horizon) was quoted to be 500 mm instead of 250 mm, layer 3 was quoted to be 1250 mm instead of 750 mm and layer 4 (Saprolite) was quoted to be 1750 mm instead of 500 mm depth (More detail is available on CD as Appendices). Percent rock, which has been quoted in Griffins soil form (More detail is available on CD as Appendices), was not provided by this project and this seems to be another soil parameter used by SWAT model. It is also not clear how this was determined. It is possible that higher quoted sand percentages can simulate high hydraulic conductivities hence overestimation of streamflow.

10.3.4.2 ACRU model

It is not clear which soil parameters were used to simulate the ‘second run’ or ‘new soils info’ However, it is stated by modellers that Griffin soil form was used to “characterize subcatchment 1 representing the upland recharge areas of the catchment; while Katspruit soil form was used to characterize sub catchment 2 representing the riparian responsive zone of the catchment”. These soils were used to adjust soil depth and soil texture parameters. We therefore expect no difference from SWAT in the way our soil information will handle ACRU model if the same quotations were used. Both SWAT and ACRU simulated streamflow using “new soil” are almost identical, implying that same quotations were used in both models.

10.3.4.3 WAVE model

According to the modellers, only soil texture was used from the information provided. This information was used to derive drainage characteristics such as wilting point, drained upper limit and saturation. In the WAVES model configuration, there are a number of vegetation parameters available to accurately describe the characteristics of the crop which can have a significant impact on the soil profile water content. The fact that WAVES model simulates various components ‘within a one-dimensional soil-plant-atmosphere system’. It seems unlikely that a model simulating within a one – dimensional system will be capable of reliably simulating lateral water movement in a soil profile which is one of the flow mechanism in this catchment.

10.3.5 Conclusion on Two Streams

It is not surprising that soil information provided was not able to improve hydrological models. Despite some incorrect quotations, it would still have been unlikely that so basic soil information provided can yield right results. This could be because of the following; Information has been limited to only physical properties, without much desired hydraulic properties that can characterize well hydrology of soils. For example, ACRU utilizes drainage characteristics such as drained upper limit (DUL) and lower limit (LL), “saturated” redistribution fraction from topsoil horizon into subsoil and fraction of saturated soil water to be redistributed daily from subsoil into intermediate/groundwater store. All this information was not supplied, rendering our information short of key properties influencing streamflow. Even if these properties were supposed to be estimated, it not known how reliable such estimations could be. In the absence of hydraulic properties for these soils, well developed pedotransfer functions (PTF) are necessary. PTFs are developed carefully on a number of samples in the laboratory and *in situ*. Additional information from other studies is also incorporated statistically in the development of PTFs. This is one of the main objectives of the next phase of this project, to develop sound PTFs that can be proper vehicle between catchments. With PTFs, basic soil information similar to the one we provided can become helpful. It is also necessary to learn, as pedologists, specific soil related components of models, such that provided information should be relevant to specific model.

10.4 CATHEDRAL PEAK VI

Cathedral Peak VI catchment was not modelled with new soil data to evaluate the impact of improved soil data in the hydrological modelling. The model testing was done by in Everson *et al.* (1998) using detailed soil water contents and other soil properties. This was prior to the current project. Even though soil survey was conducted in this catchment, soil map was not used to by Everson *et al.* (1998) to test their model. Models used were ACRU (Agricultural Catchments Research Unit) and TOPOG. ACRU model was developed within the Department of Agricultural Engineering, University of Natal to provide a simple decision making tool for agrohydrological problems (Schulze, 1995). The aim of the model is to partition the distribution of soil moisture and simulate evaporation. Rainfall not removed as interception or stormflow first enters and resides in the A-horizon. When that is filled the remaining precipitation percolates into the B-horizon. Should the B-horizon attain saturation, vertical drainage into the groundwater store takes place, from which baseflow is generated. Evaporation takes place from previously intercepted water as well as simultaneously from the topsoil horizon (soil water evaporation) and from all horizons in the root zone (plant transpiration). The roots absorb water in proportion to the root mass density of the respective horizons. Evaporative demand

on the plant is estimated according to atmospheric demand (through a reference potential evaporation) and the plant's stage of growth (Everson *et al.*, 1998).

The generation of stormflow in ACRU is based on assumption that after initial abstractions (through interception, depression storage and infiltration before runoff commences) the runoff is a function of the magnitude of the rainfall and the soil water deficit from a critical response depth of the soil. The soil water deficit antecedent to a rainfall event is simulated by ACRU's multi-layer soil water budgeting routines on a daily basis. The critical response depth depends on the dominant runoff-producing mechanism. Depths are generally shallow in arid areas characterized by eutrophic (poorly leached and drained) soils and high intensity storm which produce mostly surface runoff. By contrast, interflow and "push-through" runoff mechanisms dominate high rainfall areas with dystrophic (highly leached, well drained) soils and depths are generally deeper. Not all stormflow generated by a rainfall event is the same day response at the catchment outlet; stormflow is therefore split into quickflow (i.e. same day response) and delayed stormflow, with the "lag" dependent on soil properties, catchment size, slope and drainage density.

The time series graph of actual and modelled streamflow is shown in their Figure 2. In general ACRU under-estimated streamflow by 358 mm, over the five year simulation period (Everson *et al.*, 1998). The agreement between the actual and modelled trends was good (r^2 0.80). The model performed better in the average rainfall and dry years of 19991/92, 1992/93 and 1994/95. The biggest deviation was in the very wet year of 1993/94 when ACRU was clearly under-estimating the catchment runoff.

Even though simulation undertaken with the ACRU model indicates that hydrological processes in the catchment can be modelled successfully, Everson *et al.* (1998) suggests that refinements may be necessary to reduce the 15% under estimation of streamflow. It is expected that detailed soil information can provide improved soil parameters in ACRU model.

10.5 WEATHERLEYEY AND MOOI CATCHMENTS

Two models were run in the Weatherleyey catchment (Pitman and ACRU). More detail is available on CD as Appendices.

10.5.1 Pitman modelling results

Two levels of soil data were incorporated in the Pitman model in order to simulate outflow from the catchments. Level 1 are soil parameters obtained from the Land Type data base (Land Type Survey Staff, 2002) and level 2 are soil observed soil data from a soil survey conducted in the Weatherleyey catchment. The main difference between the two input levels was the mean

soil depth; 650 mm for level 1 and 1323 mm for level 2. The simulations were compared to observed outflows measured at the catchment's outlet.

10.5.2 Mooi catchment

Observed outflows compared to outflows simulated for two levels of soil data from the Mooi catchment are presented in Figure 10.10.

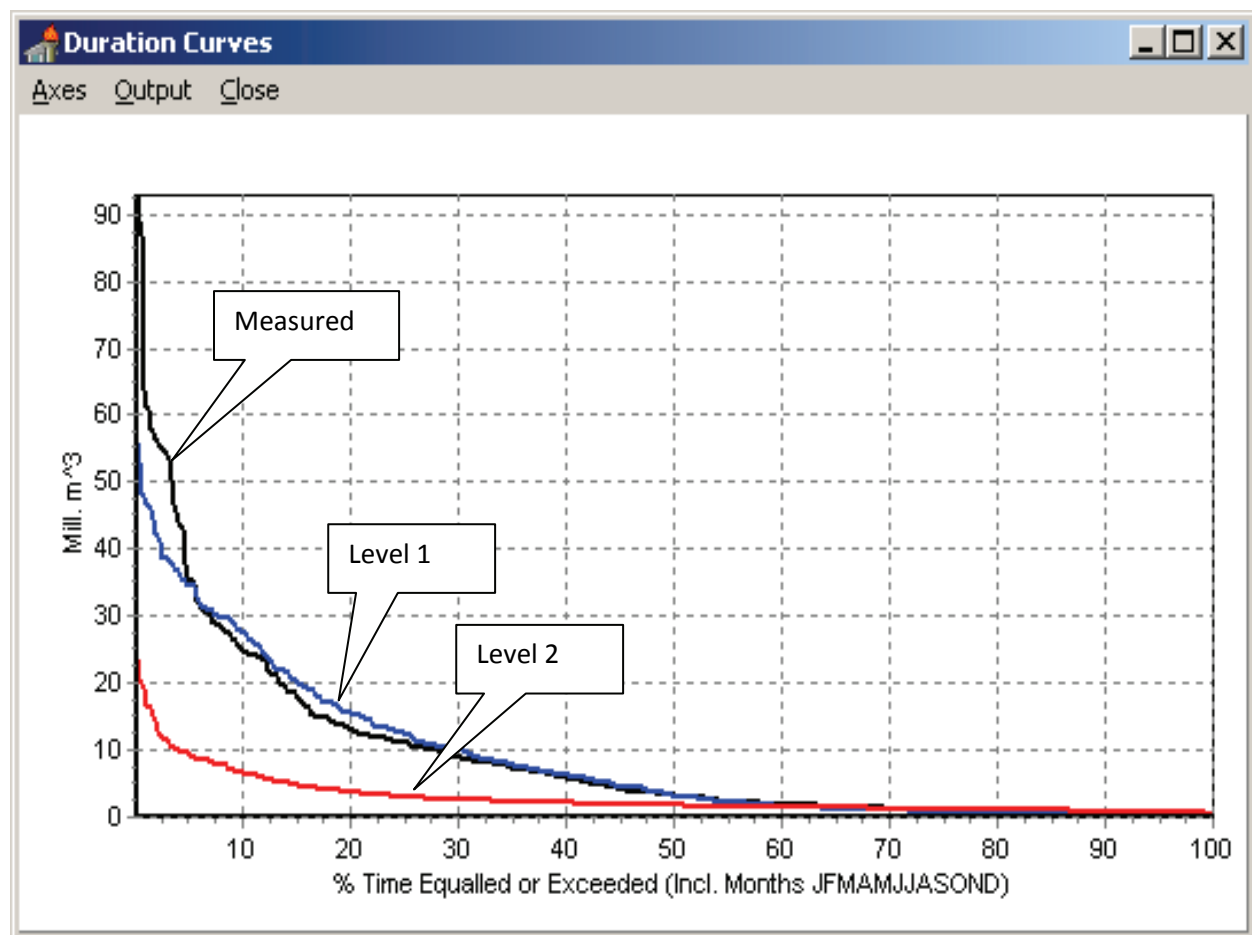


Figure 10.10 Measured outflow vs. outflow simulated with two levels of soil input from the Mooi catchment.

Land Type information (level1) gave a very good estimate of the actual streamflow. The soil survey data or level 2 did not give satisfying results and continuously underestimated outflow from the catchment. Underestimation of streamflow using level 2 can be attributed to greater storage capacity of the soils (due to deeper soils) and consequently lower outflow caused by saturation excess. It is important to note that the soil survey were done in the Weatherleyey catchment which occupy 1.5 km² which is approximately 0.5% of the 306 km² Mooi catchment, while the Land Type information is representative of the whole area.

10.5.3 Weatherleyey catchment

Observed outflows compared to outflows simulated for two levels of soil data from the Weatherleyey catchment are presented in Figure 10.11.

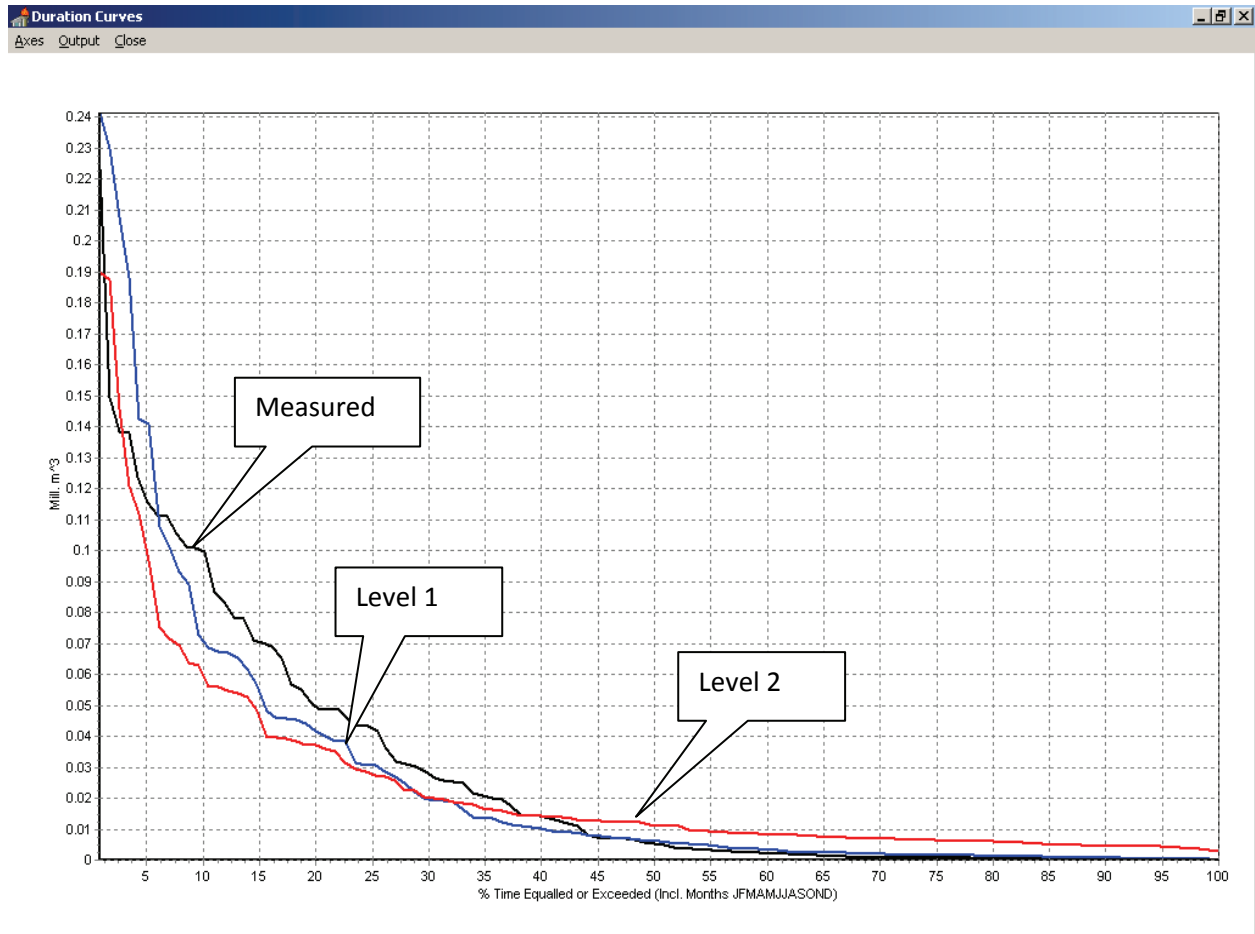


Figure 10.11 Measured outflow vs. outflow simulated with two levels of soil input from the Weatherleyey catchment.

Simulated flow using soil survey data (level 2) performed far better in estimating outflows from the smaller Weatherleyey catchment compared to the Mooi catchment especially during high peakflow events. For the majority of the outflow events level 1 resulted in more accurate simulations compared to level 2 even though level 2 represents actual conditions of the catchment.

10.6 ACRU MODELLING RESULTS

This modelling study of the Weatherley study catchment, in the northern part of the Eastern Cape, was carried out in the aim of assessing the ability of ACRU Intermediate zone to represent detailed soil hydrological response classification determined by the University of the

Free State, Department of Soil- and Crop- and Climate Sciences. This is with the eventual aim of defining values of dispersion coefficient and mean response time of the advection dispersion function which estimates discharge from the intermediate soil layer of ACRU Intermediate zone.

Baseline simulations were carried out to determine the ability of ACRU 2000 to represent the processes contributing to streamflow, such that the ability of the newly included intermediate zone routines to represent these processes can be gauged. Initially lumped mode simulations are considered, these progressed into more distributed simulations representing the different hydrological soil types classified at Weatherleyey.

ACRU Intermediate zone makes simplified representations of the hydropedological classification determined by the University of the Free State, Department of Soil- and Crop- and Climate Sciences. Similar classifications of hydrological soil response have been made in a previous study by Uhlenbrook *et al.* Values for the dispersion coefficient and mean response time are derived through dividing the streamflow hydrograph into time periods where each classified hydrological soil type is the dominant contributor to streamflow.

10.6.1 Simulation Period

For the purposes of this study a simulation period from 1998 through 2002 was used. This is due to the fact that in this period the catchment was under grassland conditions and pine and eucalypt forests were planted from 2002 onward. This resulted in a distinct change in the cumulative streamflow gradient from 2002 onward (Figure 10.12(A)).

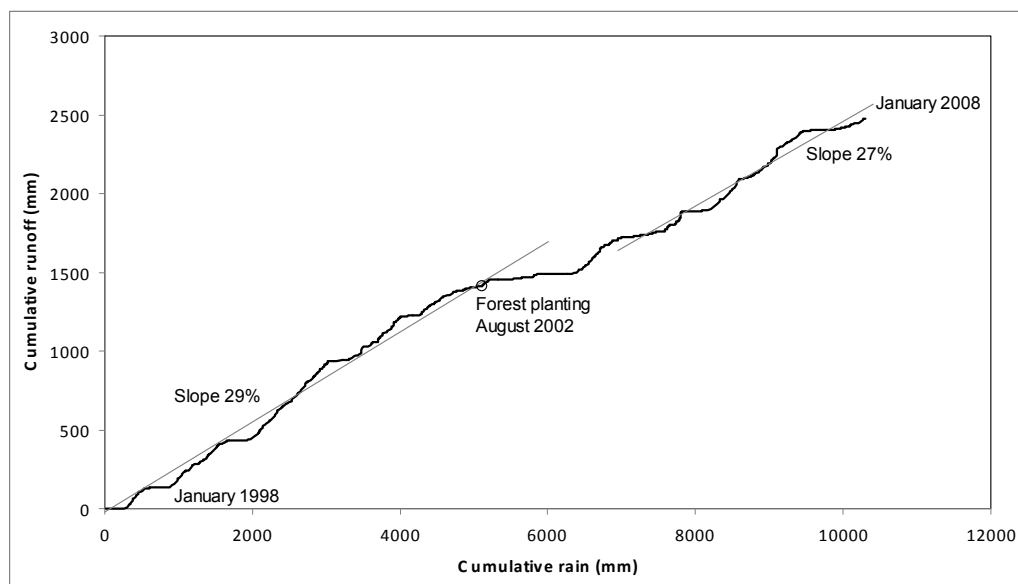


Figure 10.11 (A) Cumulative streamflow, Weatherleyey catchment (Lorentz *et al.*, 2007).

10.6.2 ACRU 2000 simulations

10.6.2.1 ACRU 2000, Single Soil Type

Initial simulations of the 1.57 km² Weatherleyey catchment were carried out using ACRU 2000 to give a baseline for comparison. This simulation was carried out in lumped mode using default values or assuming minimal available data. Soil properties are given in table 10.2

Table 10.2 Soil properties, Weatherleyey ACRU 2000 simulation default soil values.

Variable	Description	Value
DEPAHO	Depth A horizon	0.250
DEPBHO	Depth B horizon	0.500
WP1	Wilting point A horizon	0.100
WP2	Wilting point B horizon	0.100
FC1	Field capacity A horizon	0.254
FC2	Field capacity B horizon	0.354
PO1	Porosity A horizon	0.402
PO2	Porosity B horizon	0.402
ABRESP	Fraction sat soil water redistributed from A to B horizon, above DUL	0.200
BFRESP	Fraction sat soil water redistributed from B horizon to GW, above DUL	0.200

The regression analysis of observed versus simulated streamflow values yielded a value of 0.6684. Cumulative plots of simulated and observed streamflow showed that wetting and drying trends were well represented, however the amount of streamflow was over simulated by approximately 30 percent over the simulation period (Figure 10.12). The daily comparison of observed and streamflow data showed that trends in the observed data were followed relatively well. Figure 10.13.

Figure 10.14 shows observed neutron probe at nest LC2/202 at the Weatherleyey catchment, plotted against ACRU 2000 simulated soil water contents. The neutron probe data at 150 mm and 450 mm depths were used to estimate water contents at 250 mm, representing the simulated A horizon depth. Simulated soil water contents depict the measured trends, yet low flow periods are under simulated.

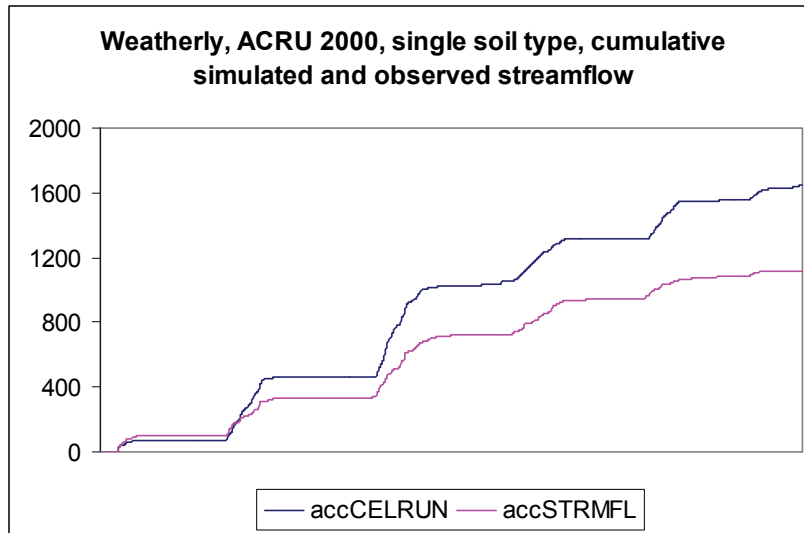


Figure 10.12 Cumulative plot of simulated and observed streamflow, Weatherleyey, ACRU 2000, single soil

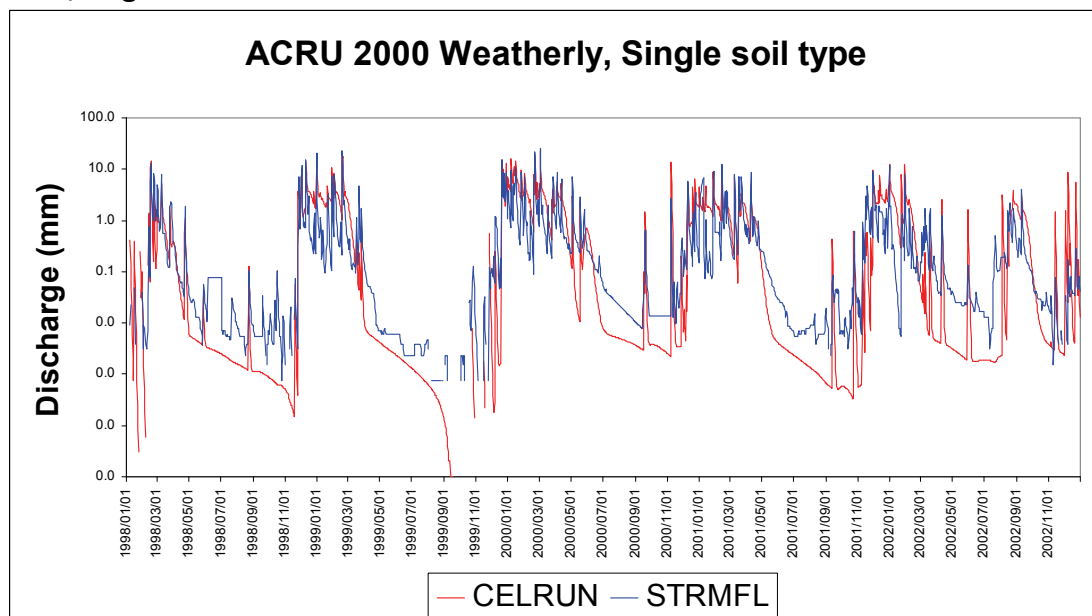


Figure 10.13 Daily comparison of observed and simulated streamflow, Weatherleyey, ACRU 2000, single soil.

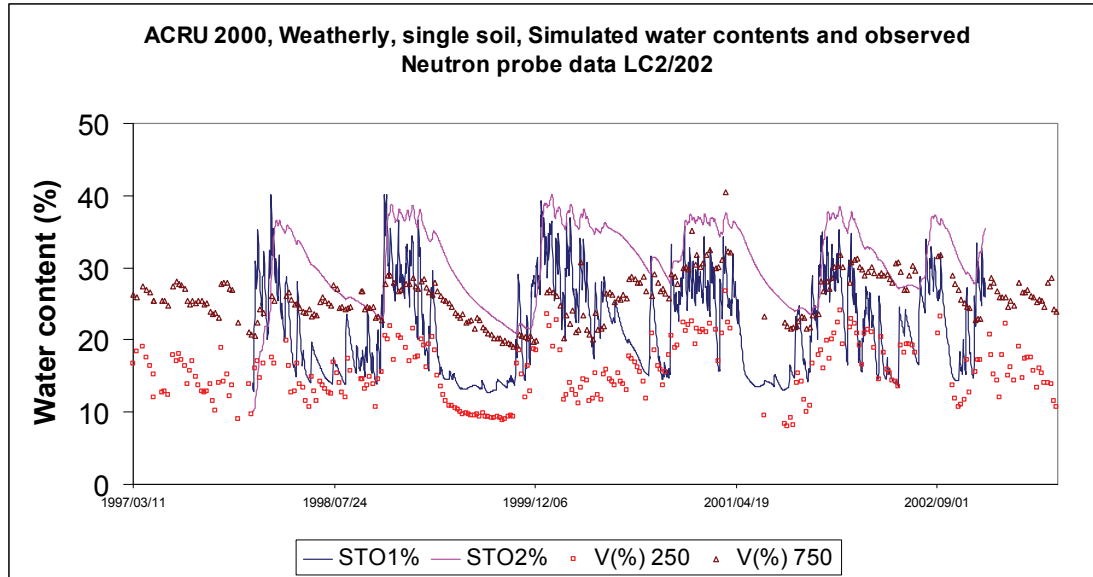


Figure 10.14 Observed neutron probe data, V(%), and simulated soil water contents, Weatherleyey, ACRU 2000, single soil.

10.6.2.2 ACRU INTERMEDIATE ZONE, SINGLE SOIL TYPE

A lumped mode simulation was carried out with ACRU Intermediate zone to determine the immediate improvement on ACRU 2000. This simulation had identical soil properties to the lumped ACRU 2000 simulation, with the exception of intermediate zone variables which are not considered by ACRU 2000 (Table 10.3).

Table 10.3 Soil properties, Weatherleyey, ACRU Int, Single soil type.

Variable	Description	Value
DEPAHO	Depth A horizon	0.250
DEPBHO	Depth B horizon	0.500
DEPINTZ	Depth Intermediate zone	1.200
WP1	Wilting point A horizon	0.100
WP2	Wilting point B horizon	0.100
WPINTZ	Wilting point Intermediate zone	0.159
FC1	Field capacity A horizon	0.254
FC2	Field capacity B horizon	0.354
FCINTZ	Field capacity Intermediate zone	0.354
PO1	Porosity A horizon	0.402
PO2	Porosity B horizon	0.402
POINTZ	Porosity Intermediate zone	0.402
ABRESP	Fraction sat soil water redistributed from A to B horizon, above DUL	0.200
BFRESP		0.200
INTZRESP	Fraction sat soil water redistributed from B horizon to GW, above DUL	0.050
	Intermediate zone response factor	

The regression analysis of observed and simulated data produced an R^2 value of 0.7227, this is an improvement on the ACRU 2000 lumped simulation. Initially the cumulative plots show a high level of accuracy when compared to the observed streamflow. However the latter stages of the simulation the plots do not mimic observed streamflow as well as the initial period (Figure 10.15).

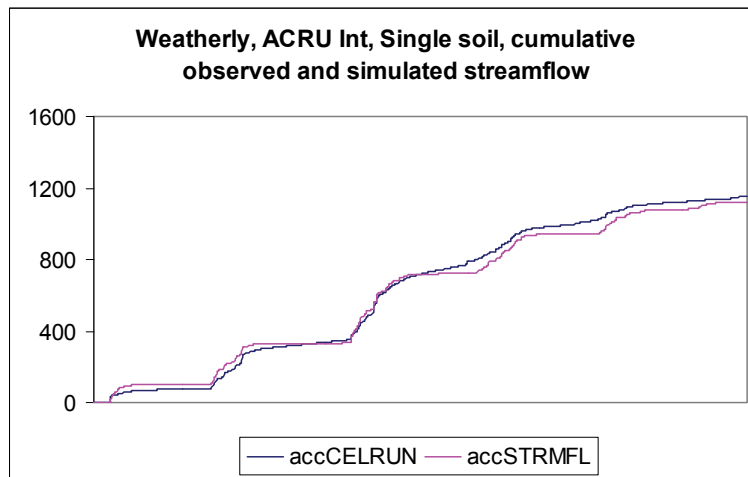


Figure 10.15 Cumulative plot of observed and simulated streamflow, Weatherleyey, ACRU Int, single soil type

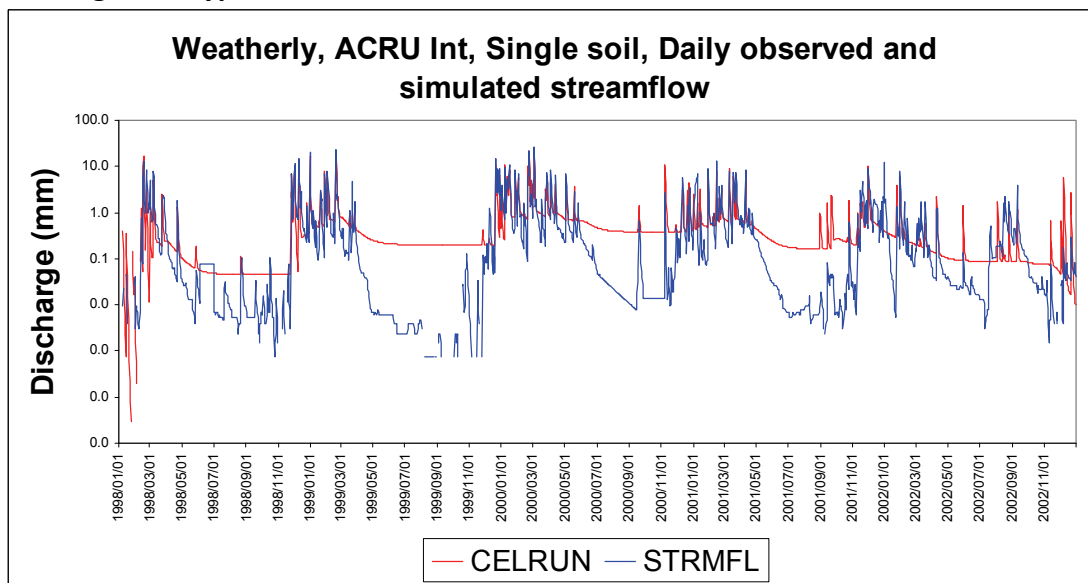


Figure 10.16 Daily observed and simulated streamflow, Weatherleyey, ACRU Int, Single soil type.

Neutron probe data at nest LC2/202, V(%), the simulated water contents (STO) appear more representative of the shallow soil horizon. Simulated water contents of the B horizon fall within the general range of observed water contents at 750 mm below the soil surface, however there is a general over simulation of wet periods and under simulation of dry periods (Figure 10.16).

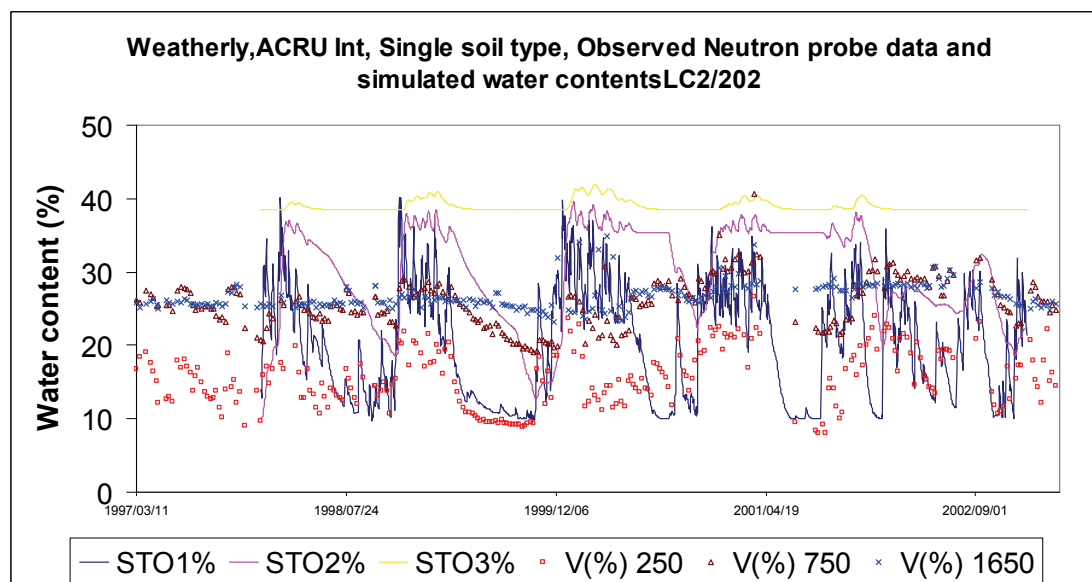


Figure 10.17 Observed Neutron probe data at LC2/202, V(%), Weatherleyey, and simulated soil water contents (STO), ACRU Int single soil type.

10.6.2.3 ACRU 2000, 3 SOIL TYPES

For this simulation the Weatherleyey catchment was subdivided into 3 catchments representing Recharge (1), Interflow (2) and Responsive (3) soils, as described in Section 5. Parameters dictating the fraction of water to be redistributed from the top soil to the subsoil, and from the subsoil to the ground water store, ABRESP and BFRESP respectively, are altered to represent the three different types of soils (Table 10.4). (0.1 slow for clays, 0.8 fast for sands). Subcatchments were routed such that subcatchment 1 (recharge) and 2(interflow) both contributed directly to subcatchment 3 (responsive).

No improvement was observed in the R^2 regression analysis of observed and simulated streamflow, at 0.6684, when compared to the lumped simulation. This is also evident in the cumulative plots of observed and simulated streamflow. While trends in wetting and drying are followed, the plots are immediately divergent (Figure 10.18). High flows remain well represented while low flows are over simulated (Figure 10.19).

Table 10.4 Soil properties used in ACRU 2000, 3 soil type simulation.

	Recharge (subcatchment1)	Interflow (subcatchment2)	Responsive (subcatchment 3)
DEPAHO	0.40	0.50	0.60
DEPBHO	0.80	0.90	0.70
WP1	.100	.100	.100
WP2	.100	.100	.100
FC1	.254	.254	.254
FC2	.349	.349	.349
PO1	.367	.367	.367
PO2	.367	.367	.367
ABRESP	0.7	0.7	0.1
BFRESP	0.7	0.5	0.1

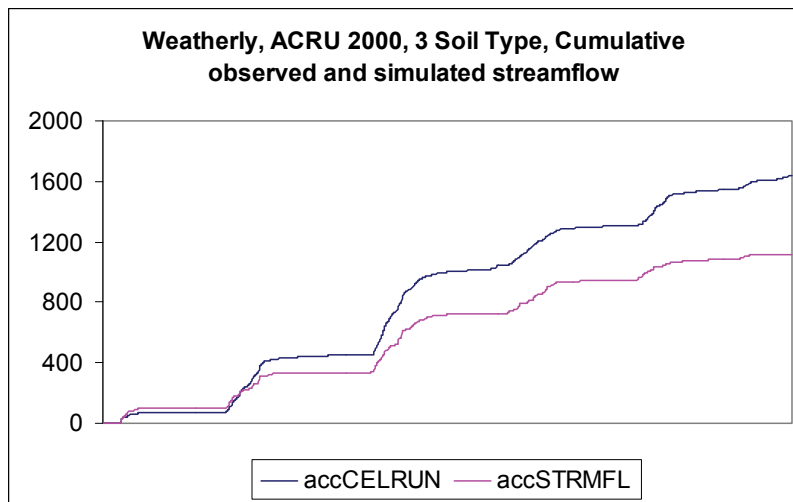


Figure 10.18 Cumulative plot of observed and simulated streamflow, Weatherley.

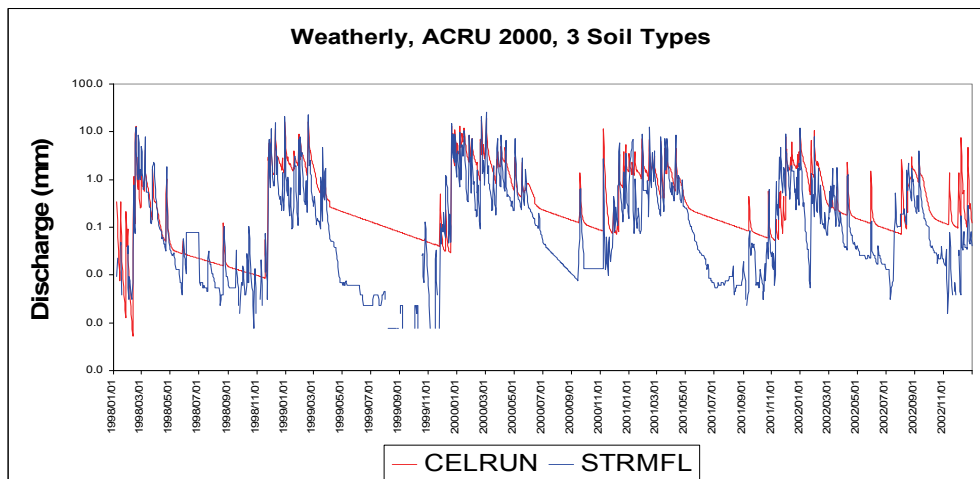


Figure 10.19 Daily observed and simulated streamflow, Weatherley.

Neutron probe measurements taken at LC4/204 showed correlations in the wetting and drying trends at the simulated depth of the A horizon (STO1%). Simulated soil water contents simulated in the B horizon (STO2%) do not follow the hydrological trends of the observed data (Figure 10.20). A similar trend is evident in the other two subcatchments.

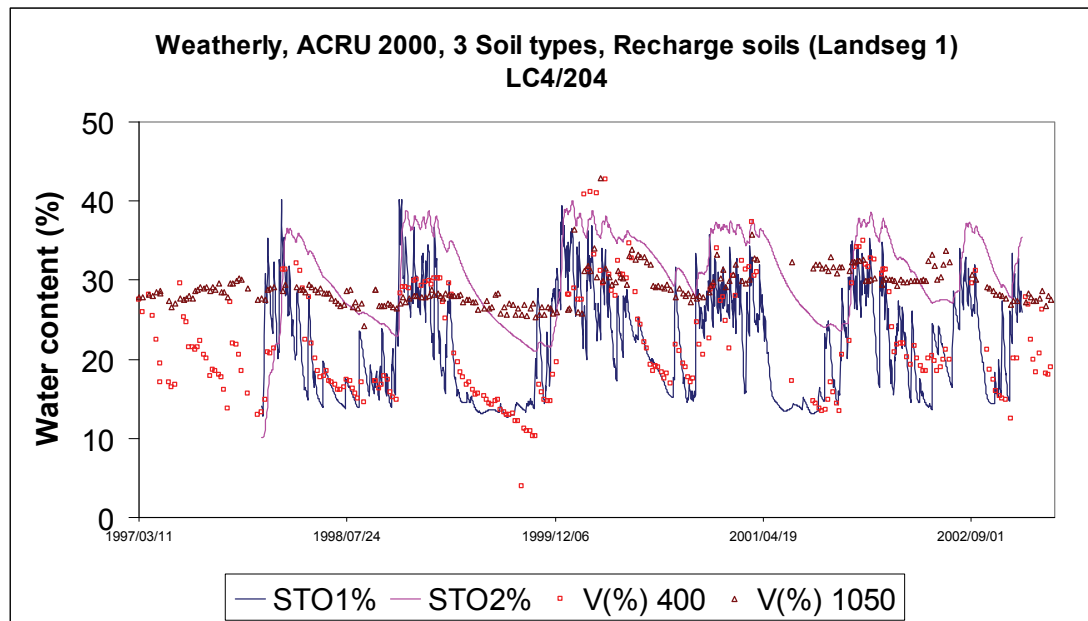


Figure 10.20 Observed Neutron probe data at LC4/204, V(%), Weatherleyey, and simulated soil water contents (STO) for Recharge soils.

10.6.2.4 ACRU INTERMEDIATE ZONE, 3 SOIL TYPES

For the purposes of this simulation soil properties were kept identical to those used in the ACRU 2000, 3 soil type simulation, with the exception of intermediate zone variables (Table 10.5). This was done to assess the level of improvement gained through the addition of the subsurface routing routines in ACRU Intermediate zone (Figure 10.21). The subsurface routing considered in this simulation was derived from the 5 hillslope conceptual descriptions of the Weatherleyey catchment (Le Roux *et al.*, 2007).

Table 10.5 Soil properties, Weatherleyey, ACRU Int, 3 soil types.

	Recharge (subcatchment1)	Interflow (subcatchment2)	Responsive (subcatchment 3)
DEPINTZ	1.0	1.0	1.0
WPINTZ	.159	.159	.159
FCINTZ	.354	.354	.354
POINTZ	.402	.367	.402
INTZRESP	.05	.05	.05

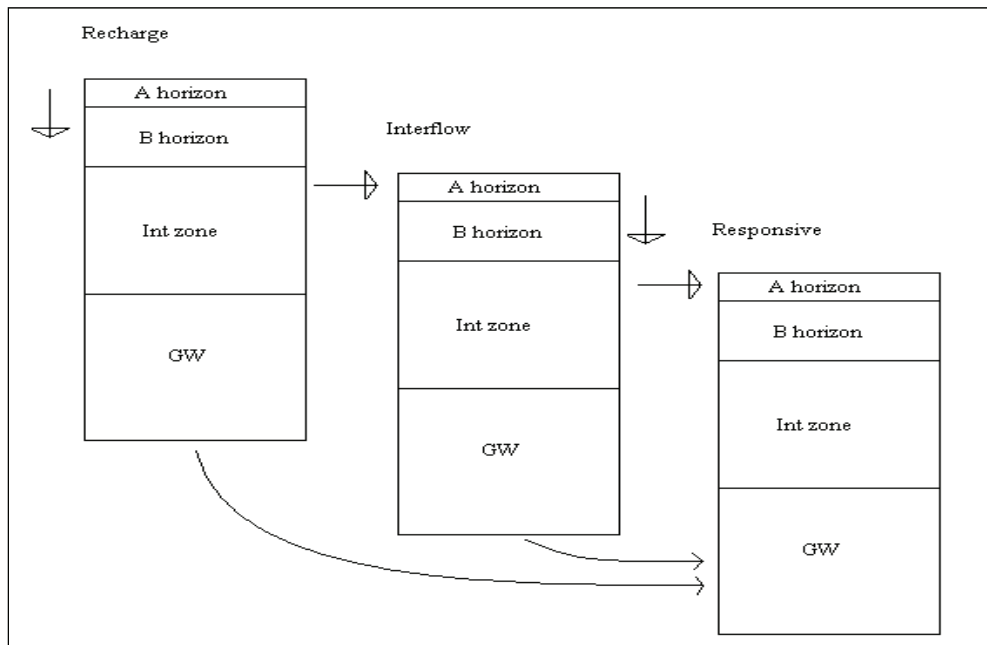


Figure 10.21 Weatherleyey, ACRU Int, 3 soil types subsurface flow routing.

An R^2 regression analysis, with a value of 0.7343 was obtained from the simulation, this is a marked improvement from the ACRU 2000, 3 soil type simulation. Cumulative (Figure 10.22) and daily (Figure 10.23) plots of observed and simulated streamflow showed that wet season flows were better represented than dry season flows. This is with respect to the over simulation of dry season flows.

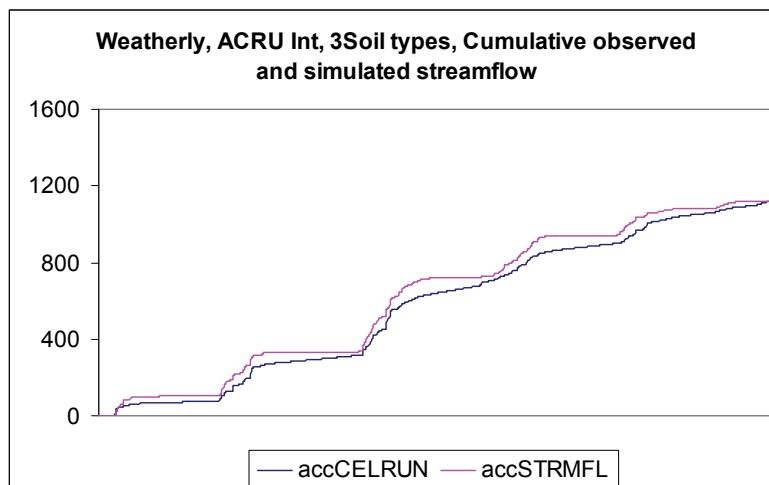


Figure 10.22 Cumulative plots of observed and simulated streamflow.

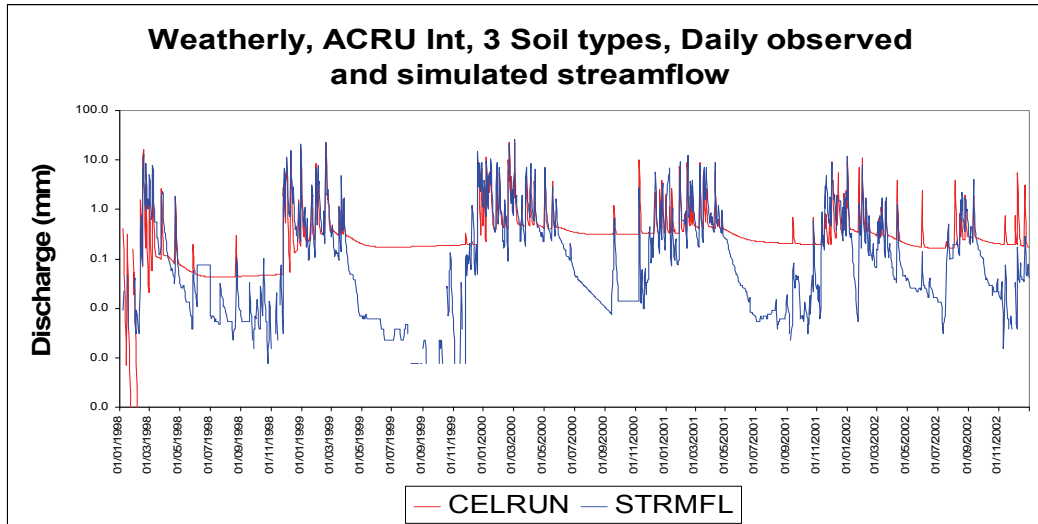


Figure 10.23 Daily observed and simulated streamflow.

Neutron probe data comparisons are consistent with earlier simulations in that topsoil water contents are simulated well, while subsoil water contents are over and under simulated during wet and dry season flows respectively (Figure 10.24). Similar trends were observed in all subcatchments' soil water content comparisons.

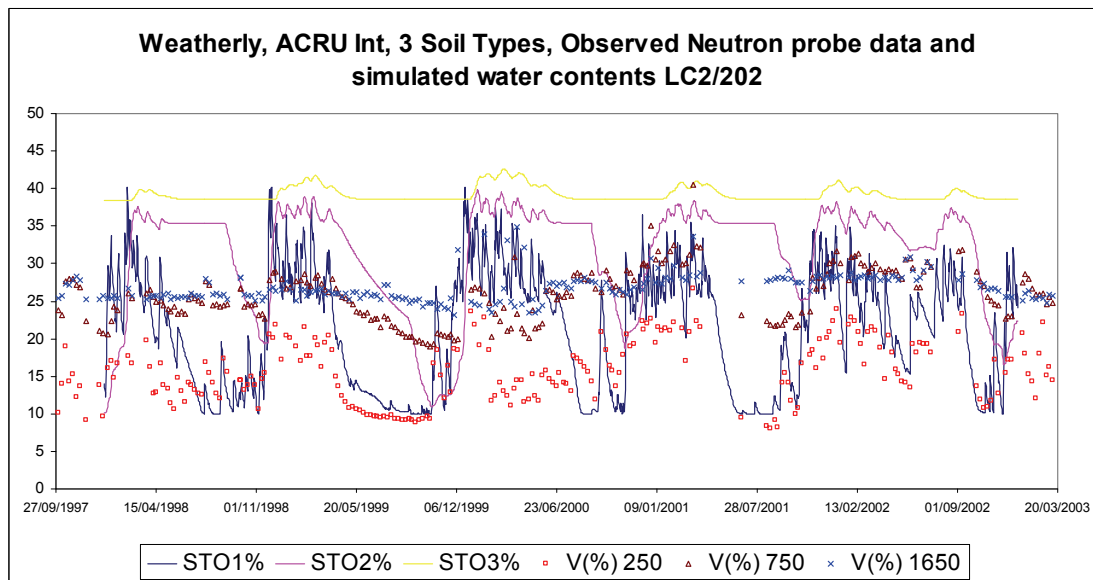


Figure 10.24 Observed Neutron probe data at LC2/202, V(%), Weatherleyey, and simulated soil water contents (STO) for Recharge soils.

10.6.3 Derivation of ADF mean response time (τ) and dispersion coefficient (D)

Up until this stage of the simulation processes default values determined by an earlier report on the development of ACRU Intermediate zone had been used to describe the ADF values of D and t. The following simulations were carried out to determine representative values of D and t for recharge, interflow and responsive soils.

The relationship between rainfall and observed streamflow ultimately leaves a signature of the manner in which the landscape transforms rainfall into runoff. The purpose of the D and t values of the ADF considered by ACRU Intermediate zone is to represent the dominant processes that are responsible for this transformation within the different hydrological soil types. This was achieved by disaggregating the observed streamflow hydrograph into different time periods at which each respective hydrological soil type is the dominant, but not the sole, contributor to streamflow. Responsive soils were deemed to be the main contributor to streamflow during the increase in flow directly after a rainfall event. Interflow soils were considered the main contributor to streamflow during periods of streamflow recession in between rainfall events, during the wet season. Recharge soils are seen as the main contributor to streamflow during low flow periods. The gradient of these changes in streamflow (mm) over time (days) was measured and plotted for a number of responsive, interflow and recharge dominated flow periods (Figure 10.25).

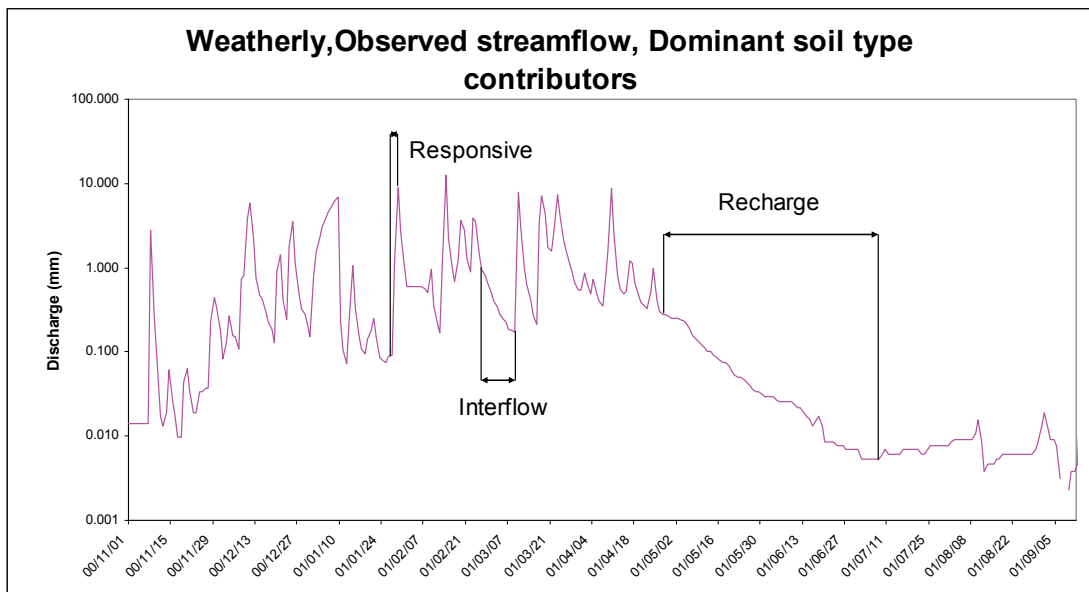


Figure 10.25 Dominant periods of flow contribution by different hydrological soil types.

The values displayed in Table 10.6 were used to determine the gradient of the change in flow over time. Gradients for the dominant responsive and interflow periods were measured only

during the wet season with high antecedent moisture conditions; this is due to the fact that these soils dominate streamflow contributions in the wet season. Recharge soils are expected to be the main contributor to baseflow; this explains the relatively short record as there are only four complete low flow periods during the simulation period.

Table 10.6 Gradient calculations for different hydrological soil types.

responsive		interflow		recharge	
t (days)	D	t (days)	D	t (days)	D
1	14.524	10	0.42	107	0.266
3	1.166	5	0.64		
2	6.83	7	0.96		
3	20.824	6	0.56		
1	1.039	14	0.25	153	0.24
1	8.89	23	0.18	68	0.27
3	8.215	21	0.277	108	0.32
3	6.56	12	0.78		
4	7.03				
1	7.82				
2	4.97				
1	6.856				
3	12.56				

The measured gradients of the different flow periods identified for the hydrological soil types was plotted to give a linear equation describing each of the different hydrological soil types.

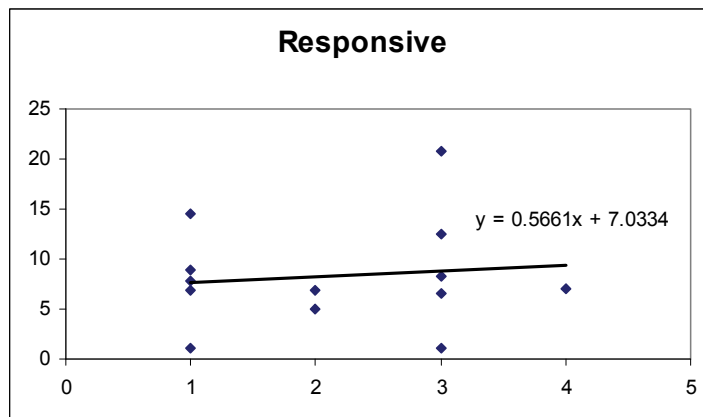


Figure 10.26 Responsive soils plot of change in flow over time

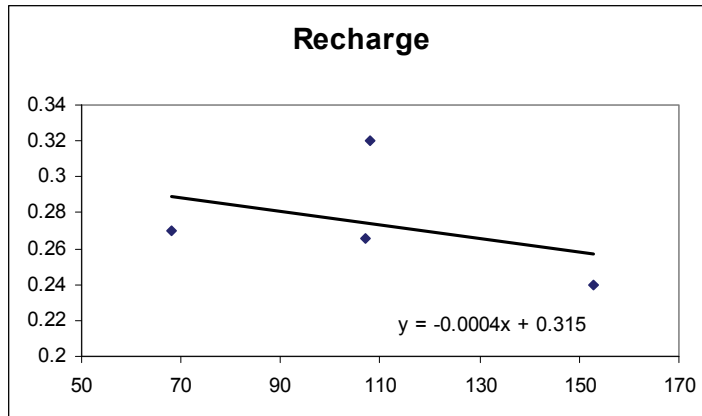


Figure 10.27 Recharge soils plot of change in flow over time

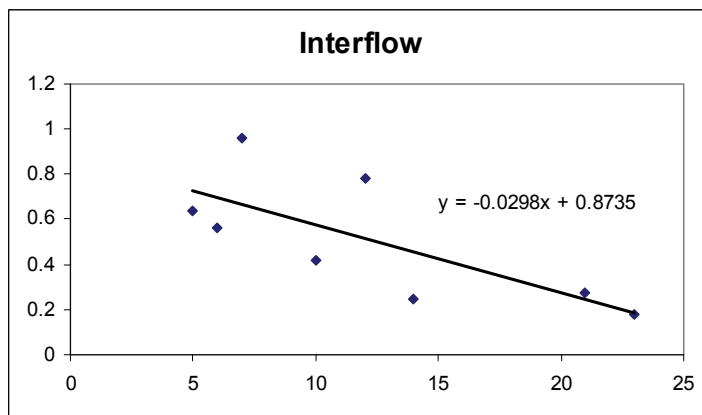


Figure 10.28 Interflow soils plot of change in flow over time.

The linear equations of the plots were used to derive ratios for D and t values describing each of the hydrological soil types. Time periods corresponding with the average duration of the each of the contributions from the hydrological soil types were substituted into the equations giving representative values of the change in flow (Table 10.7).

Table 10.7 Ratio of change in streamflow to hydrological soil contribution time.

responsive		interflow		recharge	
$y = 0.5661x + 7.0334$		$y = -0.0298x + 0.8735$		$y = -0.0004x + 0.315$	
change		change		change	
flow(y)	t, days (x)	flow(y)	t, days (x)	flow(y)	t, days (x)
7.5995	1	0.6649	7	0.275	100

These values were used to represent the ratio of the dispersion coefficient to the mean response time in the ACRU Intermediate zone simulations.

Recharge soils

Simulations of these soils showed an extended contribution to streamflow through the dry season. This is expected as these soils are deemed to be a major contributor to ground water stores (Figure 10.29). This trend is also evident in Figure 10.31, which depicts the subsurface contributions from the recharge sub catchment. Baseflow is the major component of the streamflow produced by the subcatchment and extends through the duration of the dry season. The lateral flows from the sub catchment also extend fairly deep into the dry season, which is to be expected from this subcatchment as its contributions are mainly in the form of deep level ground water.

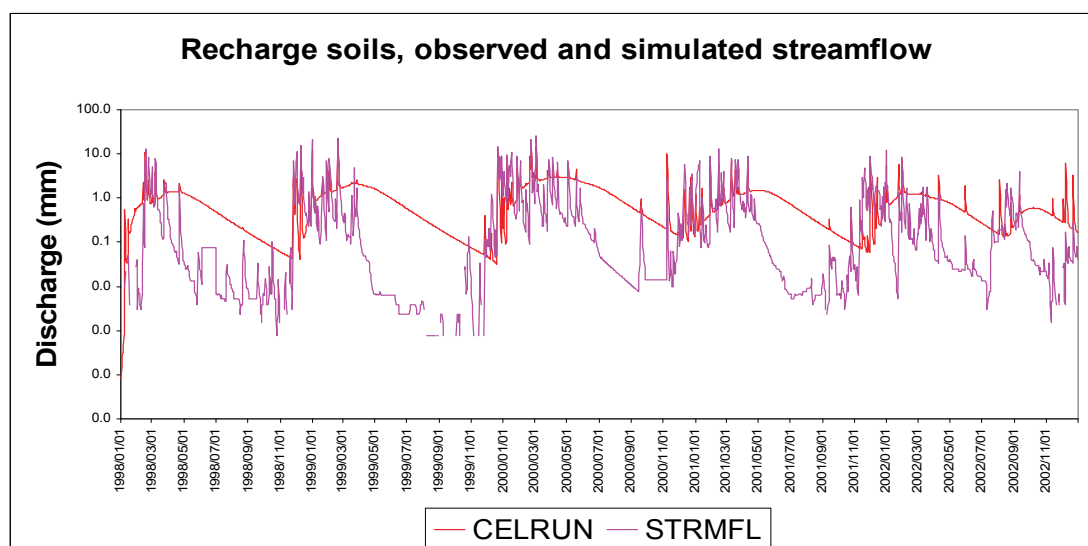


Figure 10.29 Weatherleyey, ACRU Int 3 soil types, observed and simulated streamflow.

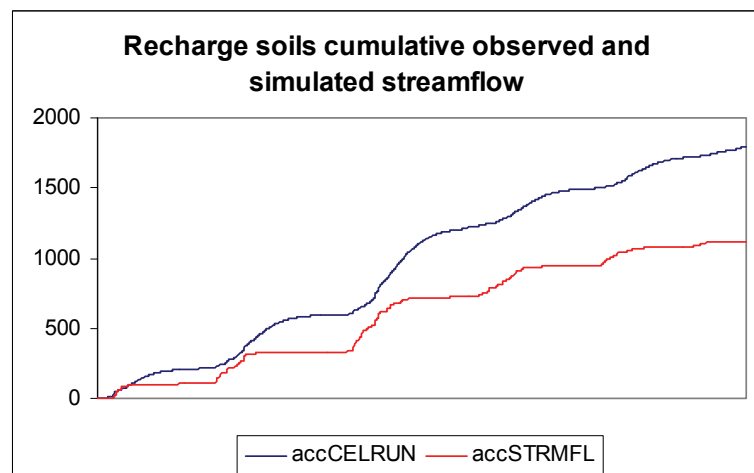


Figure 10.30 Weatherleyey, ACRU Int 3 soil types, cumulative observed and simulated streamflow.

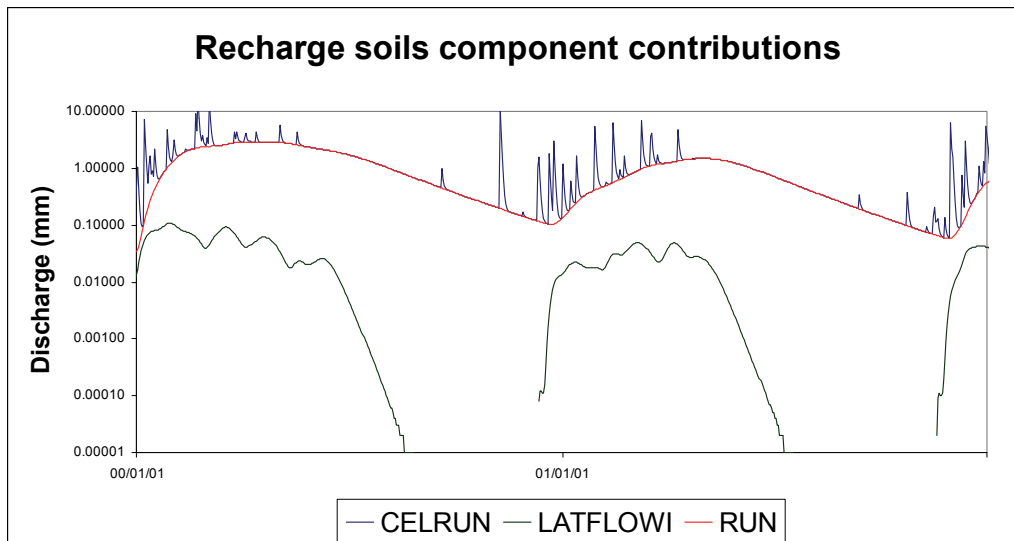


Figure 10.31 Weatherleyey, ACRU Int 3 soil types, subsurface contributions

Comparisons of observed neutron probe data and simulated soil water contents showed marked improvements on previous simulations. A and B horizon contents were faithfully simulated, while intermediate zone contents could not be directly compared with measured data as the simulated soil depth of the intermediate zone extends deeper than any observed data. Comparative plots for observed and simulated water contents are shown for two different instrument nests both situated within recharge soils (Figures 10.33 and 10.34).

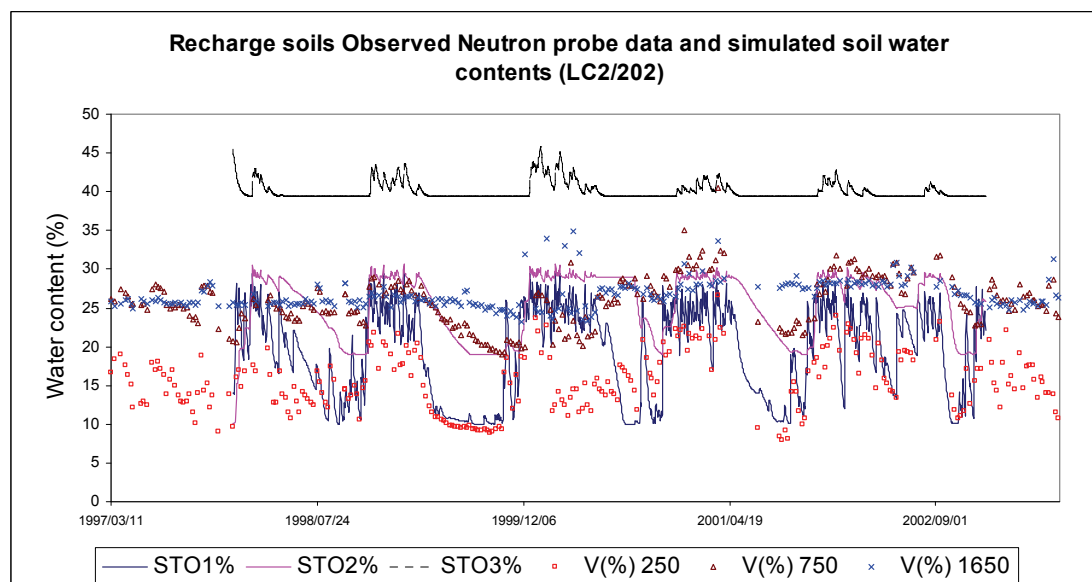


Figure 10.32 Weatherleyey, ACRU Int 3 soil types, observed neutron probe data and simulated soil water contents, nest LC2.

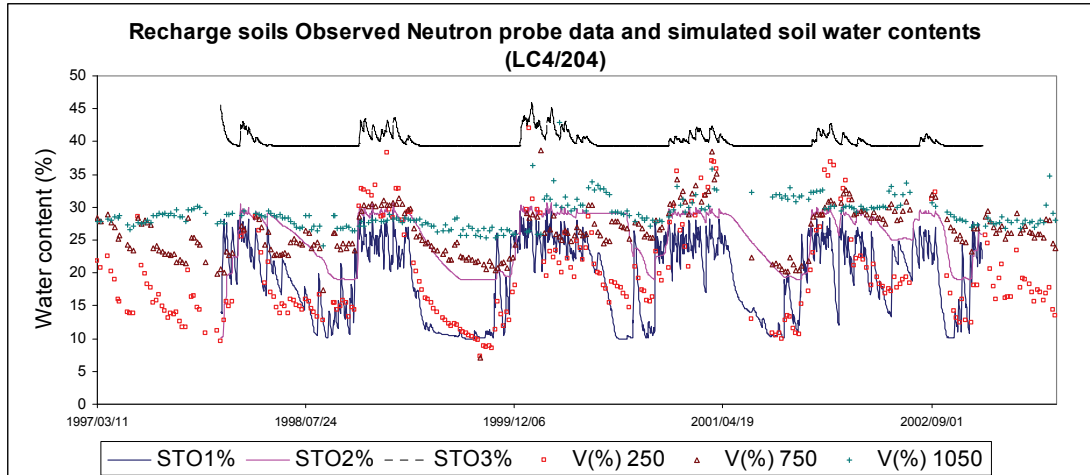


Figure 10.33 Weatherley, ACRU Int 3 soil types, observed neutron probe data and simulated soil water contents, nest LC4.

Interflow soils

Interflow soil simulations show a pronounced response to rainfall during the wet season. The daily and cumulative plots of observed and simulated streamflow show that interflow soils contributions are dominant during the wet season (Figure 10.34 and 10.36). Analysis of the subsurface contributions shows that lateral subsurface flows dominate contributions by interflow soils (Figure 10.36).

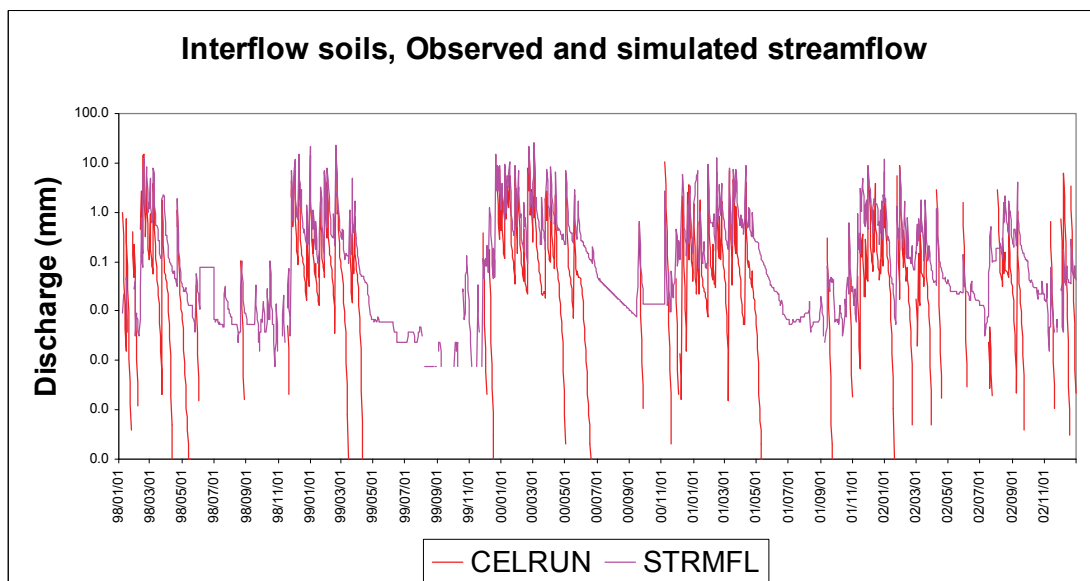


Figure 10.34 Weatherley, ACRU Int 3 soil types, observed and simulated streamflow.

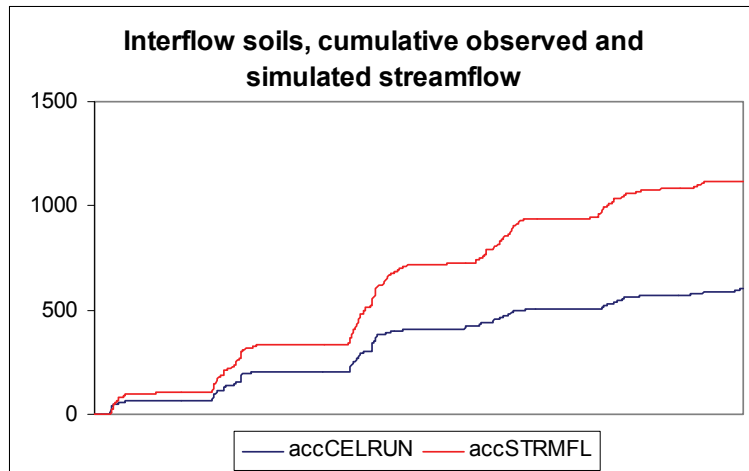


Figure 10.35 Weatherley, ACRU Int 3 soil types, cumulative observed and simulated streamflow.

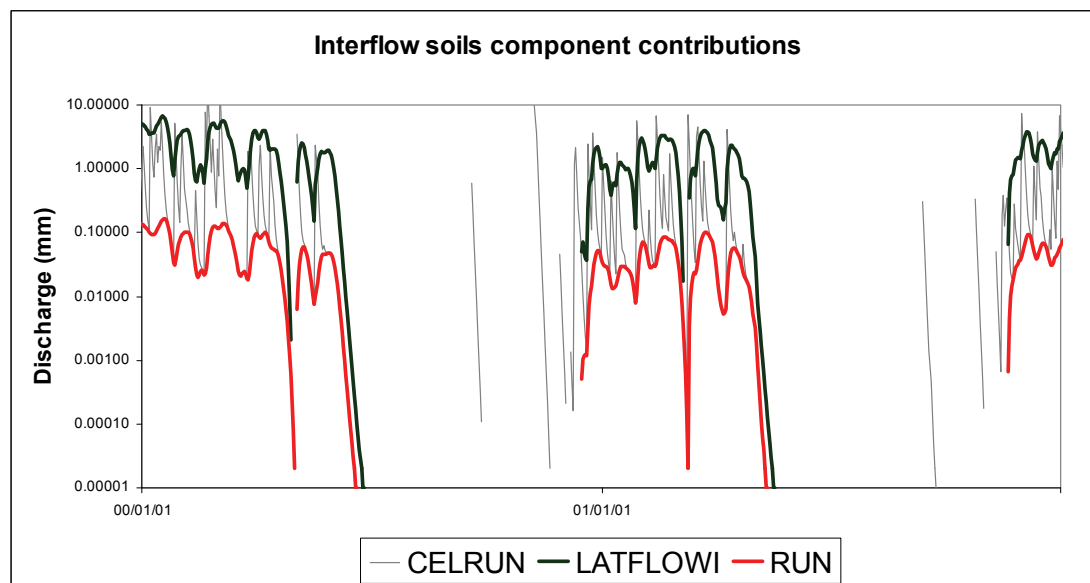


Figure 10.36 Weatherley, ACRU Int 3 soil types, subsurface contributions.

Comparisons of observed neutron probe data and simulated soil water contents, at nest LC5 situated within an interflow soils area, show good correlation between observed and simulated contents in the top soil and sub soil horizons. While observations of water contents at depths of the simulated intermediate zone are not available (1.75 m), observations at slightly shallower soil depths (1.35 m) show similar trends, in that water contents remain fairly stable throughout the simulation period (Figure 10.37)

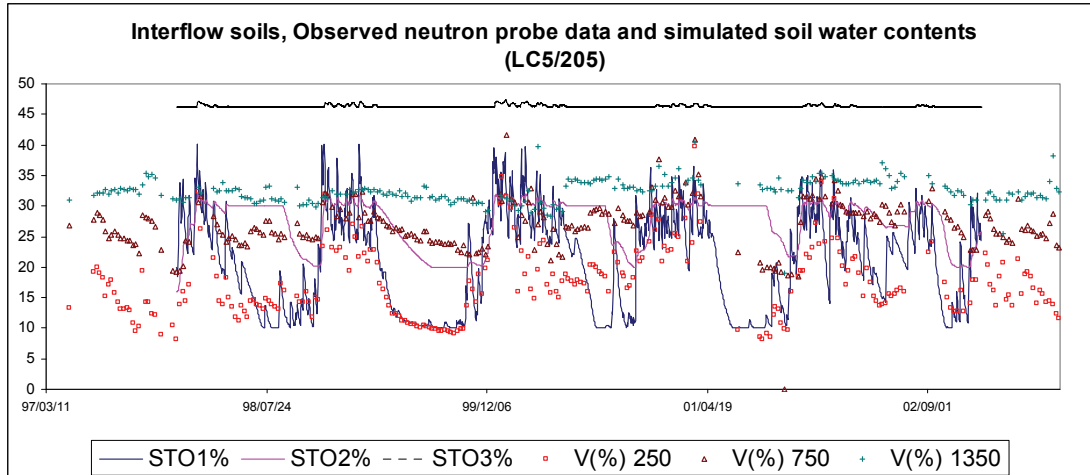


Figure 10.37 Weatherley, ACRU Int 3 soil types, observed neutron probe data and simulated soil water contents, nest LC5.

Responsive soils

Responsive soils in the Weatherley catchment are considered as highly responsive wetland soils (Katspruit). This can be seen in the plot of daily observed and simulated streamflow where the dominant process contributing to flow from responsive soils is quickflow (Figure 10.38 and 10.41). A regression analysis of observed and simulated streamflow produced an R^2 value of 0.7365. This value is in the same order as earlier, less detailed simulations, yet the simulated responses are much improved relative to the initial ACRU simulations.

The cumulative plot of observed and simulated streamflow shows a marked improvement the initial ACRU Intermediate zone simulation. This is with respect to the mimicking of the observed cumulative streamflow by the simulated cumulative streamflow (Figure 10.39). It is evident from Figure 10.39 that while low flow periods are well simulated, there appears to be a slight under simulation of wet season flows.

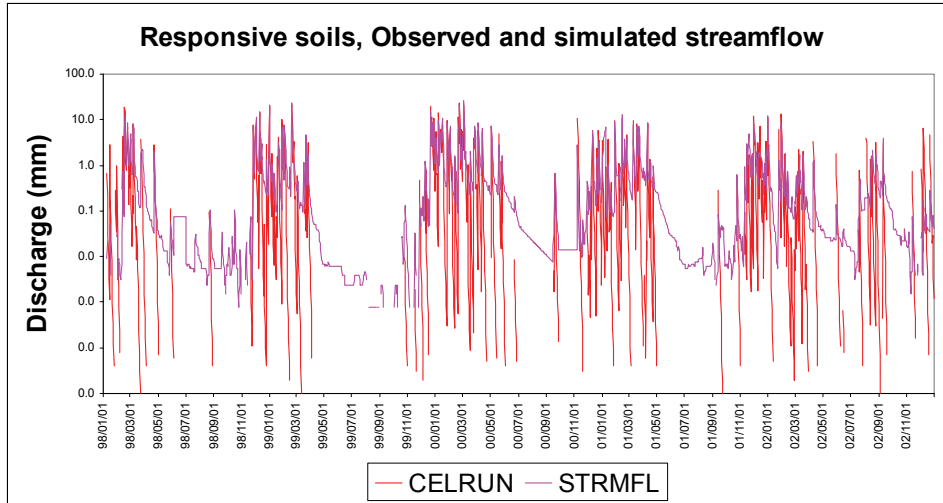


Figure 10.38 Weatherley, ACRU Int 3 soil types, observed and simulated streamflow.

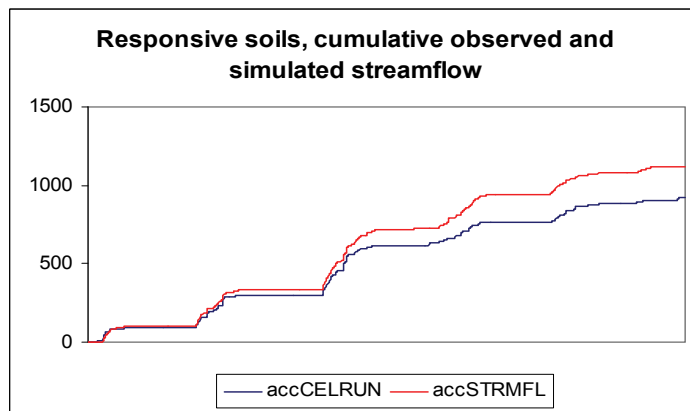


Figure 10.39 Weatherley, ACRU Int 3 soil types, cumulative observed and simulated streamflow.

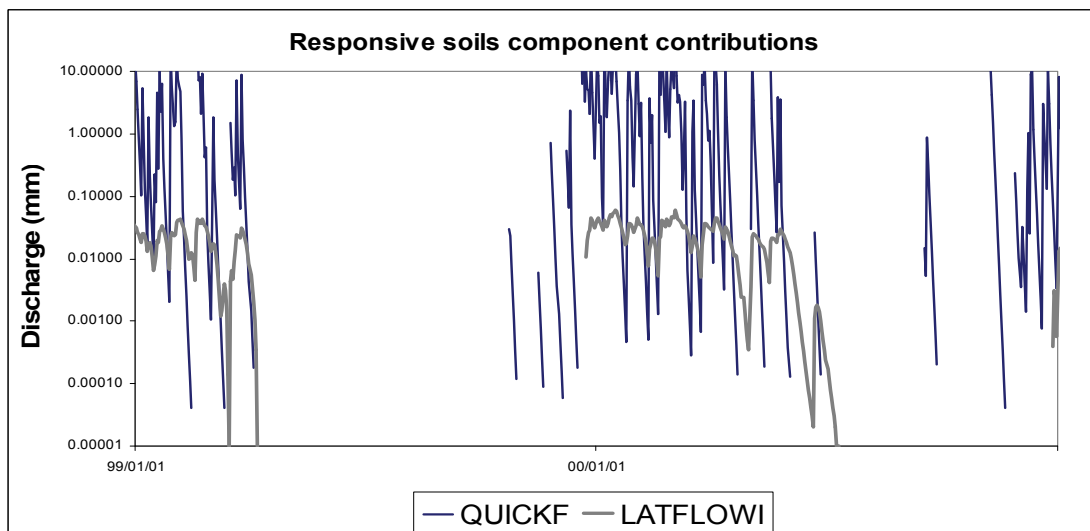


Figure 10.40 Weatherley, ACRU Int 3 soil types, subsurface contributions.

As with the recharge and interflow subcatchments, the soil water contents of the responsive subcatchment are well represented in the top soil and sub soil, while a lack of data prevents intermediate zone soil water comparisons (Figure 10.41).

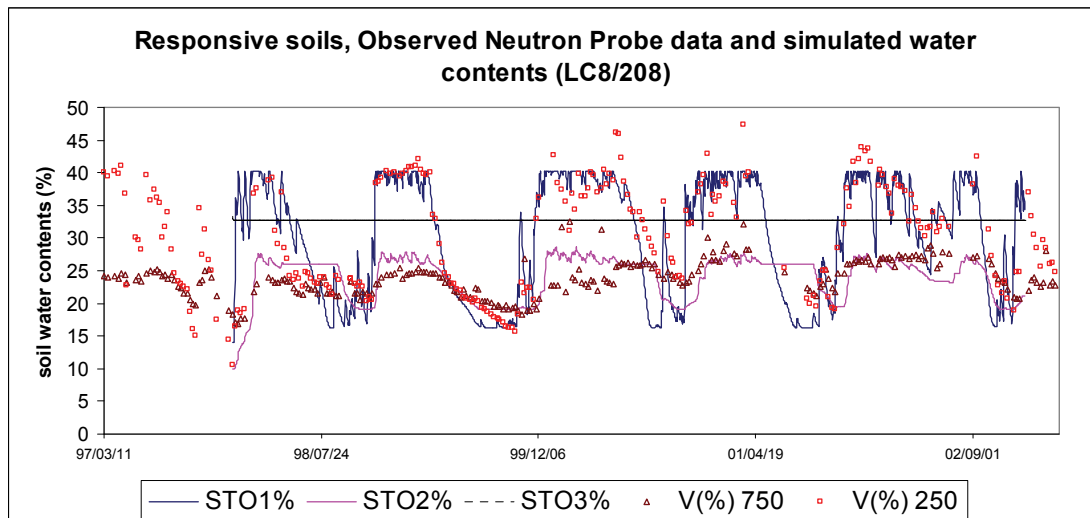


Figure 10.41 Weatherley, ACRU Int 3 soil types, observed neutron probe data and simulated soil water contents, nest LC8.

10.6.4 Discussion and conclusions

The addition of detail to the ACRU Intermediate zone simulations resulted in improved soil water and process representations. However streamflow estimations suffered greatly through the addition of increased soil data. Shallow soil water fluctuations are well represented, with the exception of the B horizon in most simulations. Deep level soil water contributions to flow proved difficult to accurately assess as the availability of observed data at such soil depths is not available for all instrument nests.

Examination of the rainfall to runoff relationship over the simulation period shows that 25% of rainfall ultimately leaves the catchment as streamflow. This means that a vast amount of the incident precipitation leaves the catchment via processes not directly concerned with the soil properties. For this reason the accuracy of the simulated streamflow should not be considered as important as ACRU Int's representation of the different soil moisture levels. This is due to the fact that the streamflow leaving the catchment is a function of the entire hydrological cycle, and not only the soil properties considered in this study. The good level of correlation between observed neutron probe data and simulated soil water contents, especially in the more detailed

simulations, verifies the University of the Free State, Department of Soil- and Crop- and Climate Sciences hydropedological classification of the Weatherley catchment.

While the method used to determine the D and t values of the ADF for the detailed simulations is not totally sound from the point of view that the hydropedological soil types are the dominant, and not the sole contributor to streamflow during the different stages of the hydrograph. With this in mind further studies could possibly focus on individual event hydrograph separation. This will aid in determining the individual contribution from the different hydrological soil types on an event by event basis.

10.7 CRAIGIEBURN CATCHMENT

The ACRU2000 and ACRU_Int model was run in the Craigieburn catchment from 1 October 08 to 8 April 09 (this was a period with unbroken meteorological and streamflow data) by E. Riddell. More detail is available on CD as Appendices.

10.7.1 Results

The models (ACRU2000 and ACRU_Int) were run in two modes: a simple configuration, using only soil attributes presented in Tables 8.2 and 8.3 and a detailed configuration, incorporating the cascading hillslope effect (Figures 8.3 and 8.4) and soil attributes presented in Tables 8.4 and 8.5. Results of the simple configuration are presented in Figures 10.43 to 10.44 and Table 10.8 and for the detailed configuration in Figures 10.47 to 10.50 and Table 10.9.

10.7.1.1 Simple configuration

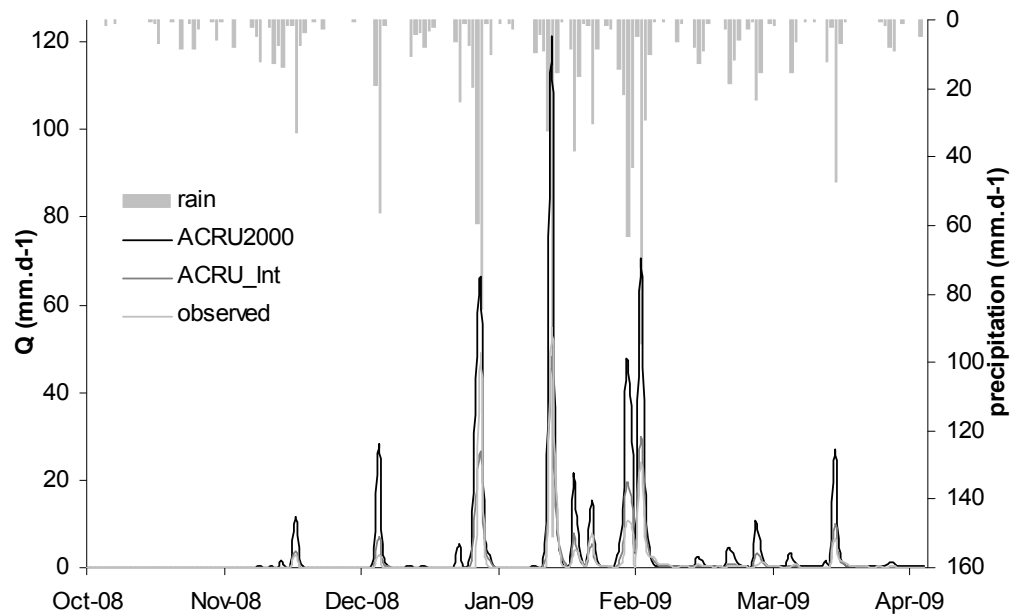


Figure 10.42 Plot of modelled (CHOUTF) and observed streamflow for the simple configuration.

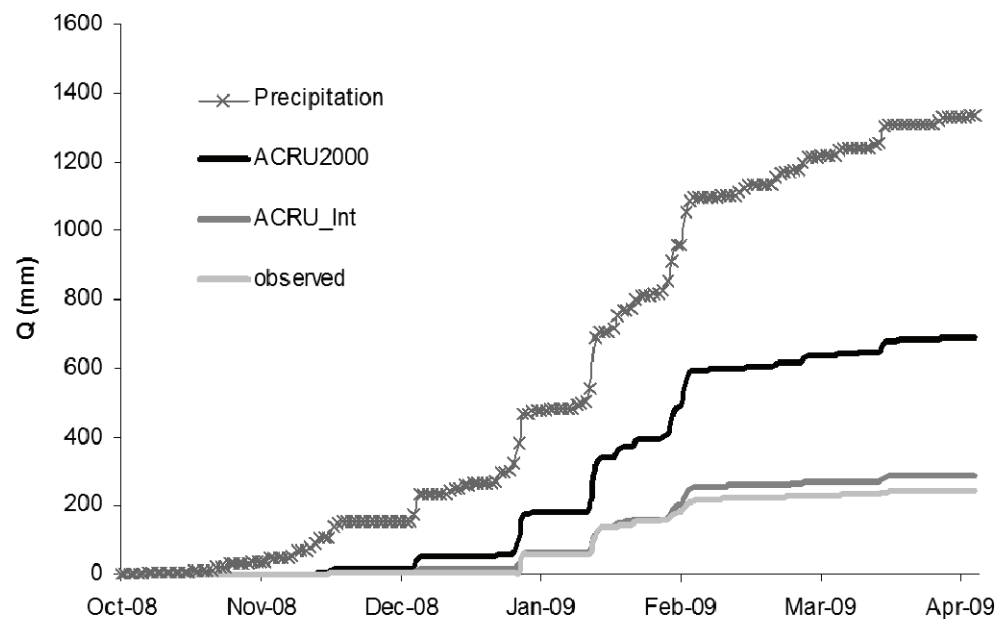


Figure 10.43 Cumulative plot of modelled (CHOUTF) and observed streamflow for the simple configuration

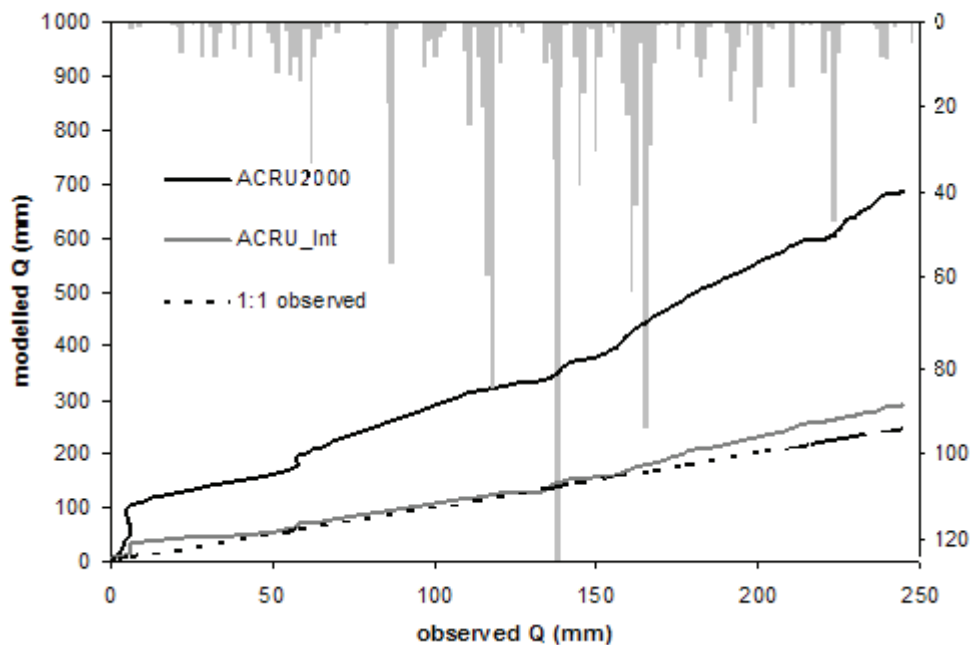


Figure 10.44 Plot of cumulative departure of two modelled against observed streamflow for the entire simulation period ($m = \text{slope}$) simple configuration.

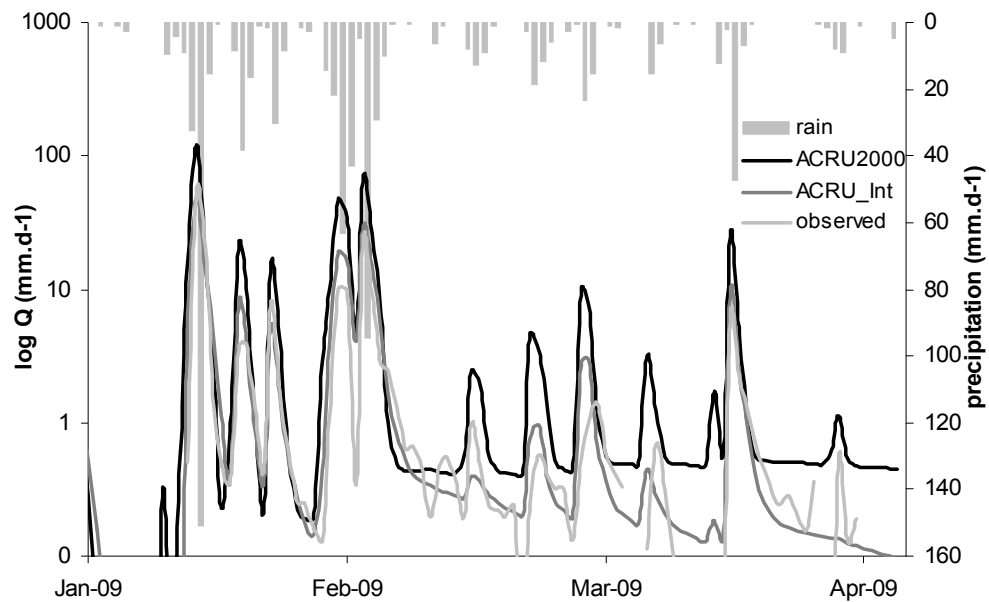


Figure 10.45 Log-normal plot of modelled (CHOUTF) and observed streamflow for the simple configuration between 2009/01/01 and 2009/04/08.

Table 10.8 Modelled (CHOUTF) efficiencies against observed daily streamflow for the simple configuration (R^2 , coefficient of determination; NS , Nash-Sutcliffe; W , Willmott)

Efficiency	R^2	NS	W
ACRU2000	0.805	-0.961	0.798
ACRU_Int	0.836	0.834	0.952

10.7.1.2 Detailed configuration

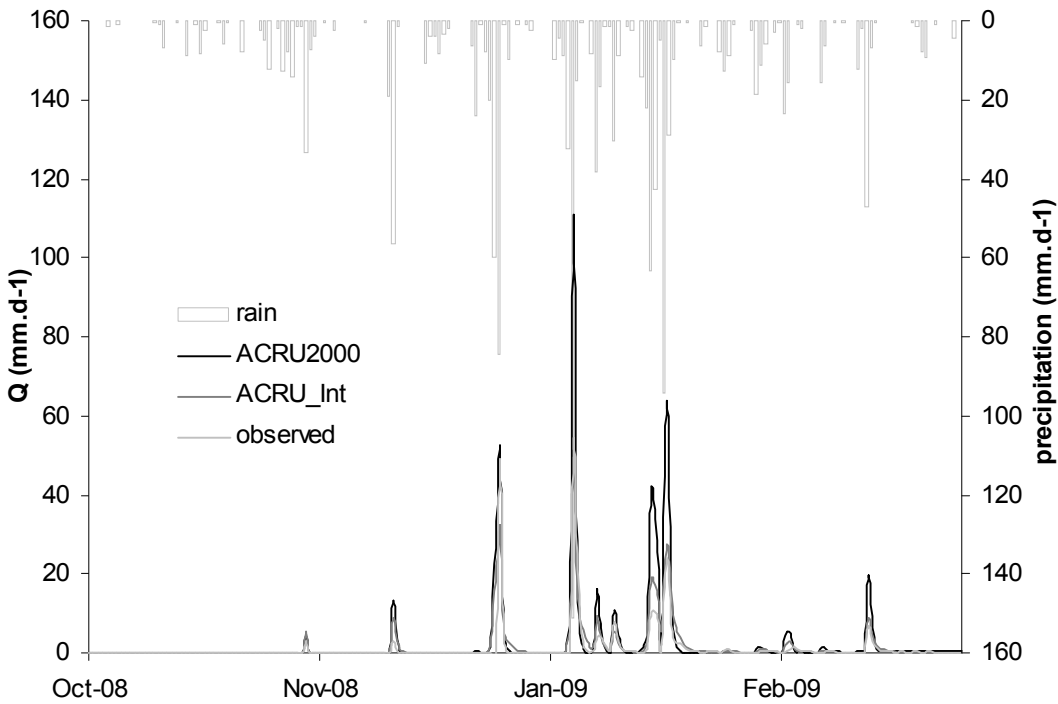


Figure 10.46 Plot of modelled (CHOUTF) and observed streamflow for the detailed configuration.

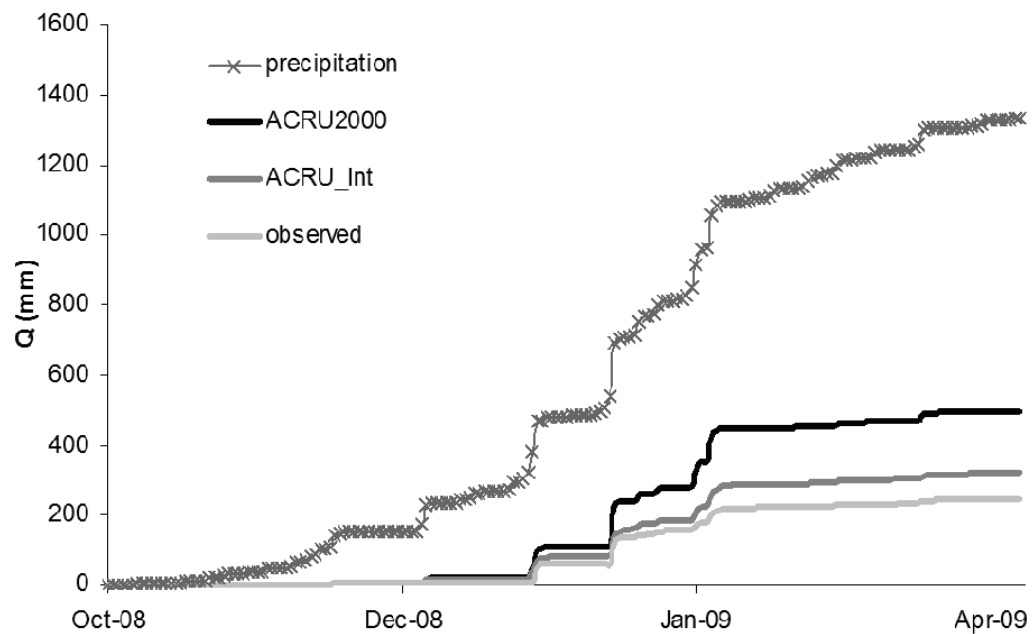


Figure 10.47 Cumulative plot of modelled (CHOUTF) and observed streamflow for the detailed configuration.

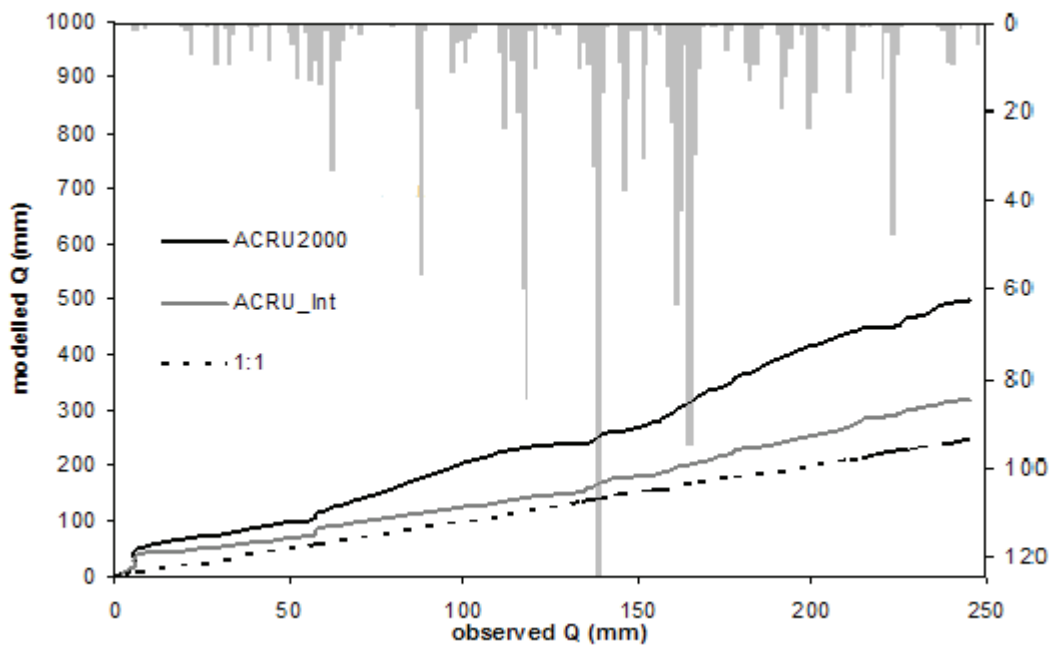


Figure 10.48 Plot of cumulative departure of two modelled against observed streamflow for the entire simulation period (m = slope) detailed configuration.

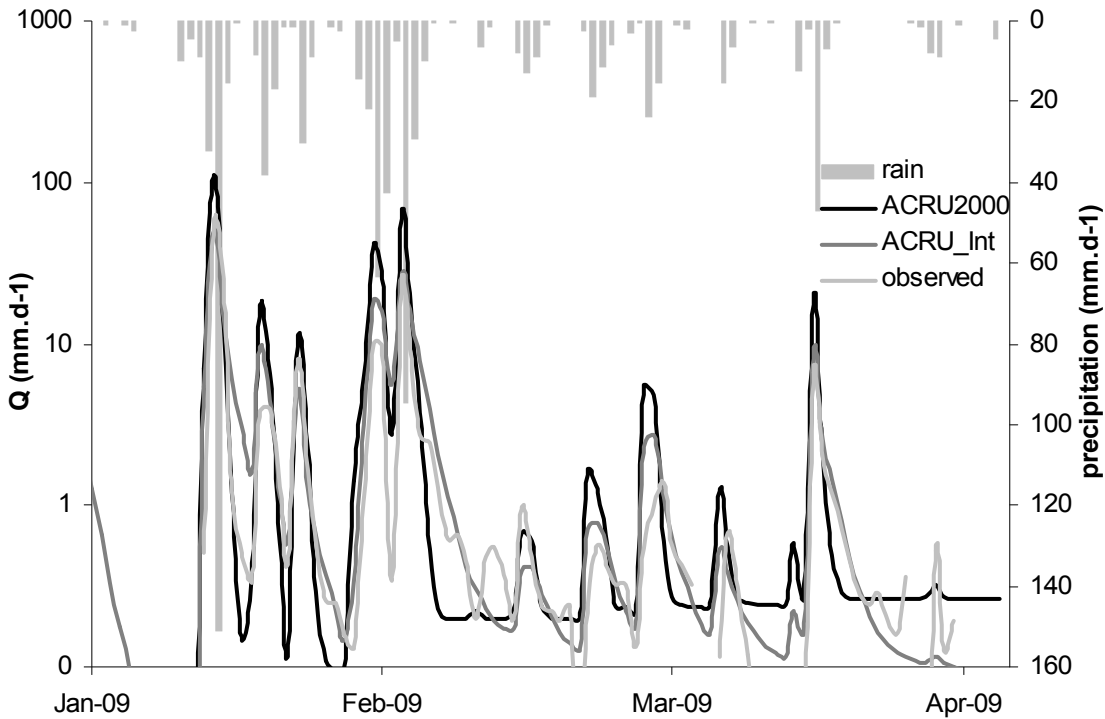


Figure 10.49 Log-normal plot of modelled (CHOUTF) and observed streamflow for the detailed configuration between 2009/01/01 and 2009/04/08.

Table 10.9 Modelled (CHOUTF) efficiencies against observed daily streamflow for the detailed configuration (R^2 , coefficient of determination; *NS*, Nash-Sutcliffe; *W*, Willmott)

Efficiency	R^2	<i>NS</i>	<i>W</i>
ACRU2000	0.811	-0.184	0.851
ACRU_Int	0.828	0.824	0.951

10.7.2 Discussion

The exercise in distributed hydrological modelling using the proposed ADF parameters has given insights into the new ACRU_Int model's performance particularly with respect to low flows. However, these findings must be discussed given the constraints in overall model performance with particular reference to the benchmark of the ACRU2000 model. It would have been apparent to the reader that despite the relatively high R^2 values generated by the ACRU2000 model in both simulations, it significantly under performed as was noticeable under the cumulative plots, and this may have been attributed to the non-effective parameterization of the model in which land segments failed to relinquish soil moisture to the atmosphere. However as is revealed in Table 10.4, for both instances of ACRU and under both configurations, the difference in evapotranspiration between the two models is no greater than 25 mm, the shortfall from the far greater potential evapotranspiration being attributable to the

significant soil moisture deficit at the start of the simulation. Certainly, the quickflow response fraction may have also been inadequately addressed in the ACRU2000, or at least that may have been assumed had it not been for the improved representation of streamflow by this model in the detailed configuration which maintained the same value for QFRESP. The more detailed configuration tended to have both lower peak and low flows. Since it was only the soil type distribution that was varied in this regard it suggests that accounting for a greater representation of soil types goes some way to improving catchment runoff, as would be expected. Moreover, the need to reduce QFRESP in the detailed configuration for sufficient peak flow performance by ACRU_Int is most likely attributable to the greater proportion of interflow and responsive hillslope units in this configuration. This is because the simple configuration had 9% and 5% of the catchment under interflow and responsive land segments respectively, whilst the detailed configuration had proportions of 17% and 6%. Of course this reduced QFRESP in the detailed ACRU_Int would also have been offset by the increased response function (INTZRESP) and macropore responses (MPRESP) of the interflow regions.

Table 10.10 Total potential and actual (modelled) evapotranspiration

	pET	ACRU_Int	ACRU2000
	584 mm		
Total aET simple		392.13 mm	373.37 mm
Total aET detailed		365.02 mm	389.49 mm

Whilst ACRU2000 seemingly improved through the incorporation of greater heterogeneity in hillslope units, ACRU_Int's performance may have been negligibly worse than the simpler configuration, but still captured the low flows and peak flows reasonably well. Despite this the question of why the ACRU_Int model did not at least improve in the same way as the ACRU2000 model remains. Since improvement of the ACRU2000 model was achieved through the inclusion of greater heterogeneity in the A and B soil horizon domains, the fact that the ACRU_Int zone which had the same detailed configuration, albeit with the inclusion of a third 'intermediate' soil horizon suggests that this is where the problem of un-improved model performance may reside. This may simply be due to inappropriate configuration of the soil compartment distribution, specifically the distribution of valley bottom wetland sub-catchments, which in the simple configuration was represented as one lumped sub-catchment (C5). Meanwhile in the detailed configuration, the wetland position was not lumped but treated as three different hillslope entities, which may have not been correctly configured in terms of their routing network or internal parameter development. In this case they all discharged directly to the stream. This needs to be explored further.

A distinct limitation of the application of the ACRU_Int zone algorithm to the Craigieburn catchment is of course with respect to the true low flow or base flow periods, by this it is meant

the long dry winter period, rather than the low flow inter-rain periods of the summer wet season. Since the monitored headward region of the Craigieburn catchment is essentially a seasonal wetland catchment albeit with a very flashy streamflow response, the fact that streamflow cessation occurred soon after the end of the rains and the limited streamflow data set available for the catchment negates a true assessment of ACRU_Int's performance at the scale of the individual sub-catchment. Nevertheless, what the ACRU_Int model did achieve was an adequate representation of seasonal streamflow cessation under both model configurations and in this represented ephemeral reaches of this semi-arid river system quite well. However, up-scaling of the ACRU_Int to several sub-catchments at the headwaters of the Sand River to a gauging site (or otherwise) further downstream, will certainly provide a useful understanding of the hillslope (soil) type contributions to catchment processes and particularly whether baseflows arise as accumulative reflection of these hillslope types and their ADFs, now that it has been successfully applied with hydro-pedological interpretation. One wanders whether the nature of the wetland intermediate zone soils, which are clays with a very high water retention capacity, may yield baseflow augmentation at much broader scales than would be observable within these sub-catchments. This is a necessary requirement given the apparent net-use of water by wetland vegetation in these systems during the dry winter months (Riddell & Lorentz, 2009), one needs to determine if there is any excess available for baseflow augmentation. Thus a next step would possibly be to incorporate this quantified wetland water use into the ACRU_Int algorithms.

A point must also be made about where the ACRU_Int model showed poor performance, and this relates particularly to low rainfall days. Regarding Figures 9 and 13 there are periods, for instance the 12/02/2009 and 27/03/2009 where there were minor increases in flow, for which there was no response by ACRU2000 or ACRU_Int. Or, 16/02/2009 and 10/03/2009 where ACRU2000 showed a peak flow response, but ACRU_Int's response fell far short of the observed. This is quite clearly a reflection of the models failure, at least within the restraints of the parameters that were set to account for low threshold triggers to flow. Furthermore, the fact that on occasion both models failed to generate peak flows in response to low order events is likely to have arisen due to complexities on the ground that were not captured in the model, namely small drainage channels which will aggregate towards the wetlands outlet. These are assumed to increase the discharges out of the wetland, and are believed to be one of the main anthropogenic forces facilitating wetland degradation (e.g. Pollard *et al.*, 2006). Whilst this is an apparently obvious omission from the models construct the scale at which these drainage channels have been applied (several within a 100 m² area) would necessitate a whole new exercise in parameterisation beyond the objectives of this manuscript. Nevertheless, it should not be ignored in further studies of this kind where they are applied in a complex socio-biophysical landscape. It is issues such as these that have recently been discussed by Zehe & Sivapalan (2009) in relation to closely coupled 'human-geoecosystems' and how to model these

interactions from the process to the meso-(catchment) scale. This is pertinent given the acknowledged degradation of certain soil types in the Sand River wetland catchments, namely of the Kroonstad (Planosols) which up to this point have been termed interflow hillslope units, which tend to interface the responsive wetland soils with upslope recharge areas. Whilst these soils have been the subject of detailed process based modelling, Riddell *et al.*, (in prep) conclude that not only do these interflow soils yield quick lateral flows they also relinquish upslope water to threshold induced macropore flow. This has similarly been modelled in the ACRU_Int zone here, by applying high values of D and low values of τ for the lateral and macropore response. Whilst in the same manuscript (Riddell *et al.*, in prep) through hydrometric observation and modelling at the hillslope scale reveal the recharge phenomenon of upslope hillslope units and responsive valley bottom wetland units and these were represented well in ACRU_Int by applying low D and high τ values to recharge regions and high D and low τ to responsive regions. One wanders therefore what the implications are of altering the extent and distribution of the interflow soils, which are slowly being modified through the impacts of subsistence farming on marginal lands. In the spirit of Zehe & Sivapalan's (2009) discussion, this poses the question of how these threshold type behaviours may be altered at the hillslope scale and how this will be reflected at the scale of the catchment.

Despite some limitations to the modelling as has just been described, it has been shown that the introduction of non-linear transfer functions between soil compartments on hillslope units, using hydro-pedological inferences of dominant hillslope processes has yielded a much improved representation of the wetland-catchment hydrology, particularly in the low flow domain. The use of hydro-pedological knowledge in this form of distributed hydrological modelling has clearly allowed for the simplification of process to a few parameters, that would otherwise have required parameterisation of soil physical laws governing variably saturated flow in heterogeneous media, which at the scale of the catchment would be replete with complexities exacerbating the notions of equifinality and uncertainty in model performance. This conforms with the recommendations of Kampf and Burges (2007) who note that when considering which processes to represent in a model, it is necessary to seek balance between a comprehensive representation of dominant flow processes whilst having a minimum number of parameters, and more specifically with attention given the importance (or dominance) of process. Furthermore, these should be manifested at the appropriate scale, and in the case the hillslope response type unit is probably the most appropriate. What is more, Pachepsky *et al.* (2006) suggest that whilst hydrological modelling can learn a lot from the field of pedology, this opens the door to further pedological development in terms organizing or classifying soil (and hillslope) behaviours that are useful to the hydrologist. This seems to have already begun with the collusion of hydrologists and soil scientists in South Africa as has been demonstrated here.

Chapter 11 **CONCLUSIONS AND RECOMMENDATIONS**

The grand challenge for predictions in ungauged basins (and for hydrological modeling as a whole) requires a holistic approach based on an improved understanding of the complex hydrological system and landscape heterogeneity. Soil acts as first order control in catchment hydrology through governing of water flowpaths and thereby influencing residence times and storage mechanisms. Water controls soil formation to such an extent that the soil carries signatures (morphological properties) of the hydrological processes involved in soil genesis. Based on this interactive relationship, soil scientists can make a valuable contribution to the improved understanding of the hydrological behaviour of the system.

Five catchments were surveyed with advanced soil survey techniques which focus on modal hillslopes. This technique incorporates land type data (with the catena concept as basis), GIS interpretations and transect surveys. The hillslope forms the basic building block for a number of catchment hydrological models and is the backbone of process hydrological studies and is therefore a fundamental landscape unit in the hydrological cycle.

The interactive relationship between soil and hydrology was demonstrated in the five catchments studied, through conceptualizing the dominant hydrological processes at hillslope scale, based on interpreted soil properties. In the Weatherleyey, Cathedral Peak VI and Two Streams catchments the conceptual representation was evaluated against measured data. Results supported the interpretations and emphasized the different hydrological behaviour of different soils. This led to identification of three hydrological soil types namely recharge, interflow and responsive soil types, based on water movement and storage within these soils. This is similar to the Hydrology of Soil Types (HOST) and the Hydrological Response Unit (HRU) approach used in a number of countries. It is recommended that this classification should be refined as an enhanced understanding of the hydrological behaviour of soils evolves.

There is abundant evidence from international and local sources that soil information can improve efficiency of hydrological models. Detailed hydrological interpretation of characteristics of the main soils which occurs in catchments was supplied to hydrological modelers of various institutions. This data was incorporated into hydrological models: ACRU, PITMAN, SWAT and WAVES. The soil data improved the efficiency of the models, with the greatest improvement in the models capable of simulating enhanced process complexity. Modelers agreed that the simplification and conceptualization of the landscape through interpretation of soil properties and distribution improved process understanding and facilitated application of the correct model configuration.

In Cathedral Peak VI catchment, the impact of various soil forms on streamflow was accentuated through hydrograph analysis. The impact of soil moisture on the streamflow and catchment storage was also illustrated in the Weatherleyey, Two Streams and Bedford catchments. Soil moisture should be used to integrate soils with hydrology through easily observable pedo-morphological indicators. This

might aid in explaining non-linear response of catchments to rainfall and the impact of land use change on streamflow. In the Weatherleyey catchment, average soil moisture content decreased significantly after afforestation.

There is need to expand these hydropedological studies in order to improve qualitative and quantitative understanding, conceptualization and characterization of flowpaths, connectivities, thresholds, non-linearities and residence times at hillslope scale. This can only be achieved through intensive studies of soils in hillslopes over a wide range of climates and geologies.

Because hydropedological studies are still in their infancy in South Africa (and in the world) huge gaps exist between the modelers (hydrologists) and experimentalists (soil scientists). Future studies should aim to close the gap by more interaction with all stakeholders. Only through interdisciplinary research can problems like pollution, land use change, floods and climate change be solved.

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