DEFINING SMALL CATCHMENT RUNOFF RESPONSES USING HILLSLOPE HYDROLOGICAL PROCESS OBSERVATIONS

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DECLARATION

I hereby certify that the research reported in this dissertation is my own original and unaided work except where specific acknowledgement is made.

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ABSTRACT

The Umzimvubu catchment on the eastern coastal escarpment of South Africa is sensitive to anthropogenic influences, with commercial and subsistence agriculture, irrigation, domestic and rural settlements and forestry compete for water use. An adequate supply of water to the region is seen as imperative in the light of the recent establishment of forest cultivation. In order to provide a sound assessment of the impacts of afforestation on the catchment, the subsurface hydrological processes of hillslopes on the Molteno sedimentary formations of the region must be clearly understood. Since the runoff hydrograph is, to a large degree, dependent on the subsurface processes, a number of models that simulate small catchment runoff have been developed. However, recent successful application of tracer techniques to hydrological modelling has shown that the subsurface processes are still not fully understood (Schultz, 1999), and whether or not the subsurface processes are modelled adequately is most often not verified, since there is a lack of relevant data. It is, therefore imperative that the subsurface component of these small catchment runoff models be improved. This can be achieved by first observing detailed subsurface water dynamics and assessing these against the catchment runoff response.

In this dissertation, results from a detailed experiment that was initiated in a 1.5 km^2 catchment in the northern East Cape Province are shown. Nests of automated tensiometers, groundwater level recorders and weather stations have been placed at critical points around the catchment, and these, together with soil hydraulic and physical characteristics are used to define and identify the dominant hillslope processes. Two crump weirs record runoff from these hillslopes.

The results of this subsurface study highlight the dynamics of surface and subsurface water in the hillslope transects. It is evident that the subsurface processes are strongly influenced by the bedrock topography as well as the soil characteristics, such as macropore flow and deep percolation. Using the monitored data and 2-D vadose zone modelling, the dominant hillslope processes have been defined and are used to aid in the selection of critical parameters to be used in estimating the catchment runoff. Results show that a clear understanding of the subsurface dynamics can lead to a realistic estimation of catchment scale runoff response.

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1. INTRODUCTION

"Hillslope hydrological processes, both during rainfall and hydrograph events, may greatly control the response of streams" (Taha *et al.,* 1997).

It has generally become accepted that the understanding of hillslope hydrological processes is of paramount importance in estimating catchment scale hydrological responses (Paniconi and Wood, 1993; Brammer and McDonnell, 1996; Robinson and Sivapalan, 1996; Taha *et al.*, 1997; Schmidt *et al.*, 1998; Schultz, 1999). The catchment response can be attributed to two physically based and independent processes, namely the hillslope response and the network response. The hillslope response includes the transport of runoff from the location of its generation on a hillslope to the nearest stream. The network response is the transmission of all the hillslope contributions through the stream channel network to the catchment outlet. Since the catchment hydrograph is dependent on these and the hillslope response is dependent on its subsurface processes, a number of attempts have been made to simulate small scale catchment runoff from hillslope process observations.

Despite considerable research effort, controls on hillslope flow pathways and their subsurface processes are still not fully understood (Binley and Beven, 1992; Freer *et al.*, 1997). Recent hydrological models subdivide the catchment into a number of area elements and perform respective flow component (surface and subsurface) calculations for each area separately. These sophisticated models often provide accurate runoff simulations (Schultz, 1999), but do not represent the subsurface flow components adequately. Since the soil water dynamics is an important component of these models, which describe (both spatially and temporally) water movement horizontally (evaporation, transpiration, interception, percolation) and vertically (surface flow, interflow, groundwater flow) within the soil, it should form the "heart" of catchment hydrological models. According to Schultz (1999), most models incorporate simplifications to describe responses in the subsurface component and therefore the models are calibrated so that the nett performance is satisfactory. Whether or not the subsurface processes are modelled adequately is most often not verified due to the lack of relevant observations. It may seem irrelevant for the modeller to concern himself with subsurface details if the model allows for accurate results, however, the need to be able to model and understand these details becomes evident if the land use changes. In order to be sure that the changed responses have been accurately modelled, the modeller needs to have a concise understanding of the subsurface processes.

General results from the recent, successful application of tracer techniques to hydrological modelling, especially subsurface modelling, reveals some interesting results which were previously not known to the hydrological modeller, or at least not applied in most hydrological models. These results include

- indirect flow (a flow component not directly related to a precipitation event) decreases with increasing runoff,
- smaller precipitation events produces more pre - event water than larger events,
- a much higher portion of runoff comes from groundwater than anticipated using common model constraints and,
- infiltration quickly activates outflow from groundwater to streams.

It is clear, therefore, that current hydrological modellers still do not know how the subsurface water is generated (ie. event or pre - event water). They are also seemingly unaware that subsurface flows are much higher than predicted by most present models. For these reasons it is imperative that the subsurface component of models be improved in order to model a catchment more realistically.

Recently the issue of scaling has become an area of interest in hydrological modelling (Kirby, 1999). Although the research is still in its early stages, researchers are trying to develop a model that can be used on a number of scales without compromising or changing the models overall structure or concept (Bormann *et al.*, 1999). The hillslope scale subsurface model plays an important role in this concept as it is more practical as well as financially viable to model a catchment based on field observations from one of its hillslopes rather than to implement the costly and time consuming process of obtaining field observations at a much larger scale. With the use of geographical information systems (GIS) data bases and digital elevation models (DEMs), hydrological models may be able to predict catchments response at a large scale (1000 km^2) from hillslope observations at a much smaller scale (1 km^2).

Considering the above issues, it is clear there is a need for observation of subsurface processes at a hillslope scale as well as a need to link these subsurface processes with the overall catchment runoff, particularly in the light of land use change. For this reason, the Weatherley research catchment in the northern East Cape Province was established in order to gain a clear and concise understanding of the subsurface processes that occur at a hillslope scale. Past research at Weatherley by Esprey (1996-1997) identified the dominant processes that are evident on a small section of a Molteno hillslope in the 1.5 km^2 experimental catchment.

Bearing this in mind, the main objectives of this dissertation are two-fold:

- To continue to identify and monitor the subsurface processes over an entire catchment;
- To use these data and findings in a prelimary modelling exercise to highlight the complexity of the dominant hillslope processes and to provide a first impression on how these processes are integrated within a catchment to generate the streamflow.

The catchment was intensively instrumentated with 20 "nests" each comprising three automated tensiometers recording soil matric potentials at 12 minute intervals at different levels. A piezometer network was also installed to record groundwater levels with ten of these piezometers being automated, so as to monitor the dynamics of the groundwater levels. Soil moisture data were also determined from a neutron probe network with readings being taken on a weekly basis. Soil hydraulic characteristics were determined during an intensive field and laboratory measurement programme. Two crump weirs, situated in the main stream, one in the upper reaches of the catchment and one in the lower reaches at the outlet, monitored runoff responses. The above instrumentation was used to gain a clear understanding of the factors linking hillslope processes to the overall catchment runoff as well as to determine important parameters to be used in the prelimary modelling exercise highlighting the complexity of the hillslope processes.

A multi-component, numerical simulation model, *HILLS*, was then used in a prelimary modelling exercise to simulate runoff from these processes. The *HILLS* model tracks water movement within the subsurface zones and links surface, unsaturated and saturated subsurface flow in a two-layer, two-dimensional hillslope transect (Hebbert and Smith, 1996). In order to simulate the catchment response, the contributing hillslope section's approach was used. The catchment was divided up into a number of hillslope segments and each segment modelled separately and subsequently integrated to yield the catchment response.

The data from fieldwork and observations as well as the simulated results from the initial modelling exercise provide a valuable insight into the complexity of the subsurface processes as well as providing useful feedback and data for the hydrological modeller.

Finally, recommendations regarding future monitoring of the catchment hillslope during afforestation are made.

2. LINKING HILLSLOPE PROCESSES AND RUNOFF

The hydrology of sloping land during storm events is a highly dynamic and complex process, in which many surface and subsurface factors and subprocesses play a role (Römkens *et al.*, 1990). Hillslope hydrology is concerned primarily with the partition of precipitation as it passes though the vegetation and soil between overland flow and subsurface flow on a hillslope. Kirkby (1998), pointing out the significance of hillslope hydrology, reported that in hilly areas, up to 95% of the stream water has passed over or through a hillslope before it reaches the channel stream/network. The rest of the water falls directly onto existing water bodies such as wetlands and rivers. A catchment response is made up of the hillslope response and the network response (Robinson and Sivapalan, 1996). The network response is the transmission of all the hillslope contributions through the stream channel network, to the catchment outlet. The hillslope response includes the transport of runoff from the location of its generation on a hillslope to the nearest stream and is dependant primarily on subsurface and overland flow.

2.1 Overland Flow

Overland flow is broadly defined as the flow of water above the surface of the ground (Anderson and Burt, 1990). The influence of the hillslope has a direct effect on overland flow. Hillslope characteristics such as slope angle, land use and vegetation, soil types, depressions and gullies and rock outcrops all affect the way water moves down the hillslope to the stream. Past research efforts have identified three main types of overland flow (Kirkby, 1988; Burt, 1989; Gerits *et al.*, 1990). *Hortonian overland flow* is flow produced when rainfall or snowmelt rates exceed the prevaling infiltration rate. *Saturated overland flow* occurs when, on part of the hillslope, the surface horizon of soil becomes saturated as a result of either the buildup of a saturated zone above a soil horizon of lower hydraulic conductivity or the rise in shallow water table to the surface. Since this results in the storage capacity of the soils becoming completely filled, all subsequent additions of water are forced to flow over the surface. *Return flow* occurs in areas where the profile has a concave shape and/or where there is flow convergence on the hillslope. It is also present where soil thickness and/or permeability decreases downslope or where the bedrock intercepts the soil surface. The subsurface flow is constrained in these areas and forced to exit the soil layer onto the surface, becoming return flow. These flow types influence the hydrograph characteristics such as peak runoff rates and lag times (Kirkby 1988). Figure 2.1 gives a generalized example of how a catchment responds to these different flows.

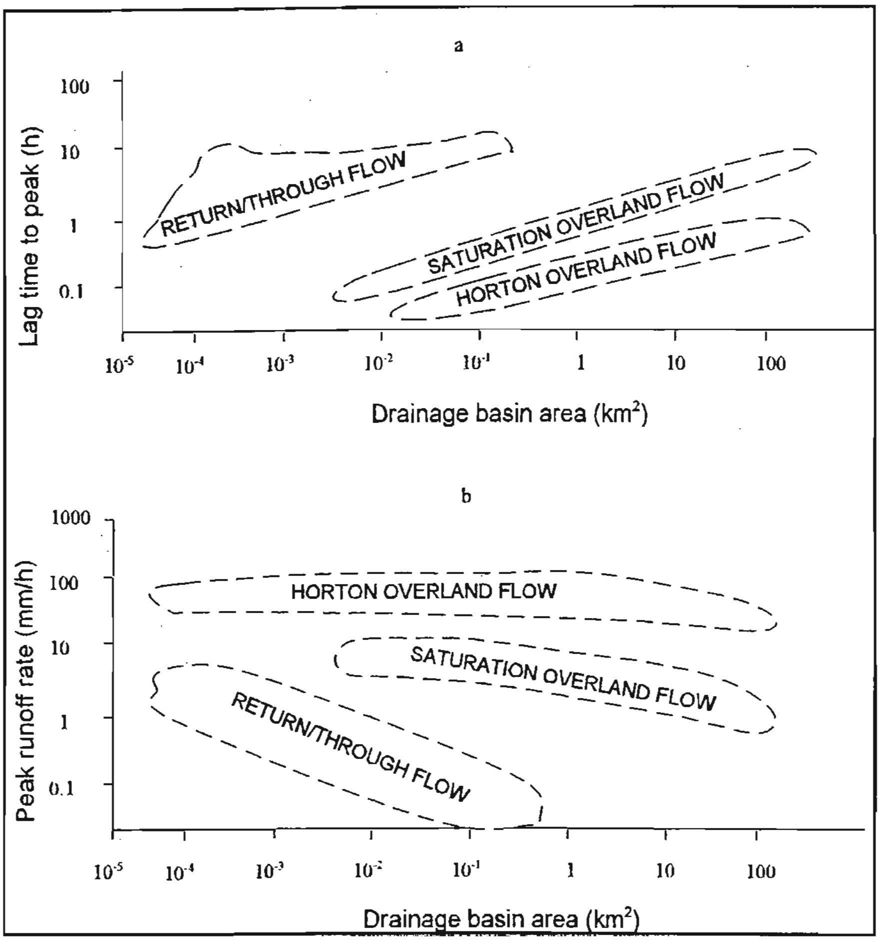


Figure 2.1 Generalised responses of catchments to hillslope flows (after Dunne, 1978) (a) Lag times, (b) Peak runoff rates

The lag times to the peak of the hydrograph is lower for overland flow than return/through flow due to the fact that movement through the soil media retards the flow of water to the stream. Lag times for saturated overland flow are also less than for return flow due to the fact that return flow only occurs after the soil has become saturated. The peak runoff rate is therefore highest for Hortonian overland flow as rain falling on the hillslope runs directly into the stream, thus accounting for the highest percentage of water that runs off a hillslope.

2.2 Subsurface Flow

In many catchments the subsurface flow is the major contributor to catchment runoff (Kirkby, 1988; Burt, 1989; Weiler *et al.,* 1998; Schultz, 1999). It is defined as "the flow of water in soil zones above water impeding layers, especially in basal hillslope soils, which discharge water directly into the stream channel without entering into the groundwater zone" (Chorley, 1978). Historically, the influence of subsurface flow contribution to runoff has been underestimated. Horton (1933) devised a simple approach which assumed the sole source of storm runoff was the excess water that was unable to infiltrate into the soil. This theory dominated catchment hydrology for several decades until Hewlett (1961) defined the variable source area concept, a concept that is still dominant in hillslope hydrology (Anderson and Burt, 1990). Schultz (1999), showed that there has been a significant improvement into research efforts concerning subsurface/runoff relationships on hillslopes, accompanied by better understanding of these processes. Results from recent tracer studies by Rice and Hornberger, (1998), Weiler *et al.* (1998), Uhlenbrook and Leibundgut (1999) and Schultz (1999) show that the influence of groundwater (a component of subsurface flow) on runoff is still underestimated. The results also show that a surprisingly high portion of flow from hillslopes is subsurface flow.

Subsurface flow is dependent on the subsurface processes within the hillslope transect. There are many different subsurface flowpaths that influence the hillslopes response. Examples of these subsurface processes are given in Figure 2.2

Most water in a stream channel has cascaded down at least part of the hillslope toposequence (Schulze, 1998). The subsurface flow reaching a stream via the hillslope may be subject to a number of the processes shown in Figure 2.2, depending on the hillslope characteristics.

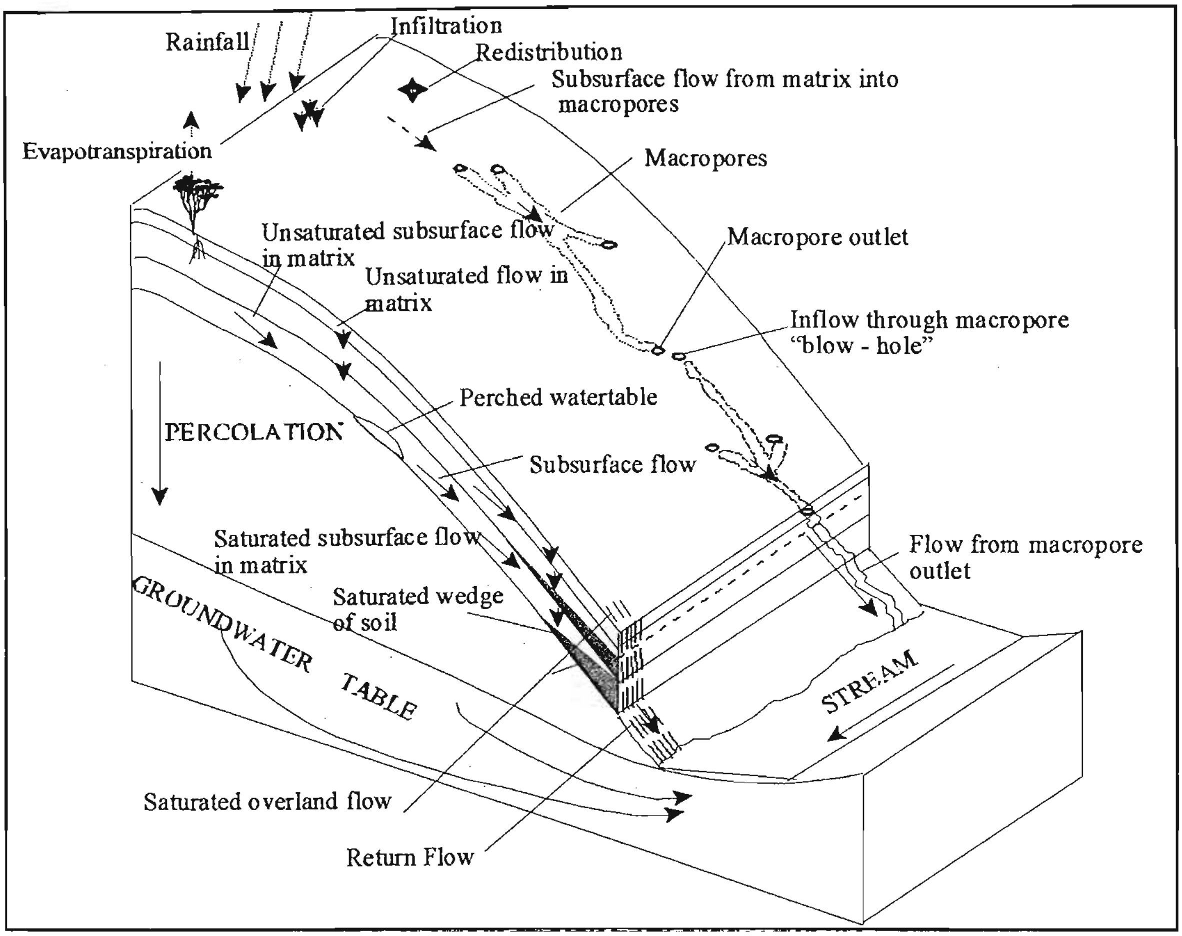


Figure 2.2 Flow routes of different hillslope processes (after Esprey, 1997)

Infiltration of water into the soil is one of the most important factors in determining the amount of excess rainfall available for runoff and is affected by a number of factors; the most important being the soil antecedent moisture content (AMC) and the rainfall duration and intensity. Infiltration is defined as the rate at which water enters into the soil. Upon entering the soil, water is redistributed by various subsurface flow paths, in the direction of potential gradients due to both gravity and soil pressures/tensions (Kirkby 1988). Infiltrated water usually moves down the soil profile in the form of a wetting front, with the area behind it becoming saturated. The way in which this water is redistributed after infiltration is also dependant on the soil characteristics such as its hydraulic conductivity and its water retention characteristics. Since these soil characteristics often have a high degree of spatial variation on a hillslope, subsurface flow contributions from the different parts of the hillslope are not equal, hence the importance of the contributing areas concept; a concept which identifies which parts of the hillslope are responsible for contributing water to the runoff hydrograph.

In areas of deep coarse textured soils, the flow direction is usually vertical while in fine textured soils, the resistance of *vertical flow* usually results in lateral movement of shallow subsurface flow (Beckedahl, 1996, cited in Esprey, 1997). *Lateral flow* is also common in shallow soils where the bedrock or impermeable surface force water to flow laterally above it (Wallach and Zaslavsky, 1991).

Of fundamental importance to runoff contributions from subsurface flow, is the existence of *macropore* or *pipe flow* and *surface cracking* (Figure 2.2). Macropore flow has been subject to considerable debate amongst researchers regarding definitions and the mechanisms of macropore flow (Coles and Trudgill, 1985; Pearce *et al.,*1986; Coles *et al.,* 1997). Macropores are defined as "large" pores or animal burrows, such as worm tunnels or channels formed by roots as well as cracks in a soil structure (Germann, 1990).

Pipes, like macropores also speed up the soils drainage rates. Defining the boundary between pipes and macropores is extremely difficult (Anderson and Burt, 1990). Pipes can be considered to have larger diameters and are usually formed by erosion and hence show a greater connectivity network than macropores. Pipes are usually fed by overland flow and lead to rapid lateral water movement just at or just below the soils surface. Surface cracking generally occurs in soils with a high percentage of clay which tend to shrink during dehydration. Cracking usually only occurs during hot wet months and can create a considerable increase in the storage deficit and infiltration rates. Coles *et al.* (1997) report observing cracks of some 15 mm in width and 150 mm in depth.

Macropore flow, pipe flow and surface cracking can account for up to 90% of water flowing into a stream. Edwards (1988), cited in Germann, (1990), estimated that holes wider than 5 mm can carry as much as 10% of an afternoon thunderstorm's water in Ohio, U.S.A. The fact that these holes can deliver this water at greater velocities and lower tensions than the surrounding soil matrix (Beven and Germann, 1982) also makes this type of flow a major driving force in linking subsurface flow to runoff.

Recent knowledge acquired from tracer studies have highlighted the importance of the *ratio of "old" to "new" water* components of the subsurface contribution to a runoff hydrograph (Schultz, 1999). This ratio indicates how the "new" rain water is redistributed and mixed with the "old" water already present in the subsurface. Marc (1994), working at the Maurets catchment, France, showed that a stream flow event may derive up to 80% of its flow from "old" water stored in the groundwater system from previous events. This indicates that while a catchment may have rapid infiltration and discharge characteristics, the runoff could be comprised mainly of "old" water stored from previous events and certain catchment may therefore have excellent soil/groundwater storage capabilities.

The *topography* is also a major controlling factor of subsurface flows (Wollock and McCabe, 1995; Beven, 1997; Freer *et al.*, 1997; Becker and McDonnell, 1998). The concavity or convexity of the slope as well as slope length to depth ratios all influence the rate at which subsurface flows contribute to runoff. Bedrock topography has also been shown to influence the subsurface processes. Research conducted by Lorentz and Esprey (1998) has shown that flow along the bedrock may be different to that of the topography and thus needs to be taken into account when considering subsurface processes. Land use practices and vegetation type cause other processes such as root water uptake or evapotranspiration to become part of the hillslope hydrological cycle and thus also have an effect on the subsurface flow of a hillslope.

Localised or perched water tables (Figure 2.2) may develop in areas where a layer of lower conductivity occurs. These localised water tables usually move laterally downslope in response to hydraulic gradients (Esprey, 1997). If there is sufficient rainfall on an already saturated hillslope, *percolation or deep percolation* through the less impermeable layer or bedrock may occur (Figure 2.2). This leads to the contribution of water to the groundwater table, a process referred to as *groundwater recharge*. Groundwater aquifers are also influential in the runoff response of hillslopes as they often "feed" streams directly from below the surface as seen in Figure 2.2. If the soils are shallow or an impermeable layer is present, the groundwater level may rise and intercept the surface level causing water to return to the surface or *exfiltrate* and in turn, become *return flow* (Figure 2.2). This is often referred to as *groundwater ridging* (Esprey, 1997), and is dominant in the lower parts of the slopes near the streams (Tsukamoto and Ohta, 1988).

This chapter has given an insight into the complex reality of processes that occur on a hillslope scale and how these affect the runoff hydrograph. A number of hillslope models exist which are aimed at simulating the dominant hillslope processes and the subsequent catchment runoff response using the results of these dominant processes. The following chapter reviews the different approaches that modellers have adopted in attempting to simulate catchment runoff response using the complex dynamics of hillslope processes.

3. CATCHMENT SCALE MODELLING APPROACHES USING HILLSLOPE PROCESSES

There are a plethora of hydrological models that simulate catchment runoff. In the following chapter, only those models that use, as a starting point, the dynamics of hillslope processes in their algorithms are evaluated. Rather than discuss each model individually, groups of modelling approaches which have similar methodologies have been defined and the groups are discussed in the light of their respective strengths and shortcomings.

3.1 The Topmodel Approach

"Topography is recognised as an important factor in determining streamflow" (Wolock and McGabe, 1995).

This approach is possibly the most commonly used simplified approach which incorporates the hillslope influence on subsurface processes and subsequent runoff generation. It combines the advantages of a simple lumped parameter model with the important distributed effects of variable source areas in the way that reflects their dynamics over space and time (Beven and Kirkby, 1979). The variable source area concept implies that overland flow is produced only over a small fraction of the total catchment area. In this approach the land surface areas that produce overland flow are taken as those that become saturated during precipitation events; they occur where the water table rises to the surface. Overland flow is produced when precipitation falls on a saturated surface or when subsurface flows return to the surface (Dunne *et al.,* 1978). The saturated land surface areas (called source or contributing areas) are variable in that they contract and expand over specific parts of the watershed. The dynamics of the saturated land surface areas are controlled by catchment topographic and subsurface hydraulic characteristics and the state of wetness over the catchment (Wolock and McGabe, 1995).

In this approach a parameter is derived from the topography of the catchment to describe the wetness of a soil profile with respect to its position on a hillslope. The controlling parameter is the wetness index (WI) which is described by

$$WI = ln(\alpha / tan\ \beta) \qquad \textbf{(3.1)}$$

where α is the upslope area draining through a point (per unit contour length) from upslope and tan β is the local slope angle. The use of DEMs is vital in the computation of the wetness index's frequency and spatial distribution as they increase the accuracy as well as the applicability of the model. All the points in the same wetness index are assumed to be hydrologically similar with respect to their soil water response; thus it is not necessary to make calculations for all points in the catchment.

A problem with this assumption is highlighted by Freer *et al.* (1997), who show that not all flow paths converge in the hollow regimes. To try to overcome this problem, two algorithms for topographic parameters were created; a single flow direction algorithm and a multiple flow direction algorithm. Grids created by this approach and having single flow directions or multiple flow directions are shown below in Figure 3.1

Wolock and McGabe (1995) conducted research into comparing these two flow algorithms within Topmodel and found that the model's efficiency and simulated flow paths were only effected slightly when the wetness index was computed using the different algorithms. It was, however, concluded that the multiple flow direction algorithm was more efficient in calculating spatial hydrological characteristics such as soil moisture content than the single flow direction algorithm. Quinn *et al.* (1994) showed that while the single flow direction algorithm approach is asymptotically more accurate as the grid scale used in the watershed becomes finer, coarser scale grids give rise to local inaccuracies, particularly on divergent slopes. It is therefore stressed, that this modelling approach must be used with care and perhaps modified to suite particular circumstances (Beven, 1997).

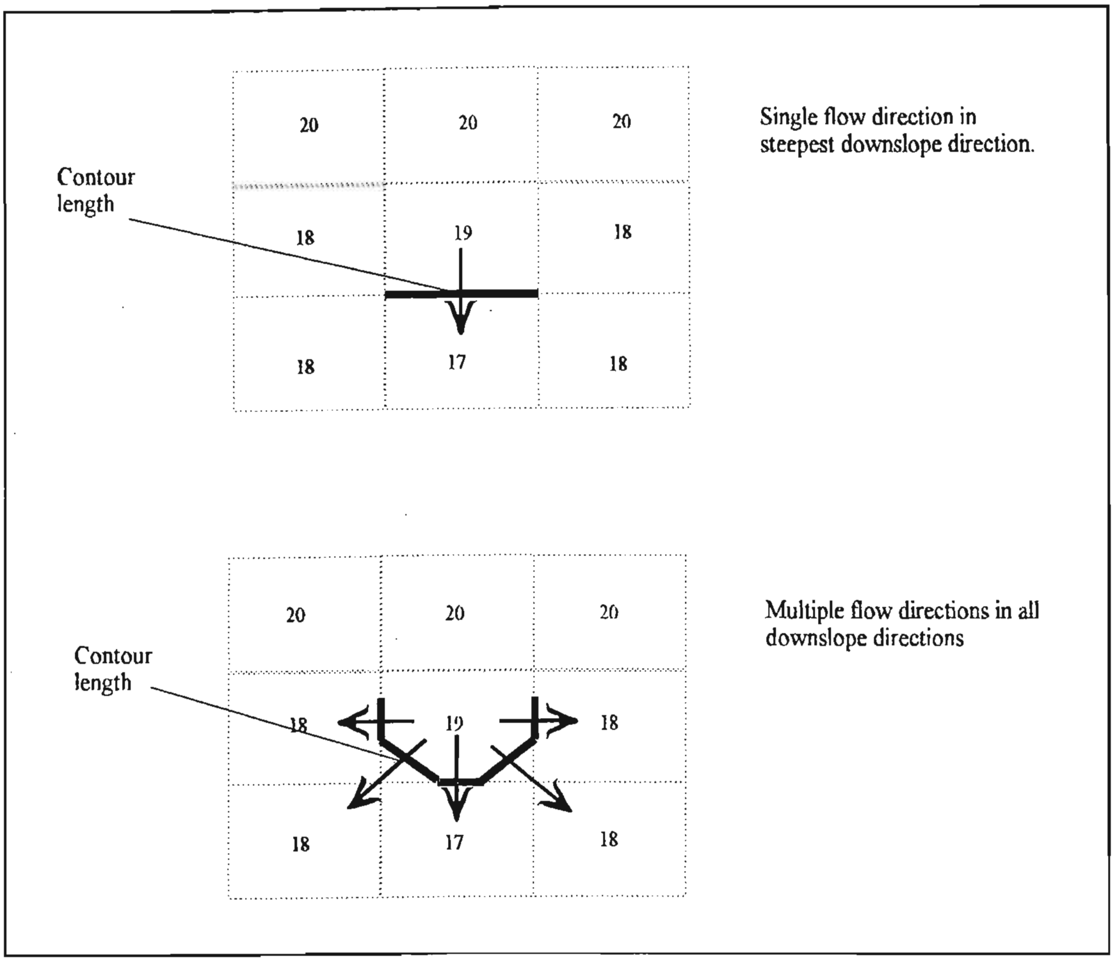


Figure 3.1 Plan view of an elevation grid showing different contour lengths for single and multiple flows (after Wolock and McGabe, 1995)

Reference levels are predetermined points within the catchment whose paths and hydraulic gradients are different to that of the topography with known co-ordinates and groundwater levels and, as such, can help overcome the problems of flow. Determining a reference level entails determining a reference gradient of the water table surface from field measurements. Where the water table intersects the surface level, surface values are used, but when the water table drops below the surface, the new reference gradient levels are used. The differences in these two levels can be used to obtain an estimate for storage and travel times in the unsaturated zones. The use of reference levels with multiple flow algorithms have led to satisfactory results in predicting flow paths and hydraulic gradients that are different to that of the topography (Quinn *et al.,* 1994).

There are shortcomings in this approach which are currently being addressed by researchers and are worthy of mentioning.

- Problems regarding scale issues are highlighted in Becker and McDonnell (1998) which indicate that this approach is acceptable at a catchment scale, but not at a hillslope scale where details regarding flow paths in some parts of the catchment are omitted or not well represented.

- The bedrock topography also plays an important role in determining the hillslope response, especially in shallow soils (Lorentz and Esprey, 1998), and in most cases the approach does not account for bedrock variations. Freer (1997) showed that where there is considerable difference between the bedrock surface and surficial topography, the bedrock has sufficient influence on the local gradients and hence the dominant flow paths.

- Another problem arises in using this approach in relatively flat areas and areas of perched or localized water tables, where grids are not able to represent the flow paths accurately (Freer, 1997).

- Becker and McDonnell (1998) emphasis the need for more research into studying the matrix, macropore and preferred path flow using this method. They also emphasis the fact that perched water tables and bedrock influences cannot be ignored.

3.2 The Contributing Hillslope Sections Approach

This approach, sometimes referred to as pie-sliced modelling, involves dividing the catchment into a number of sections. Each section has a segment with a wider crest, narrower midslope and converging toe, and each is considered individually in defining a catchment's response. This approach, used in Taha *et al.* (1997) in an attempt to model the link between hillslope water movement and streamflow, involves separating a storm's hydrograph into "old" and "new" water. This approach uses isotopic flow separation with a slope unit and the river as its base. The streams hydrograph and catchment response is then calculated from adding the sum of the unit hydrographs for the stream.

On a complex hillslope Band *et al.* (1993) use a similar approach. The stream network was determined using a DEM. The topographical surface was segmented into the component hillslope segments. Each hillslope segment is parameterised separately using information drawn from geographically registered soil and remote sensing data sets and then modelled. The advantage of this method is the relatively conservative variation of parameters within the hillslope segments compared to the more distinct variation between the hillslope segments. However, it is important to be careful with the degree of representation used which can lead the loss of accuracy within the catchment. An example is the approach used by Herath *et al.* (1999), where it is assumed that soil characteristics are similar for the entire catchment. Some of the advantages and disadvantages of this approach are listed below.

- A shortfall with this approach is the assumption of hydrostatic equilibrium (i.e. with steady state conditions of flux applied to all boundaries). The catchment would need to have sufficient antecedent moisture conditions or a steady rainfall event of sufficient time to allow for the segment to wet up sufficiently in order to reach hydrostatic equilibrium. An example is that of the Maurets experimental catchment in France, where half an hour of steady rainfall was required to achieve equilibrium (Taha *et al.,* 1997). This approach is therefore not appropriate in areas which experience short intense rainfall events.

- This approach may be advantageous in small catchments where localised seeps or gullies play an important role in the subsurface hydrology. Examples are highlighted when macropore flow is evident in some regions of the hillslope segments and not in others.

- Another advantage in this approach is the ability to divide the catchment DEM into different degrees of segmentation, such as a catchment divided first into eleven stream paths and twenty two hillslopes (Figure 3.2A) then three stream paths and six hillslopes (Figure 3.2B) or one stream path and two hillslopes (Figure 3.2C).

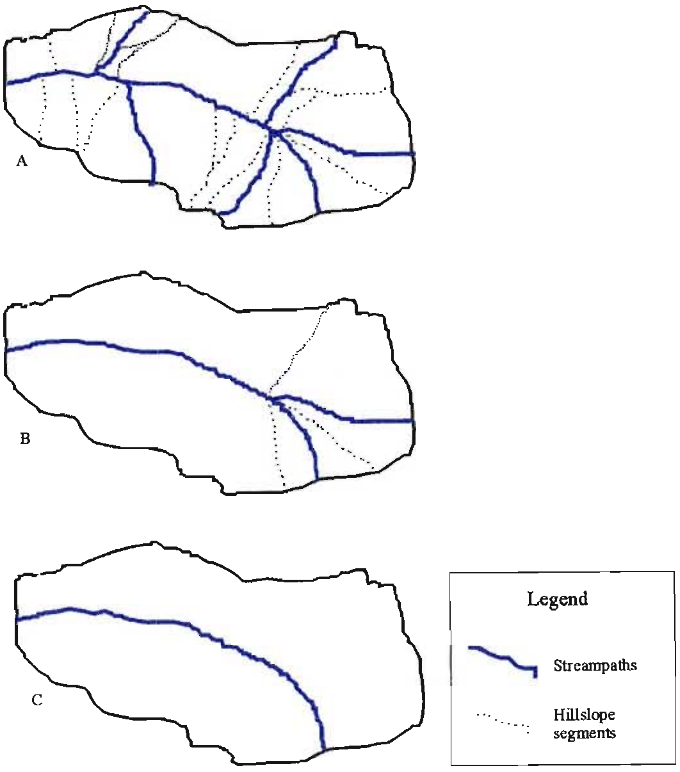


Figure 3.2 Representation of a catchment by different degrees of segmentation (after Band *et al.*, 1993)

3.3 The Detailed Distributed Surface and Subsurface Modelling Approach

The distributed modelling approach represents the catchment hillslopes in the form of raster grids and takes into account spatial variation in inputs, outputs and parameters. The entire catchment is disaggregated into cells and each individual cell's surface and subsurface processes are modelled separately. This approach has advantages since cells along the entire slope are treated individually and this allows for local features to be taken into account. The fluxes within each cell are determined by soil parameters as well as other hydrologically important variables and there are transfers between the cells and their neighbouring cells. Relative merits and shortcoming of this approach are discussed below:

- The transfers between the cells are just as important as the fluxes within a cell at the overall hillslope scale, and these transfers are often not adequately defined (Wigmosta and Burges, 1997 and Tarboton *et al.,* 1998).

- Historically, the high computational demand of this approach could only be met using supercomputers. Beven and Binley (1994) point out that to run The *Institute of Hydrology Distributed Model* (*IHDM*) for a single storm duration took between 30 and 60 hours of computing time. Paniconini and Wood (1993) reported similar findings when it required 3.6 hours of CPU time to simulate a finite element mesh on a catchment with a surface area of 11.62 km^2. Beven (1989) also stated the one of the disadvantages is that the model discretisation is often designed to minimise the computing requirements rather than to resolve key physical features. Although computer technologies are advancing at a rapid rate and central processing unit (CPU) times are currently much faster and efficient than say five years ago, most of the modelling is still adjusting and undergoing changes since smaller personal computers can handle the high data capacity in a much shorter time (Jensen and Manitou, 1994).

- Jensen and Manitou (1994) point out that a flaw in the distributed approach involves heterogeneity on a natural scale. Large scale catchment behaviour has its own characteristics influenced primarily by this heterogeneity. The heterogeneity may not always be able to be simplified by combining smaller scale, local process equations and parameters. An example is given by Gelhar (1986) who shows that the natural logarithm of hydraulic conductivities may vary from 0.2 to 5.0 in various soil formations within a small catchment. It is therefore impractical to try and represent this heterogeneity on a larger scale.

- Stochastic methodology provides a different approach for building models that need to consider spatial heterogeneity by generating synthetic sequences that are statistically similar to observed sequences (Jensen and Manitou, 1994).

- A model using the distributed surface and subsurface approach by Paniconi and Wood

(1993), showed that naturally occurring spatial and temporal variability in soils, topography, vegetation, rainfall and evaporation required complex boundary conditions and a high degree of parameterisation which required specific assumptions to be implemented in the model. Examples of these assumptions included processes such as soil hysteresis and macropore flow not being accounted for as the porous medium of each cell was considered to be isotropic. There are shortcomings in this as it is of common knowledge that macropore flow contributes significantly to the transport of water on hillslopes (Paniconi and Wood, 1993; Esprey, 1997; Becker and McDonnell, 1998; Hickson *et al.,* 1999). Hysteresis also plays an important role in determining how different soils will behave under different draining conditions. Because of the non-uniqueness of the matric potentials, considerable difficulty is encountered when modelling soil water movement in nature. Since hysteresis can be avoided by modelling only a wetting or draining cycle, it has been neglected for most practical applications (Rawls *et al.,* 1993).

- Kambouta and Sivapalan (1997) used a complete disaggregation and aggregation approach which divided the catchment into a number of hillslope flow strips and modelled each strip with a distributed model. Although the results were encouraging, the need for further research was stressed.

3.4 The Hydrological Response Unit (HRU) Approach

This approach is very similar to that of the contributing hillslopes. However the HRU approach groups areas of similar soils, topography or land use as an HRU. Flügel (1997) defined HRUs as "distributed heterogeneously structured modelling entities within a river basin having a common climate, land-use and underlying pedo-topo-geological associations controlling their hydrological transport dynamics, evapotranspiration and runoff generation." An underlying concept of the HRU is that topography, soils and geology are closely associated with each other as a result of to weathering and erosion processes. This interdependency has led to the identification of soil catenas; areas of soils having the same properties with respect to their location on a hillslope/topography. Each pedo-topo-geological association is characterised by a specific land class which can be considered as homogeneous if compared with neighbouring land uses. The hydrological process dynamics are controlled by the land-use management (*viz.* type of vegetation or crop) and the physical properties of the respective pedo-topo-geological associations. The variation of the hydrological process dynamics within a HRU is negligible if compared with such variations in a different HRU. Each HRU is therefore assumed to have unique characteristics and is therefore modelled accordingly (Helmschrot, 1998).

In using this approach, it is of paramount importance to ensure that the model used preserves the three-dimensional physiographic heterogeneity of the basins "real world". Flügel (1997) also points out that this condition is not met if dynamics from a catchment (especially those obtained from satellite imagery and GIS) are associated with an "average" appearance of the basin physiographic properties and used as modelling entities nested within a model. Some advantages and disadvantages are listed below.

- In using this approach, transfers between different scales are possible. Using a GIS to delineate HRUs is not restricted to a particular scale and can be applied on a number of different scales provided the required raster resolutions are available from the DEM. There is, however, a corresponding loss of basin heterogeneity when upscaling takes place.

- Fluxes between the different HRUs are also critical to the catchment response and need to be accounted for. Analysis around each of the HRUs to monitor flux variations is therefore essential. The modelling of complex basins with a high degree of heterogeneity requires sophisticated hardware as well as more complex models and this area still requires further research efforts.

3.5 The Geomorphometric Hydrological Response Unit (HRU) Approach

Catchment morphology and hydrological processes are inextricably linked through the geomorphometric process of soil development, erosion and deposition (Beven, *et al.,* 1988). Geomorphometric parameters may be defined as "parameters describing effects of landforms structure and topology on hydrologic processes, which we term effective geomorphometric parameters" (Schmidt *et al.*, 1998). Soils on hillslopes can have definable characteristics simply by their position on a hillslope. Band *et al.* (1993) also discussed determining trends in soils properties with respect to topographic position (i.e. the existence of a catena). By identifying areas of similar geomorphometric characteristics (slope angles and local parameters such as soil characteristics), hillslope forms or even basin characteristics), the modeller can identify hydrological response units based on their geomorphometric characteristics with the assumption that each geomorphometric response unit will be unique.

An example of this modelling approach can be taken from Schmidt *et al.* (1998), who used high resolution DEM and a powerful GIS to investigate the effects of geomorphometry on rainfall-runoff processes at different scales. The results were encouraging and it was concluded that quantifying geomorphometric attributes and hydrological variables can give important and useful information regarding rainfall-runoff processes and hence a catchment response. However, two fundamental difficulties were encountered:

- It remains questionable whether the derived relationship between morphometry and hydrology remains constant under variable boundary conditions (i.e. in conditions of flux or no fluxes between the unit boundaries, Schmidt *et al.*, 1998).

- The analysis interactions were based purely on modelled results and the question of whether it is possible to transfer these findings (the geomorphometry-catchment response relationship) into real situations needs to be verified.

In identifying the importance of geomorphometric properties in hydrology, Schmidt *et al.* (1998) stress the importance of scaling effects when using this approach since some runoff-morphometry relations may be invariant over certain spatial ranges. Figure 3.3 represents some dominant geomorphometric features in a spatial and spatio-temporal context. Generally, local scale, hillslope scale and catchment scale are often used to distinguish different spatial scales in hydrology (Kirkby, 1988). On the local scale, water path geometries, flow velocities and quantities are influenced by morphometric parameters such as slope angle and upslope drainage areas. In addition to this, geomorphometry affects hydrological processes indirectly through their dependancy on several other factors like soil parameters (Schmidt *et al.*, 1998). The hillslope scale is dominated by runoff producing mechanisms influenced by soil properties (overland and subsurface flows) and hillslope form. On the catchment scale the hydrograph is influence by the basin morphometry parameters such as catchment height distribution (relief indices), length and form of the basin (form indices) and parameters describing the drainage networks (Cook and Doornkamp, 1990).

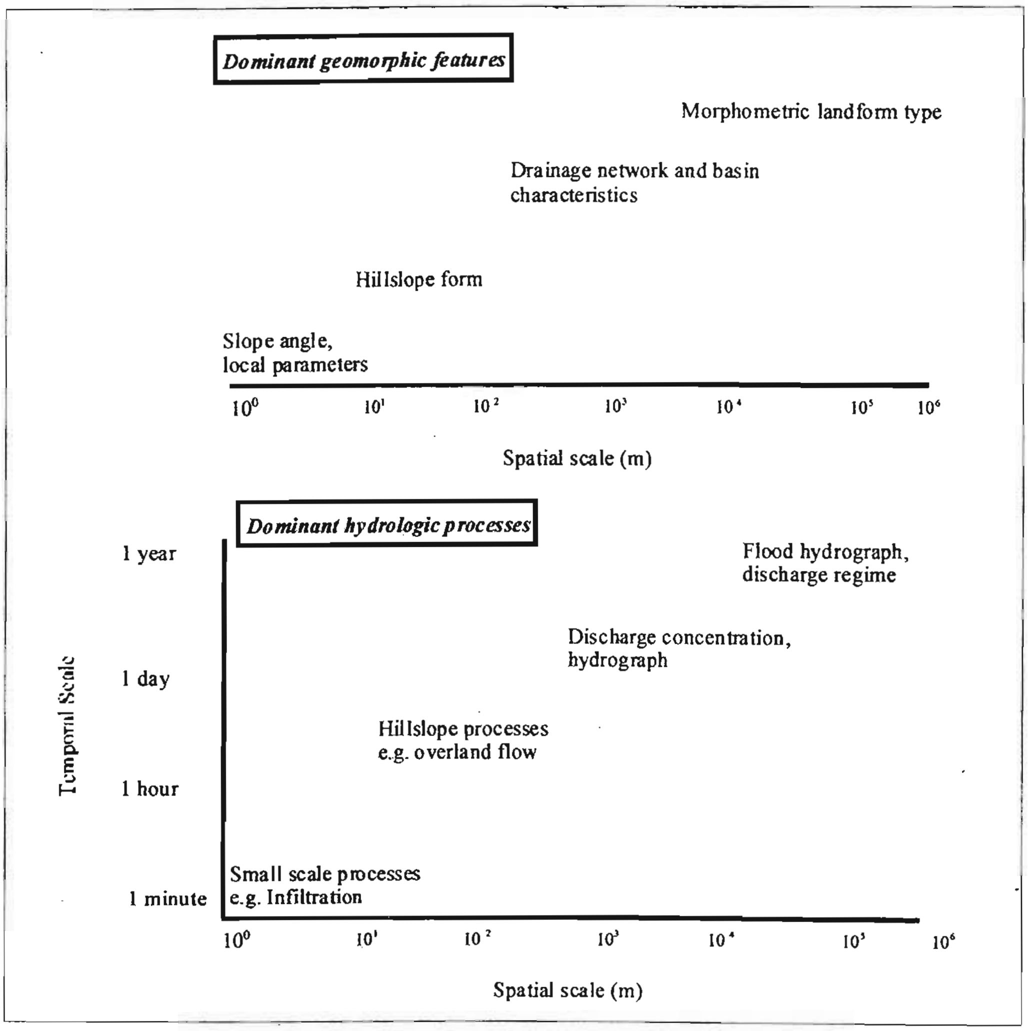


Figure 3.3 Spatial and spatio-temporal context of scales in hydrology and geomorphology (after Schmidt *et al.*, 1989)

As with all types of models, these scale issues need to be clearly defined when attempting to model a catchment's response using this geomorphometric H.R.U. approach as using inappropriate parameters and scales can lead to inaccuracies in model results.

It can generally be concluded that the geomorphometric H.R.U. approach is still in its pioneering stages of development and further work may yet yield promising results.

This chapter has provided an insight to the main modelling approaches that have been adopted to simulate catchment response using the complex dynamics of hillslope processes. It can be seen that there is no specific "universally" accepted modelling approach and that each catchment needs to be considered unique with its own characteristics and an approach adopted accordingly. In order to identify such an approach the modeller needs to fully appreciate the complexity of the hillslope subsurface processes prior to modelling the catchment response. At the Weatherley catchment, fieldwork and monitoring networks were used to gain insight into the complex hillslope dynamics prior to adopting the modelling approach. The observed results which are discussed in Chapter 6 were then used to infer the catchment response.

All of the approaches discussed in this chapter were used to aid the selection of a physically based hillslope model to be used in the prelimary modelling exercise at Weatherley. The following chapter discusses the *HILLS* model and its components which were used in the prelimary modelling exercise.

4. THE *HILLS* MODEL

In the previous chapter the complexity of subsurface processes that exist at the hillslope scale and the different approaches used in modelling them were highlighted. Bronstert (1999) highlighted the importance of"physically based" models, models that use parameters that have a physical meaning and can be derived from field measurements and experiments. The prelimary modelling exercise at Weatherley involved simulating the subsurface processes that occur at the hillslope scale using the *HILLS* model. The primary aim of this simulation was to compare observed processes to the simulated processes over sections on the hillslope.A brief description of the *HILLS* model and its components are given in section 5.1 below.

4.1 Introduction to the *HILLS* Model

The *HILLS* model either treats a hillslope section of unit width sliced along flow paths or simulates an elementary catchment composed of topography analogous to an "open book" configuration comprising an assembly of hillslope section units. It is a multi-component, numerical simulation model whose major objective is to track water movement within the saturated zone in a hillslope. It links surface, unsaturated and saturated subsurface flow in a two-layer, two dimensional hillslope (Hebbert and Smith, 1996). A schematic diagram of the hillslope section as simulated by the *HILLS* model is presented in Figure 4.1.

The model can be applied on hillslopes where a relatively shallow soil is underlain by a soil of lower permeability, where perched water tables and seepage occur (Esprey, 1997). *HILLS* can also simulate the response to recharge through the soil mantle, or conversely simulate the lateral water movement through the subsurface soil. The model considers the soils to be made up of two profiles; upper and lower layers (i.e. topsoil and subsoil respectively). This is useful when simulating the runoff of a hillslope as both the subsurface and the surface flows are simulated, giving a clear indication of any overland flow as well as subsurface flow components of the hydrograph.

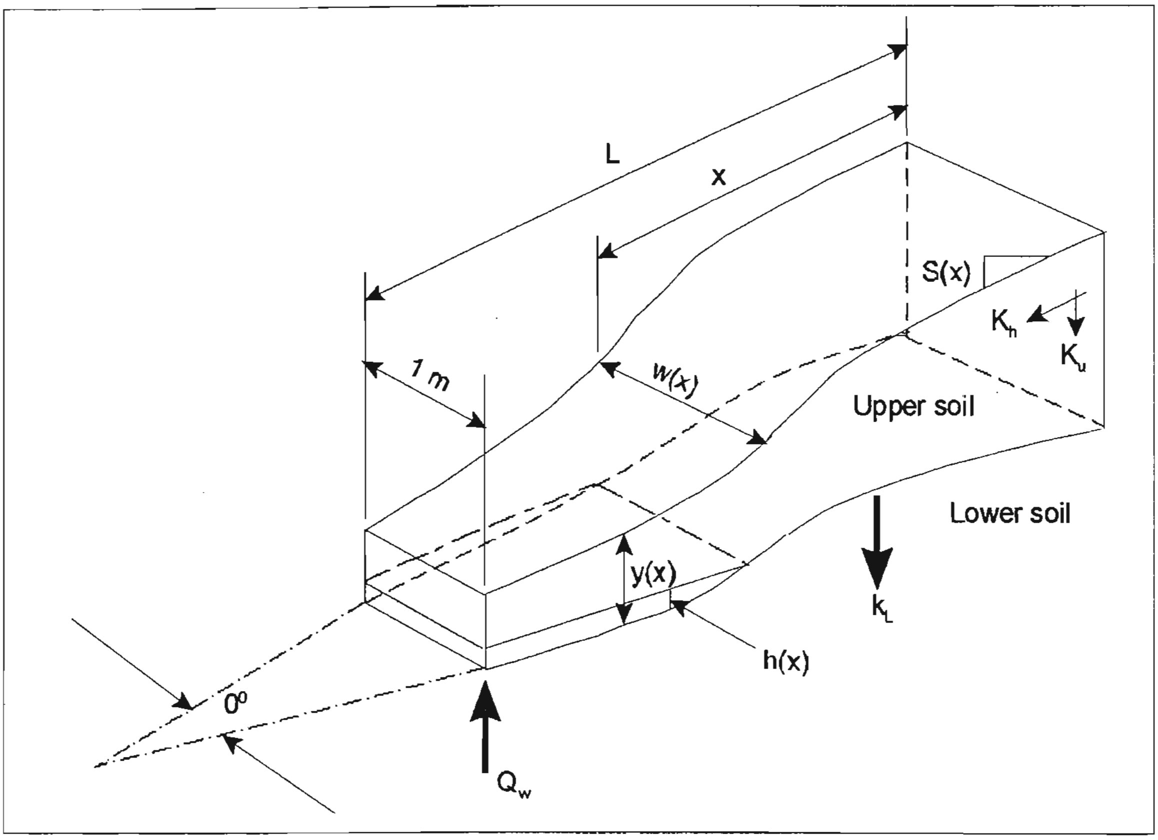


Figure 4.1 Hillslope section as simulated by the *HILLS* model (Hebbert and Smith,1996)

The movement of water in the upper soil layer is divided into two components, namely the saturated and the unsaturated zones where h(x) is the depth of the saturated zone at the foot of the wedge (m), K_u, K_h and are the vertical and horizontal conductivities respectively and K_L is the leakage rate from the base (m.h^{-1}), L the length of the hillslope section (m), x the number of segments the hillslope is divided into, $S_{(x)}$ the segment slope (%) and Q(w) the leakage flux (m.h^{-1}).

4.2 The Unsaturated Zone

The water in the unsaturated zone is assumed to move only in the vertical direction and is estimated using the Richards (1954) equation, together with a source/sink term:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial \theta}{\partial z} - K(\theta) \right] - e(z,t) \qquad \textbf{(4.1)}$$

where θ is the volumetric soil moisture content (m ^{3}.m^{-3}), t is the time (h), z is the distance below the soil surface (mm) and K(θ) is the unsaturated vertical hydraulic conductivity (mm.h^{-1}), D(θ) is soil water diffusivity (mm^2.h^{-1}) and e is a sink term (m ^{3}.m^{-3}.h^{-1}).

The total flux of soil water varies in response to different rainfall intensities. High rainfall intensities where the intensity, i, is greater than the saturated vertical hydraulic conductivity, K_u ($i >> K_u$) the diffusive properties of the soil dominate and analytical infiltration approximations are used to describe the division between overland flow and infiltration. Conversely, if $i < K_u$ the rainfall will infiltrate the soil and the unsaturated flow will be calculated accordingly.

Figure 4.2 shows a schematic flow diagram of the *HILLS* model, showing the sequencing of the model operation.

4.3 Flow in the Saturated Zone

Saturated flow occurs when the vertical unsaturated flux arrives at the interface between the upper and lower soil layers at a flux greater than the saturated hydraulic conductivity of the lower layer, therefore resulting in a perched or localised water table. The lateral flow of this surface is assumed to be parallel to the interface of this layer and the Dupuit approximation of Darcy's Law may be applied to calculate the saturated flow within the soil, as shown in:

$$Q(x,t) = K_h\left[\left(H(x,t) + c_f\right)\left[\sin\gamma - \cos\gamma \frac{\partial H(x,t)}{\partial x}\right]\right] \quad \textbf{(4.2)}$$

where Q(x,t) is the horizontal flux per unit width (mm.h^{-1}), K_h is the horizontal hydraulic conductivity (mm.h^{-1}), γ is the local soil interface slope (%), H(x,t) is the depth of the saturated flow normal to the interface and c_f is the capillary fringe height (mm).

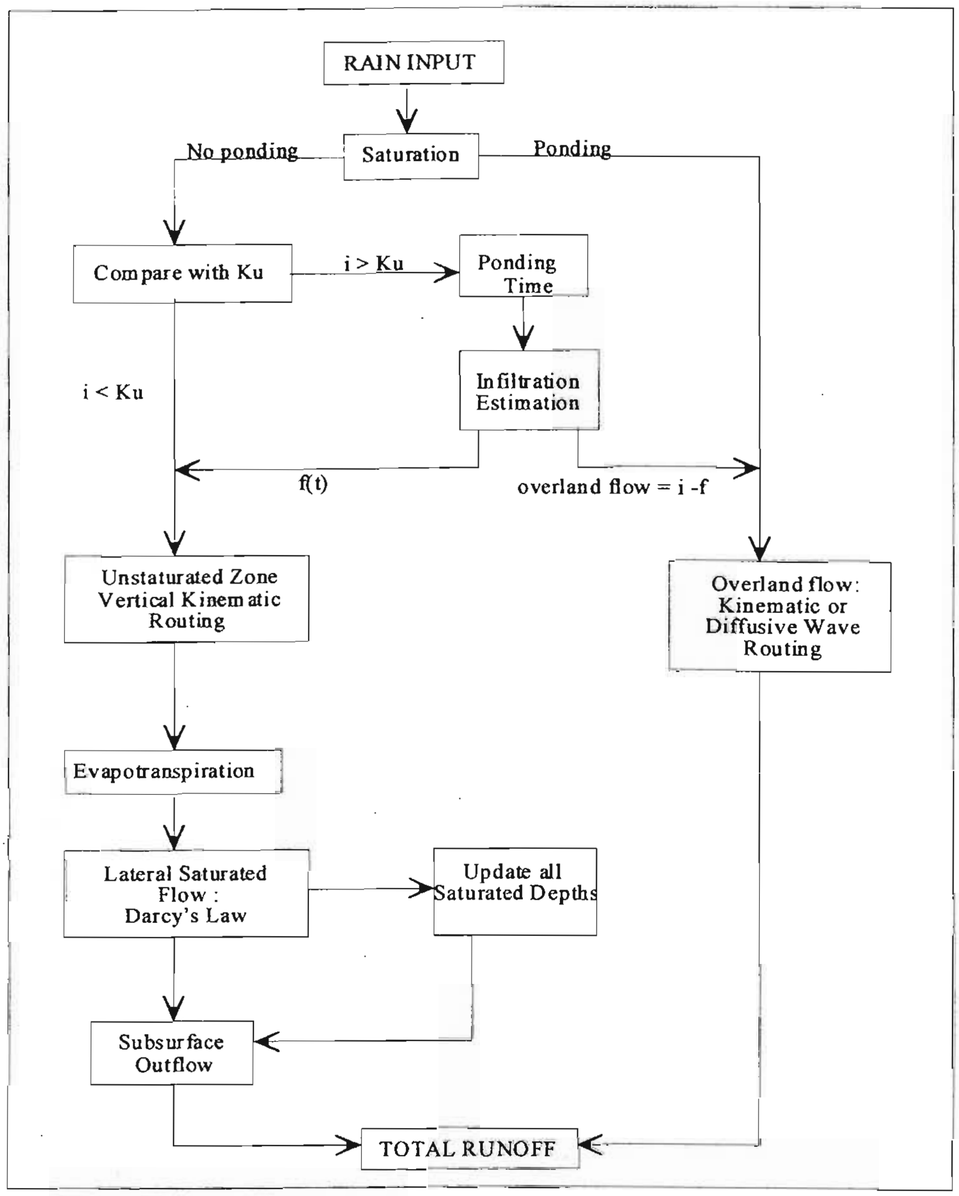


Figure 4.2 Flow diagram of *HILLS* program logic (after Hebbert and Smith, 1996)

The net slope of the phreatic surface is given by the term in the inner square bracket, where $\sin\gamma$ is the slope of the subsoil interface and $\partial H/\partial x$ is the slope of the phreatic surface relative to the subsoil interface.

The lower layer (or subsoil) below the interface is assumed to be a relative impervious zone whose vertical flux does not change significantly relative to the dynamic behaviour of the perched water table above it. Since the hydraulic conductivity of the lower layer may vary down the slope, the user must input the hydraulic conductivities of the up slope boundary (where x = 0) and the downslope (or stream) boundary (x = L). The latter may be a negative conductivity, which represents an upflow or seepage condition near the stream. Two other intermediate points may be entered between these two points and the hydraulic conductivity of the lower soil is calculated using linear interpolation.

Overland flow occurs as a result of two possible processes. The first is described as Hortonian runoff which occurs when the rainfall intensity exceeds the infiltration capacity at the upper soil surface. The second is referred to as saturation runoff which occurs when the perched aquifer or groundwater in the surface soil intersects the surface forming a saturated, directly contributing area (Smith and Hebbert, 1996). A kinematic wave approximation is used to route overland flow over the soil surface. This combines a mass conservation relation and a Manning type friction relation to give:

$$\frac{\partial a}{\partial t} + C_X bpR^{b-1}\frac{\partial R}{\partial x} = w(x)(i - f) \qquad \textbf{(4.3)}$$

where C is $M_n\sqrt{S_o}$, with M_n being the Manning roughness coefficient and S_o is the hillslope surface slope (%), a is the cross sectional overland flow area (m^2), R is the hydraulic radius (m), p the wetted perimeter (m), w is the local section width (m), b is the hydraulic exponent and i-f the rainfall excess (mm).

Evapotranspiration and salt transport routines are also available in the model, but are left out of this discussion since short duration events are to be simulated where evapotranspiration is inconsequential and no salt transport simulations were required. A full description can be found in Smith and Hebbert (1996).

The *HILLS* model weakness, according to Hebbert and Smith (1996), is that the soil physical parameters such as porosity and hydraulic conductivities are only specified for one site and thus may not be representative of a complex catchment with a high degree of spatial variation of soil properties.

This chapter has described the physically based *HILLS* model which was used to simulate the subsurface processes at the Weatherley experimental catchment in a prelimary modelling exercise. Results from the simulations are presented in section 6.2.

Before any meaningful modelling can take place, physical properties and parameters of the catchment in question as well as subsurface process dynamics also need to be determined by simple interpretations of the observed results for use in the model. The following chapter discusses the fieldwork and monitoring networks at the Weatherley experimental catchment and how they were used in determining the complex processes that exist.

5. DETERMINING SUBSURFACE PROCESSES AND RUNOFF AT THE WEATHERLEY CATCHMENT

The previous chapter discussed the physically based *HILLS* model that was selected to be used in the initial catchment modelling exercise at Weatherley. Physically based models such as the *HILLS* model use parameters that have a physical meaning and can be derived from field measurements and experiments. In order to determine the important hillslope parameters prior to the use of the *HILLS* model, as well as understand the hillslope processes and link them and their influence on runoff characteristics, a detailed monitoring network was set up at the Weatherley research catchment in the Northern Eastern Cape Province of South Africa with the following objectives in mind:

- Instrument the entire catchment area along three hillslope transects with automated equipment in order to be able to monitor the dynamics of these hillslopes.
- Determine soil characteristics at strategically selected sites along the transects in order to identify subsurface processes.
- Gain a clear understanding of these processes and answer questions as to the influence of hillslope processes on runoff.
- Use this understanding of the catchment's dynamics to attempt a prelimary modelling exercise of the runoff at the Weatherley research catchment using information on the subsurface processes.

5.1 The Weatherley Research Catchment

The Weatherley research catchment is located approximately 5 km south west of Maclear in the northern Eastern Cape Province (31^{0}06'00"S, 28^{0}20'10"E). It has an average altitude of 1 300 m a.m.s.l. Weatherley is considered to be in a marginal rainfall region for forest production with a mean annual precipitation of 750 mm (Esprey, 1997). Daily average temperatures range from 8 °C to 20 °C. Frosts are severe and snow falls in winter.

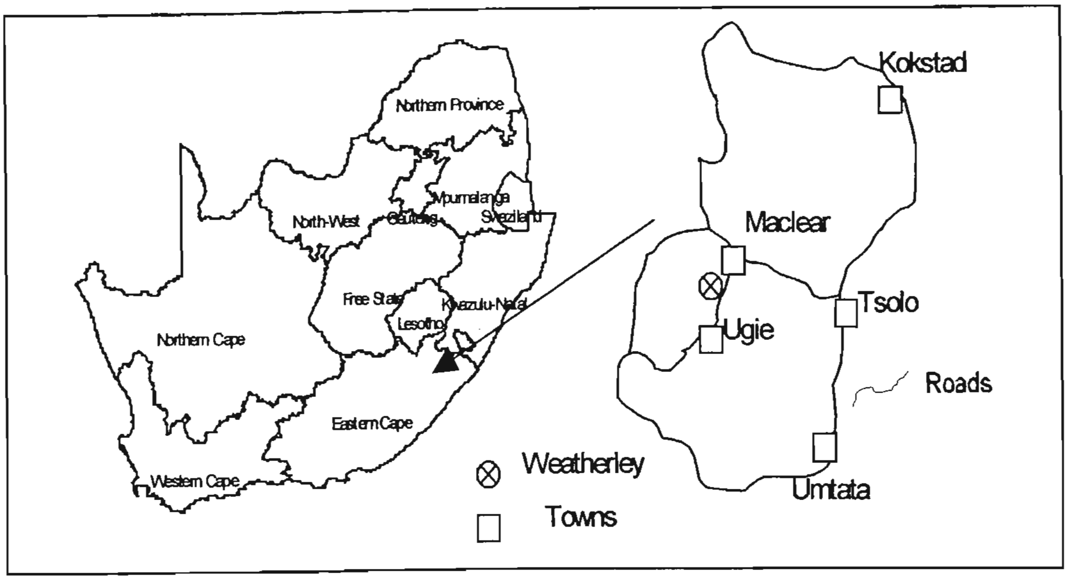


Figure 5.1 Location of the Weatherley catchment in the northern Eastern Cape Province

Climatic information for the Weatherley catchment is summarized in Table 5.1 below.

Table 5.1 Climatic information recorded at the Weatherley research catchment

Month	Rainfall (mm)	A-Pan (mm.month^{-1})	Monthly Mean of Daily Temperature (°C)		
			Maximum	Minimum	Average
January	122.5	142.6	25.2	13.9	19.6
February	119.6	128.8	25.2	14.0	19.6
March	107.5	130.2	23.7	12.1	17.9
April	42.8	102.0	24.1	10.7	17.5
May	18.2	102.3	21.2	7.2	14.2
June	10.9	90.0	17.9	3.8	10.9
July	11.2	96.1	18.6	3.8	11.2
August	18.2	117.8	18.7	5.6	11.2
September	34.5	132.0	20.9	7.7	14.3
October	61.5	139.5	20.7	9.8	15.3
November	83.3	165.0	24.4	11.6	18.1
December	109.4	142.6	24.3	13.2	18.8
Total	739.6	1488.3			

Table 5.2 shows a brief history of work and research that has previously been carried out at the Weatherley catchment.

Table 5.2 A brief history of research at the Weatherley catchment.

Date	**Description**	**Researcher/Personel**
1995 August	Neutron Probe profiles 1-29 established at various points in the catchment.	School of Bioresources Engineering & Environmental Hydrology (SBEEH)
September	Soil survey.	Mr V.Roberts & Mr M.Hensley (ISCW)
October	Installation of rain gauge at nest 1.	SBEEH
1996 February	Luke Esprey begins MSc.	
June	Hydraulic property measurements at nests 1-4.	Luke Esprey
July	Hydraulic property measurements at nests 8-10 begins.	Luke Esprey
August	Soil survey & ground penetrating radar reports complete (nests 1-4).	Mr V.Roberts & Mr M.Hensley (ISCW)
September	Installation of ISCW weather stations at the upslope & downslope weirs.	Luke Esprey
December	Installation of piezometers and tensiometers, nests 1-4.	Luke Esprey
1997 January	Instensive monitoring period 1: manual monitoring of tensiometers & piezometers.	Luke Esprey
February	Automation of tensiometers nests 1-4.	Luke Esprey
September	Construction of weirs begins.	SBEEH
December	Upslope & downslope weirs commissioned & instrumented.	SBEEH
1998 January	Installation of automated tensiometers & piezometers, nests 5-10.	SBEEH/Rory Hickson
February	Rory Hickson begins MSc.	

The land cover at Weatherley is predominantly Highlands Sourveld grassland (Acocks, 1975) which is in moderate hydrological condition, i.e. has a basal cover of 50-75% on the hillslopes (Esprey, 1997).

A monitoring network comprising tensiometers, piezometers, neutron probe access tubes, runoff weirs and weather stations was set up in the Weatherley research catchment. Figure 5.2 shows the locations of these instruments along the three main hillslope transects of the catchment. The motivation behind the positioning of the instruments can be attributed to the fact that three main topographically influenced transects were identified within the catchment. The catchment drains in a northerly direction and the contributing hillslopes are divided longitudinally into two sections, separated by a Molteno outcrop. It was envisaged that by positioning the monitoring instruments along these main transects, a clear understanding of the catchments processes as a whole could be observed by linking the results of the individual transects.

A selection of the results of an extensive soil survey are presented in Figure 5.3. The different horizons for transect 1 obtained from the detailed soil survey done by Roberts *et al.* (1996). The survey reveals a variety of different soil horizons on top of semi-impervious saprolite layers above the bedrock at Weatherley. The extensive marsh area between nest 6 and the stream is clearly visible. Although the marsh area does not extend up to nest 5 on the Eastern slope nor nest 8 on the Western slopes, field observations reveal that these soils are often a state of saturation, especially during the wet summer months.

A very complex soil system exists with a high spatial distribution of soil types (Roberts *et al.,* 1996). A detailed soil survey was carried out by the Institute for Soil, Climate and Water (ISCW), identifying 16 different soil forms within the 1.5 km^2 catchment boundary. These soils display varying degrees of wetness and colour and include red and yellow apedal mesotrophic soils as well as neocutanic and hydromorphic soils. The western slope of the catchment, (Figure 5.2), is dominated by brown to dark reddish brown Hutton form with sandy loam soils at the surface and sandy clay loam subsurface soil.

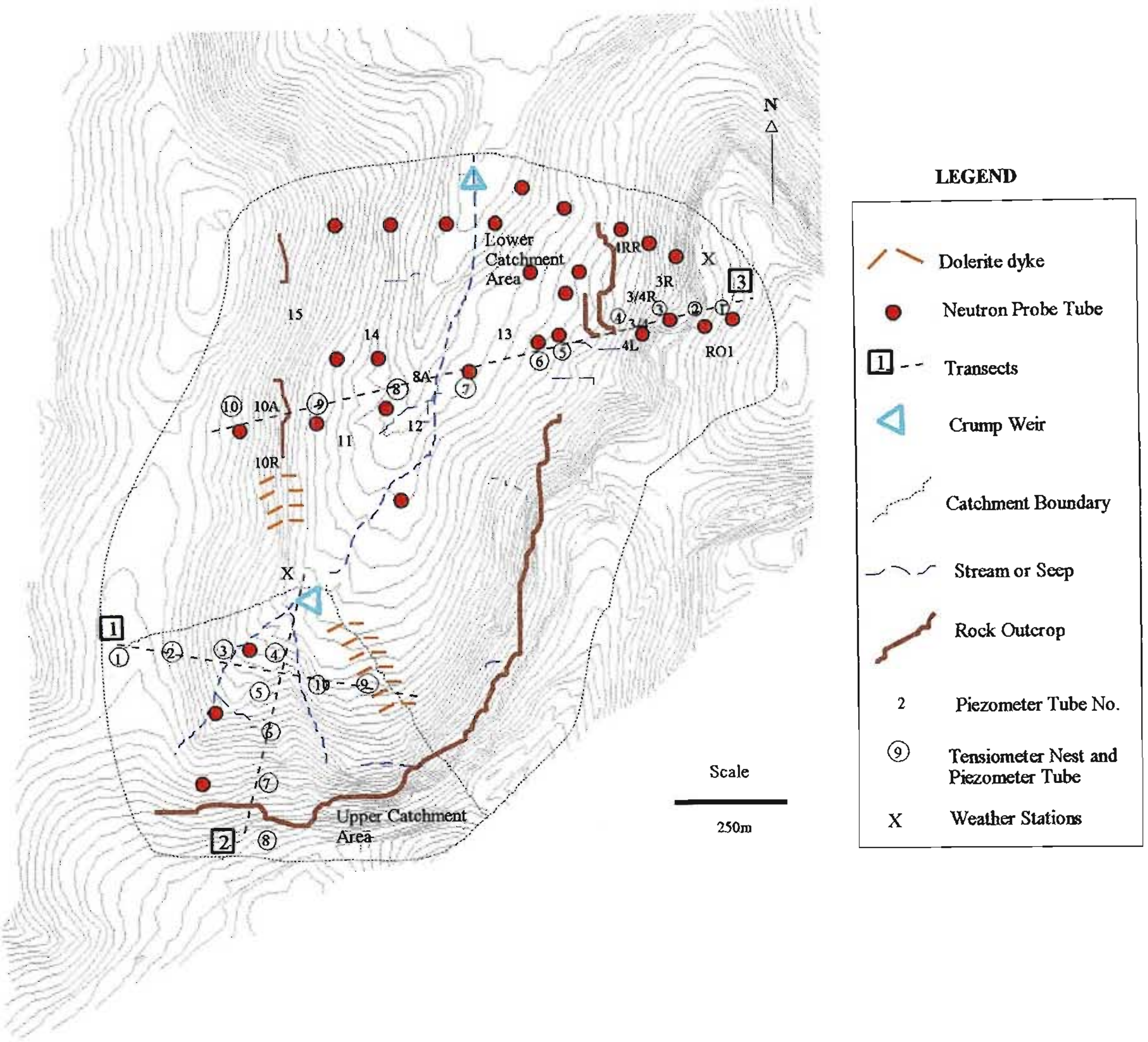


Figure 5.2 The Weatherley research catchment showing positions of instrumentation along the three main hillslope transects marked 1, 2 and 3.

Clovelly form is also encounted with bleached loamy sand and sandy loam topsoils overlying brown sandy loam subsoils. In areas where the bedrock is found close to the surface, well-drained soils with unconsolidated material are found. The eastern slope of the catchment shows a greater variation of soil forms ranging from the dominatly Kroonstad form to Katspruit, Westleigh, Oakleigh and Tukula forms. Large areas of shallow lithosols with bleached sandy loam surface soils and bare rock are found. The marsh soils are mainly Kroonstad form.

A geological survey was conducted by Esprey (1997). The geology of the area is described as predominantly mudstone shale and sandstone of the Molteno formation, as well mudstone and sandstone from the Elliot formation. There are two prominent dolerite dykes that transect the area running north to south on the western side of the catchment and north-east to south-west on the eastern side of the catchment (Roberts *et al.,* 1996).

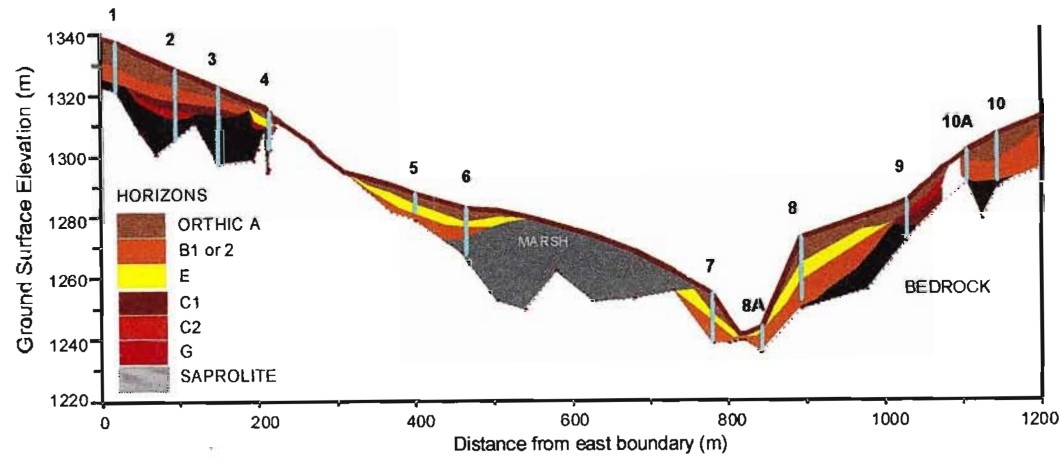


Figure 5.3 Soil survey of transect 1

5.2 Soil Characteristics

Subsurface fluxes are dependent on the soil's water retention characteristics and hydraulic conductivity characteristics of the soil. In order to determine the subsurface water fluxes and understand how the hillslope affects them, the soil's physical and hydraulic characteristics need to be determined. Since these methods are both time consuming and expensive, tests were only carried out at representative selected sites along the hillslope transects. The methods used to determine soil physical properties and hydraulic characteristics are similar to those used by Esprey (1997) and are discussed briefly in sections 5.2.1 and 5.2.2 below.

5.2.1 Soil Physical Properties

Esprey (1997) highlighted the fact that there are many methods to estimate soil physical properties. Bulk density, which is defined by Rawls *et al.* (1992) as the ratio of the weight of dry solids to the bulk volume (volume of solids and volume of pore spaces) of the soil, was determined using the corer method. This method entailed removing an undisturbed core sample of soil from the profile and determining its mass after oven drying it for 24 hours. The volume of the sample was then calculated from the size of the core and the bulk density determined from:

$$\rho_b = \frac{M_s}{V_t} \tag{5.1}$$

where ρ_b is the bulk density (kg.m^{-3}), M_s is the mass of the soil (kg), and V_t is the total volume (m^3).

Soil porosity (the total volume occupied by pores per unit volume of soil) is calculated from the bulk density and particle density, which normally has a value of 2 650 kg.m^{-3} (Rawls *et al.*, 1992), as

$$\phi = 1 - \frac{\rho_b}{2650} \tag{5.2}$$

where ϕ is the total porosity (volume), ρ_b the bulk density (kg.m^{-3}) and 2650 the particle density (kg.m^{-3}).

These properties yield information regarding how the water flux is likely to respond in soils with different physical properties. For example, as bulk density increases, water retention and hydraulic conductivity near saturation decreases (Rawls *et al.*, 1992). Soil organic matter (which is usually present in wetland/marsh areas) results in an increase in total water retention due to there being more pore spaces in the soils.

5.2.2 Soil Hydraulic Characteristics

The hydraulic properties of the soil give an indication of the rates at which water can move through the soil and the water retention capacities at different matric pressures. As with soil physical properties, there are a number of different methods to estimate the soil hydraulic properties and these are outlined in Esprey (1997).

Soils hydraulic conductivity (K) is defined by Rawls *et al.* (1992) as the measurement of the soil's ability to transmit water and is dependent on both the properties of the soil (total porosity and pore size distribution) and the fluid (density and viscosity). The conductivity of a soil is divided into the saturated (K_s) conductivity and unsaturated ($K(\theta)$) conductivity. K is a non-linear function of soil water content, and varies with the texture of the soil (a higher K_s exists at saturation for sandy soils than clay soils), and decreases as the water content of the soil decreases.

In order to determine the hydraulic conductivity at Weatherley, numerous *in situ* tests were conducted using tension infiltrometers and double ring infiltrometers developed at the School of Bioresources Engineering and Environmental Hydrology (SBEEH), formerly the Department of Agricultural Engineering (DAE). Tests were conducted at four different levels on and below the surface (surface, 0.2 m, 0.5 m, 2 m). Like the physical properties, these tests were time consuming and were only conducted at selected nests in the catchment. A full description of the infiltrometers can be found in Thornton-Dibb and Lorentz (2000).

Since the marsh area at Weatherley is extensive, it is common for the groundwater table to exist near the surface. Where this occurs, infiltrometer tests could not be carried out and the auger hole method was used to determine the saturated hydraulic conductivity (Amoozegar and Warrick, 1986). This test entailed removing water from a piezometer to a predetermined level and recording the rate of change of groundwater level height.

The equation used to determine the saturated hydraulic conductivity is given as (Amoozegar and Warrick, 1986)

$$K = \frac{4.63r^2 \Delta y}{y(He + 20r)\left(2 - \frac{y}{He}\right)\Delta t} \qquad \textbf{(5.3)}$$

where K is the hydraulic conductivity (mm.h^{-1}), r is the radius of the hole, He is the depth of the groundwater hole (mm), y is the difference between the groundwater and the depth of the hole and $\Delta y/\Delta t$ is the rate of change of y (mm.h^{-1}).

A soil's water retention characteristic (WRC) is an indication of the soil's ability to store and release water and is defined as the relationship between soil water content and matric potential (Rawls *et al.*, 1992). WRC data are presented together with a curve fitting procedure where Brooks and Corey (1964) functions are fitted to the actual data. From the procedure, properties such as pore size distribution, bulk density and porosity can be determined indirectly.

The controlled outflow method was used to determine the WRC of the Weatherley soils. This method was developed at Colorado State University, U.S.A (Lorentz *et al.*, 1991) and entailed placing a core sample of saturated soil in a closed chamber and applying air pressure to the chamber. The capillary pressure at a fixed saturation was then determined.

Results of the soil's hydraulic characteristics are presented in Chapter 6. The following subsection describes the instrumentation that was used in the monitoring network at the Weatherley catchment. It also describes two specific experiments (controlled tensiometry and a pilot tracer study). The controlled tensiometry experiment was performed to allow for a better understanding of the factors that affect the tensiometers in the field and the tracer study to provide an insight into the subsurface fluxes at Weatherley.

5.3 Field Monitoring

Past research at Weatherley by Esprey (*cf.* Table 5.2) included the installation the tensiometers and piezometers in the lower catchment at nests 1 to 4, as well as the establishment of the neutron probe network during 1995. The two crump weirs were constructed in November 1997 and runoff measurements began in January 1998. Nests 5 to 10 in the lower catchment and nests 1 to 10 in the upper catchment as well as the piezometer network were installed at various stages during 1998. The extensive monitoring network was maintained during monthly field trips. Maintenance included downloading data from the automated equipment (tensiometers, piezometers, raingauges and crump weirs), replacing batteries, replenishing tensiometers, taking groundwater level readings and general repairs to any suspect equipment. Neutron probe readings were conducted on a two week basis, however due to problems involving obtaining the data and the fact the only a few tubes in the lower catchment were in the vicinity of the hillslope transect, the data were omitted from this study. A brief description of equipment and installation follows.

5.3.1 Tensiometers

In total 20 tensiometer nests were installed at Weatherley. Each nest consisted of 1 to 4 tensiometers at different depths in the soil. The tensiometers installed were developed by the SBEEH and were an improved version of those installed by Esprey (1997). Figure 5.4 shows the two different tensiometers. The reason for the new version being developed was simply to automate the tensiometers as well as make them more robust and easier to install at different depths within the catchment. The older version was constructed with perspex tubing and had a fragile U tube which was connected to the transducer. This U tube was very brittle and broke easily, especially in cold weather conditions (Esprey, 2000). Installation was therefore difficult as the tensiometers had to be made up in the workshop to a pre-determined length and transported carefully to the field. The entire tube needed to be filled with de-aired water and sealed. This proved to be time consuming as air would often enter the tensiometer through faulty joins or cracks and there was no way to check for leaks. In addition, the cost involved in constructing the older version was considerably higher than the new version.

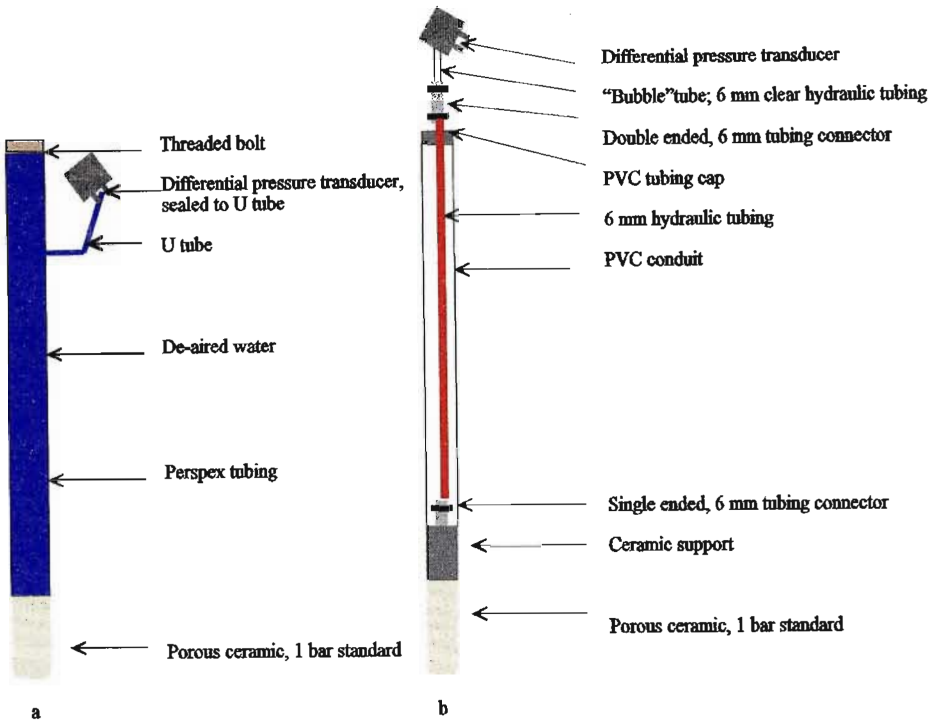


Figure 5.4 Tensiometers developed by the University of Natal, School of Bioresources Engineering and Environmental Hydrology (former Department of Agricultural Engineeering). (a) The older version and (b), the recently improved version

Advantages associated with the new version are that the tensiometer can be assembled in the field. All components are separate during transport and only the ceramics need to be attached to the ceramic support in the laboratory. Once in the field, the location and depth of the tensiometer needs to be determined. The PVC conduit is then cut to its desired length and the ceramic support glued into the conduit with tensol, a high strength PVC cement. Hydraulic tubing is then attached to the ceramic via a one way connector and threaded through the conduit. A PVC cap is used to seal the conduit at the opposite end and a two-way connector attached to the protruding hydraulic tubing. The negative port of the transducer is then connected to the other end of the connector with clear hydraulic tubing. Apart from being easily to assemble, it is also less fragile than the older version. This makes installation to depths as deep as 2 m a relatively simple task involving auguring a 25 mm hole, adding a diatomaceous powder mix (which acts as a "contact" between the ceramic and soil) to the bottom of the hole and the ceramic and inserting the tensiometer. The amount of de-aired water used in the new version was considerably less than that used by the old version, thus allowing for more accurate readings due to fewer minute air bubbles which appear to form in the water when pressures are reduced in the tensiometer.

The tensiometer is then connected to a Motorola MPX5100 differential pressure transducer. The transducer has positive and negative pressure ports. The negative pressure port is connected to the tensiometer via the clear hydraulic tubing and the positive port is left open to atmospheric pressure. The transducer has a temperature compensated silicone diaphragm that responds to differential pressure changes across the ports and is not influenced by temperature changes during operation. The transducer voltage signals are then recorded on a logger and are converted to matric pressures in a spreadsheet by means of calibrations. A detailed description of the transducer, its specifications and calibration methods can be found in Esprey (1997).

The logging systems at Weatherley were set to record data at twelve minute intervals throughout both the wet and dry season. The logger is powered by a 6 V battery which is replaced on a monthly basis during field visits. A laptop computer is used to download data from the logger in the field, thus allowing for the continuous logging of data without having to remove the loggers. The loggers proved to be robust and reliable, however, they were somewhat sensitive to moisture and needed to be placed in weather proof housing. A detailed description of the loggers and their specifications can be found in Esprey (1997).

5.3.2 Controlled Tensiometry Experiment

In order to analyse the accuracy of the tensiometers, especially with regard to different amounts of water in the bubble tubes as well as the effect of temperature on the tensiometers, a series of controlled tensiometry experiments were conducted.

Two drums of equal size were filled with a sandy soil of the same type. Before packing the drum with equal densities of soils, the soils were mixed and left to dry in the open for 24 hours to ensure that each drum had the same soil moisture content. Three tensiometers of equal length were placed at the same depth in each of the drums with different amounts of water in the bubble tubes. One bubble tube was left full of water, the second half full and the third almost empty. One of the drums was placed outdoors at the University of Natal's Ukulinga research farm, with a control tensiometer in the soil next to it. The other drum was placed in a temperature-controlled laboratory at approximately 25 °C. The data were then collected and the different sets compared to each other to assess the influence of temperature and air in the bubble tubes on the tensiometry data. Results of this experiment are shown in Chapter 6.

5.3.3 Piezometers

In order to obtain a true representation of the groundwater in an aquifer, a monitoring well is required (ASTM standards, 1994). Groundwater monitoring allows for accurate monitoring of the groundwaters fluxes, which yield valuable information regarding subsurface processes on a hillslope and their related runoff characteristics. For these reasons a comprehensive piezometer network was installed at Weatherley (*cf.* Figure 5.3) to aid the understanding of hillslope subsurface dynamics and monitor the fluxes of the marshy areas that exist in the valley of the catchment.

The piezometers were constructed using 50 mm diameter PVC pipes. These pipes were machine slotted with fine slits over the entire length of the tube to allow water to enter and exit the pipe freely from the surrounding soil. The tube base was sealed as well as slots near the ground surface to prevent any runoff water from entering the tube. Using a hand auger, the depth to the bedrock was determined. The piezometer tube was then cut to the desired length which was usually to the bedrock or a few centimetres above the bedrock unless saturated conditions were prevalent. A 100 mm diameter bucket auger was then used to bore a hole to the desired depth. Upon inserting the piezometer into the hole, coarse Umgeni sand was used to pack the area surrounding the tube and prevent the slots from becoming clogged with fine sediments, hence hampering the free flow of water.

Measurements from the piezometers were carried out using a dip-meter. It consisted of a battery, cable sensor and sounding device with a light. As soon as contact with the water was made, an LED and beeper were activated. Readings were taken manually.

Automated piezometers were installed at selected nests in the lower catchment along transect 3 during December 1998. These piezometers consisted of a Motorola MPX5050 low pressure transducer similar to the ones used in the tensiometers. The transducer was placed in a weighted PVC end cap and sealed to ensure no water entered the transducer. The positive pressure port was filled with water and left open, while a clear tube was fixed to the negative port. The weighted end cap and transducer were then lowered into the piezometer tube, making sure that the clear tubing attached to the negative port was free of any water and open to atmospheric pressure at the surface to allow for the differential pressure readings at the bottom of the tube (Figure 5.5). The transducer was then attached to the same four channel logger used for the tensiometers. The transducer was calibrated by taking the voltage readings resulting from applying a column of water at different heights to the pressure transducer. Regression equations for each transducer were developed in a spreadsheet. Figure 5.5 shows a sketch of the automated piezometer and its components.

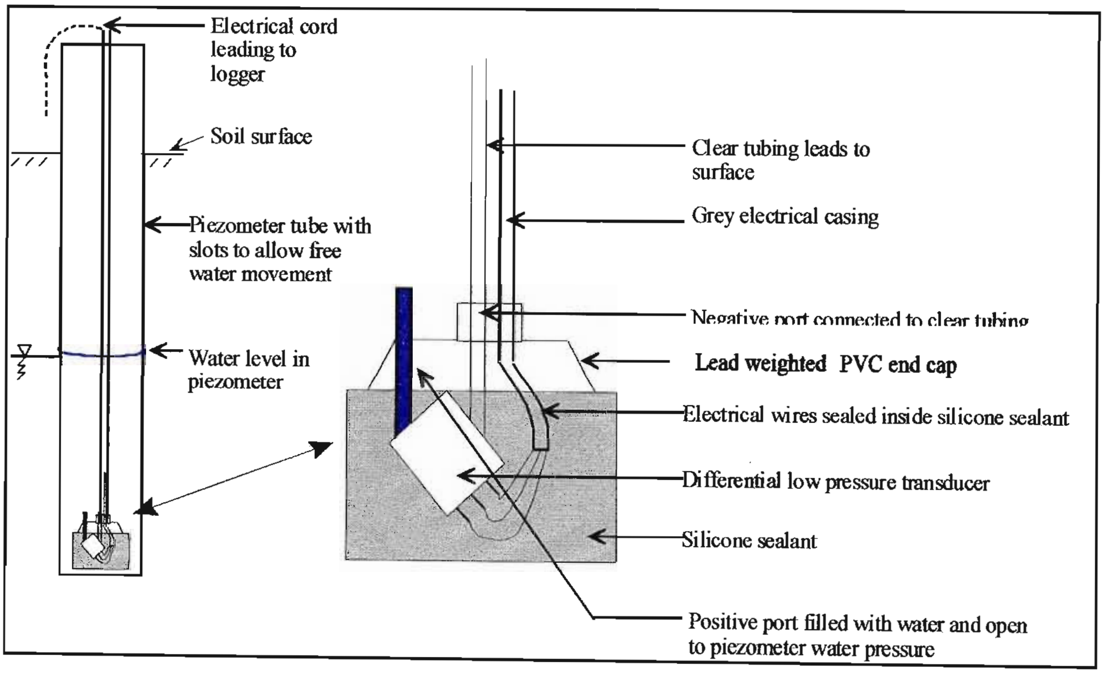


Figure 5.5 Automated piezometer and its components

These automated piezometers could only be placed in the vicinity of existing tensiometer nests due to the lack of loggers. After the automation of selected piezometers, manual readings with the dip-meter were still conducted on a monthly basis as before.

5.3.4 Runoff Weirs

In order to monitor runoff from the Weatherley catchment, two Crump weirs were constructed in the last quarter of 1997. In general, there are no specific guidelines or rules that govern the design and construction of a weir for measurement purposes. There are however, some important recommendations that need to be considered before selecting a site. These include good foundation conditions, an area on the stream with a steeper downstream slope and a relatively flat upstream slope, stable river banks, an area that is not in the vicinity of a river bend or upstream of a bridge and one that allows easy access to the site (van Heerden *et al.*, 1986). In practice a site with all the above conditions is difficult to find and it generally becomes a case of choosing the best gauging method to suit the best available site.

At Weatherley, it was decided to construct a weir in the upslope area of the catchment and one in the downslope area in order to monitor the cummulative effect of different hillslopes responses. The entire stream bed was surveyed and it was proposed that the weir be built so as to avoid any changes in the streamflow characteristics such as excess ponding of water upstream of the weir. In order to ensure minimal disturbance to the streamflow and wetland/stream interaction, the weir needed to be a submerged type. To avoid problems associated with silting up of the weir, a self cleaning type was also desired. For these reasons, the Crump design with a flat V-notch was selected for Weatherley. Figure 5.6 shows the comparisons of streamlines over the Crump weir as opposed to sharp crested weirs.

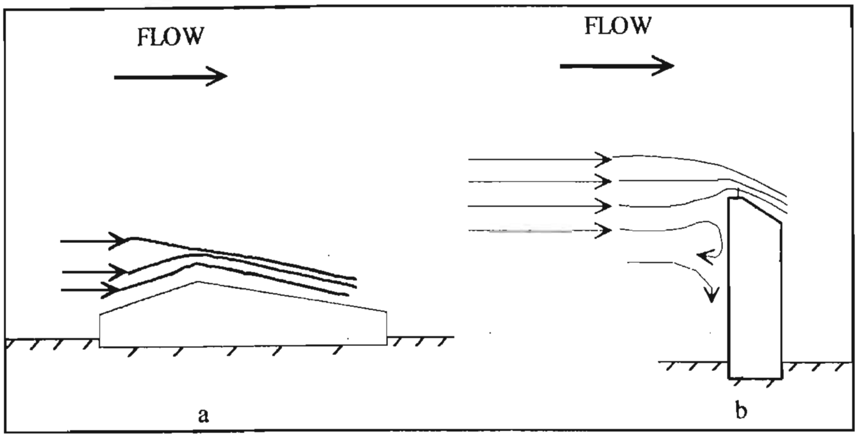


Figure 5.6 Streamline comparison between (a) a Crump design and (b) a sharp crested design.

Streamlines over a Crump weir as seen in Figure 5.6 (a) are smooth, resulting in a minimal energy loss in the upstream pool and hence providing sufficient energy to transport sediment over the weir while at the same time maintaining minimal upstream ponding conditions. Figure 5.6 (b) shows that the sharp crested design has more turbulent streamlines which result in a loss of energy at the weir and hence silt is deposited on the upstream pool. It also requires a high profile above the stream bed. Both the upper catchment and lower catchment weirs were automated with MCS loggers which were placed in galvanized steel housing next to the cut off wall on the left bank. Figure 5.7, shows a sketch of the Crump weir design which was used for the upper and lower catchment.

Attached to the MCS automated logger was a MCS-250 ultra low power shaft encoder that was used to convert a mechanical float and counterweight stream level system to a digital signal so that it may be recorded on the logger. A float attached to the shaft encoder is suspended into the stilling well which maintained the same water level as the stream via a 150 mm inlet pipe which is fixed just below the level of the V-notch.

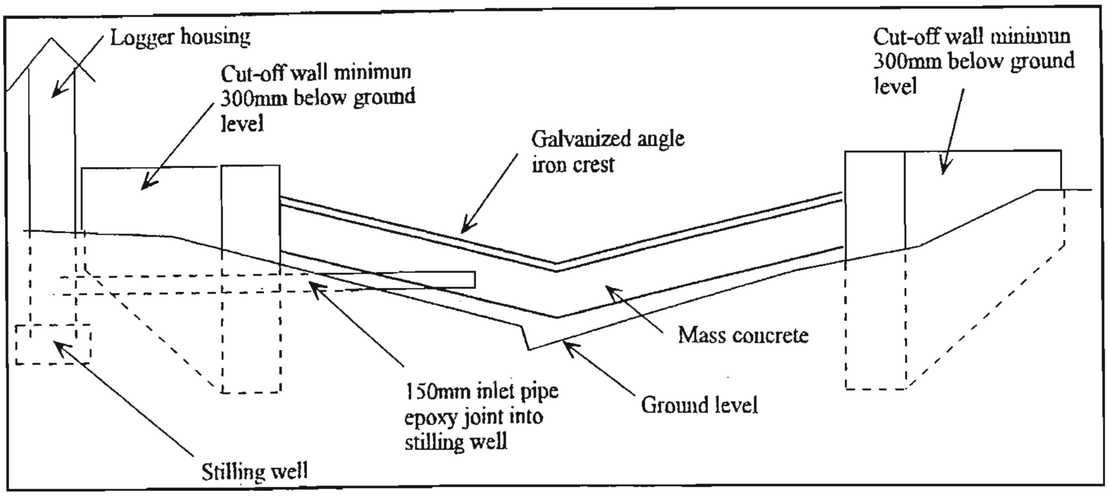


Figure 5.7 Upstream elevation sketch of the Crump weir design used at the Weatherley research catchment (not to scale)

5.3.5 Pilot Tracer Experiment

In order to study the subsurface processes that occur on hillslopes and shed light on subsurface fluxes that occur, a pilot tracer experiment was conducted at Weatherley in the upper catchment. Recent papers by Schultz (1999), Uhlenbrook and Leibundgut (1997), Mehlhorn *et al.* (1995) and Mikovari *et al.* (1995) all highlight the importance of using tracer studies as an aid to understanding subsurface processes and their contribution to runoff. These tracer studies were usually conducted on small hillslope sections of between 10 and 20 m. Artificial rain simulation was also used in order to aid the infiltration of the tracer and to simulated different scenarios. Since the objective of the study was to gain insight into the response of the entire hillslope to rainfall, a much longer section of the hillslope was used at Weatherley. In order to observe the natural effect of the runoff generating mechanisms on the hillslope, no artificial rain was applied during the experiment. Since it was considered difficult to conduct a tracer test with the described objectives in a remote area with low technical infrastructure, this experiment was considered to be low budget pilot experiment with the object of gaining knowledge of how to carry out a tracer test in these conditions

The experiment site was situated in the upper catchment on a grassland hillslope with a slope of 12%. The experiment section extended 62 m upslope from the stream. The soils comprised of deep (2 m) red neocutanic and hydromorphic soils of the Tukulu-Scheepersrus and Longlands-Sherbrook forms (Didszum, 1999).

A 250 g solution of a fluorescent dye tracer, Uranine (fluorescein) was injected 62 m upslope from the stream by means of pouring the tracer into a double rectangular frame of 1.4 m^2 which aided the vertical infiltration of the tracer and prevented overland runoff. The solution was applied at night due to the tracer's sensitivity to sunlight and 50 litres of water sprinkled over the frame to ensure complete infiltration of the tracer. Sampling was conducted by drawing water samples from piezometer tubes placed at 10 m, 20 m and 40 m downslope from the site of injection and were recorded from the piezometers and streamflow at fixed intervals for 22 days after the injection of the tracer. The piezometers were sampled manually while the streamflow samples were done automatically with an I.S.C.O sampler in order to record samples during the night. Rainfall and streamflow were recorded at the upper catchment weir which is in the vicinity of the site.

This chapter has described the methods used to determine the soil characteristics of the Weatherley catchment and the instrumentation used in monitoring the subsurface processes and runoff. Results from the methods described in this chapter as well as results from the initial modelling exercise are now presented in Chapter 6.

6. RESULTS AND DISCUSSIONS

The results from fieldwork and modelling conducted are now presented and analysed. These include results from monitored data (initial tensiometry experiment, runoff, tensiometer data, piezometer data, and results from a pilot tracer study experiment) and soil characteristic data. The soils characteristics data contain data derived from in-field measurements (tension and double ring infiltrometer tests and soil sampling) and from laboratory measurements (bulk densities, porosity and water retention characteristics). The data were collected over a two-year period (February 1998 to February 2000). Soil characteristic data for nests 1-4 in transect 1 (*cf.* Section 4.1) were obtained by Esprey (1997) and are therefore only discussed briefly in this study.

6.1 Fieldwork

Field data were obtained from numerous visits to the catchment throughout the two year study period. These frequent visits to the catchment enabled first-hand observations of the catchment's response to storm events and hence helped understand the complex processes that occur at a hillslope scale. Esprey's (1997) concluding chapter pertaining to the importance of fieldwork in successful hydrological modelling therefore proved to be an invaluable observation.

Soil characteristic data were obtained during two different month long field trips. During the first field trip (November/December 1998), the soil characteristics from the remaining section of transect 1 (nest 5-10) were determined. During the second field trip (July 1999) the upper catchment soil characteristics along transects 2 and 3 were determined. In monitoring the catchment, it was not possible to automate the entire catchment due to equipment requirements and hence some data (for example the piezometer data), were only recorded on a monthly basis as opposed to the continuous readings of the tensiometers and weirs. Results from a pilot tracer study conducted in the upper catchment area during November/December 1998 are presented.

6.1.1 Soil Data Results

A simple interpretation of the Weatherley soils derived from the detailed soil survey conducted by Roberts *et al.* (1996) is shown in Figure 6.1.

There is a high percentage of marshy area which fluctuates seasonally in the low-lying areas of the catchment. The fluctuation occurs at the perimeter of the marsh, with the marsh area receding in the dry months and expanding in the wet months. The western slope appears to be dominated by free drained soils on the crests and midslope while hydromorphic soils appear along the edges of the marsh. Rock outcrops appear in the areas characterised by shallow soils.

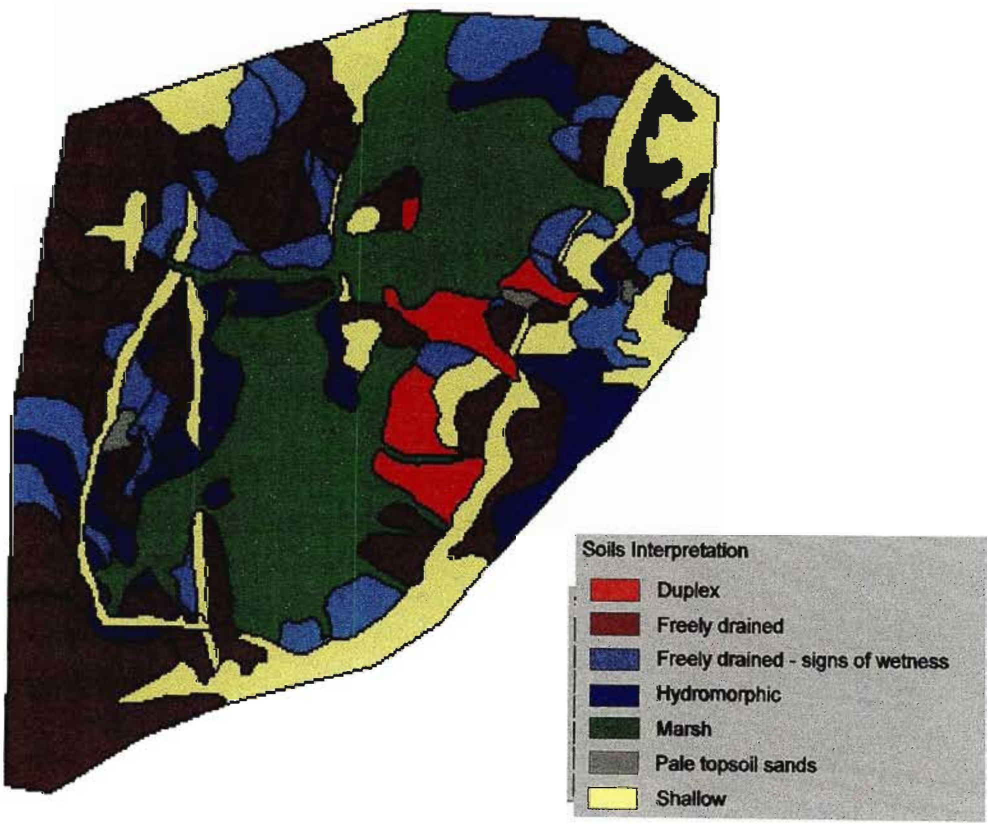


Figure 6.1 Simple interpretation of detailed soil survey map of the Weatherley catchment (ISCW, 2000)

The results from hydraulic conductivities are shown in Appendix C. Water retention characteristic (WRC) data from selected nests are shown in Appendix D. Bulk densities derived from both the corer method and WRC are presented in Appendix E. Soil data results from all the experimentation along the transect 1 to 3 are discussed below.

Transect 1, in the upper catchment, runs from nest UC1 on the crest of the hillslope, down through the stream and up the opposite hillslope to nest UC9 (*cf.* Figure 5.3). Along transect 1 at nest UC1 there appears to be an increased hydraulic conductivity with depth at the crest of the slope as seen by the high conductivities at 0.8 m at both nests UC1 and UC9 in Appendix C. The general trend is that the hydraulic conductivity decreases downslope towards the stream, while the saturated hydraulic conductivity however showed a general increase downslope towards the stream and marshy area. Saturated hydraulic conductivities at the surface and 0.2 m depths of all the nests on transect 1 are generally an order of magnitude higher than the hydraulic conductivities near the bedrock, indicating the presence of macropores in the soil. The bulk density at the crest (nest UC9, 0.8 m) is 1 780 kg.m^{-3} which can be attributed to the high sand content of the soil. The surface bulk density for the marshy area (nests UC4) is lower (1 410 kg.m^{-3}) which generally indicates a higher clay content in the soil. This gives a relatively high porosity value of 0.47 (compared to 0.33 on the crest of the slope) and the soils have a higher water retentions. Figure 6.2 shows the water retention characteristics from observed data with the Brooks and Corey (1964) curve fitted to it.

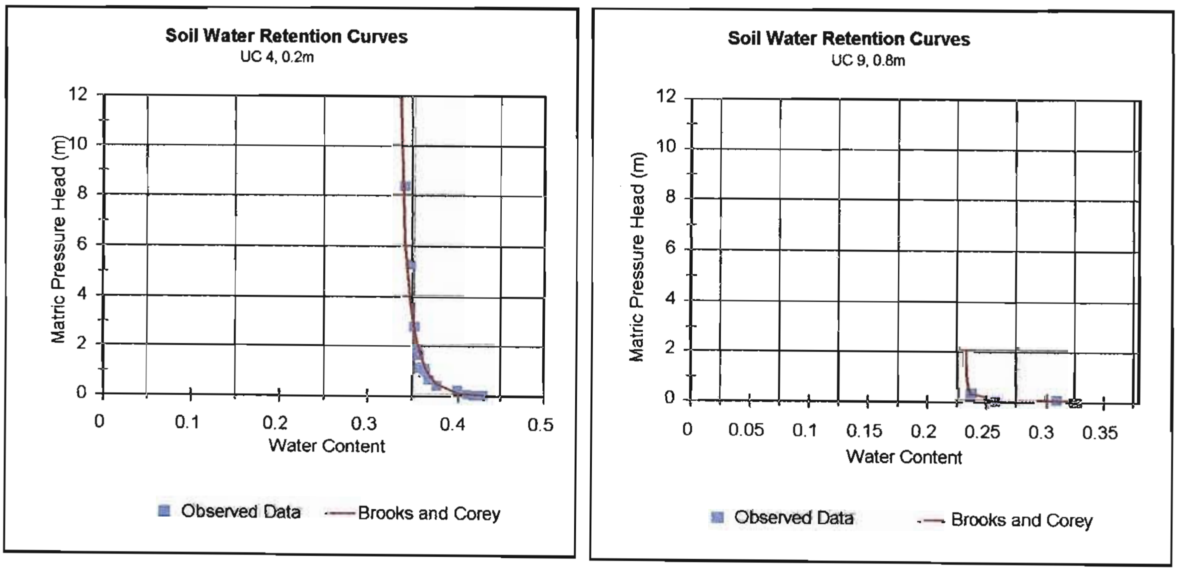


Figure 6.2 Soil water retention characteristic curves (WRC) showing the difference in water retentions observed at the crest of the slope and the toe of the slope.

At nest UC9 at 0.8 m it can be seen that there is a low retentivity as reflected in the low water content at matric pressures up to 2 m. This implies that the soils are drained fairly easily compared to those at nest UC4.

Transect 2, also in the upper catchment area, dissects transect 1, and runs from nest UC8 on the crest of the hillslope down to the weir (*cf.* Figure 5.3). There appears to be a general decrease in hydraulic conductivities downslope towards the weir. The saturated hydraulic conductivity increases downslope. The WRC at nest UC5 (Figure 6.3) shows an increase in the soils water retention with depth.

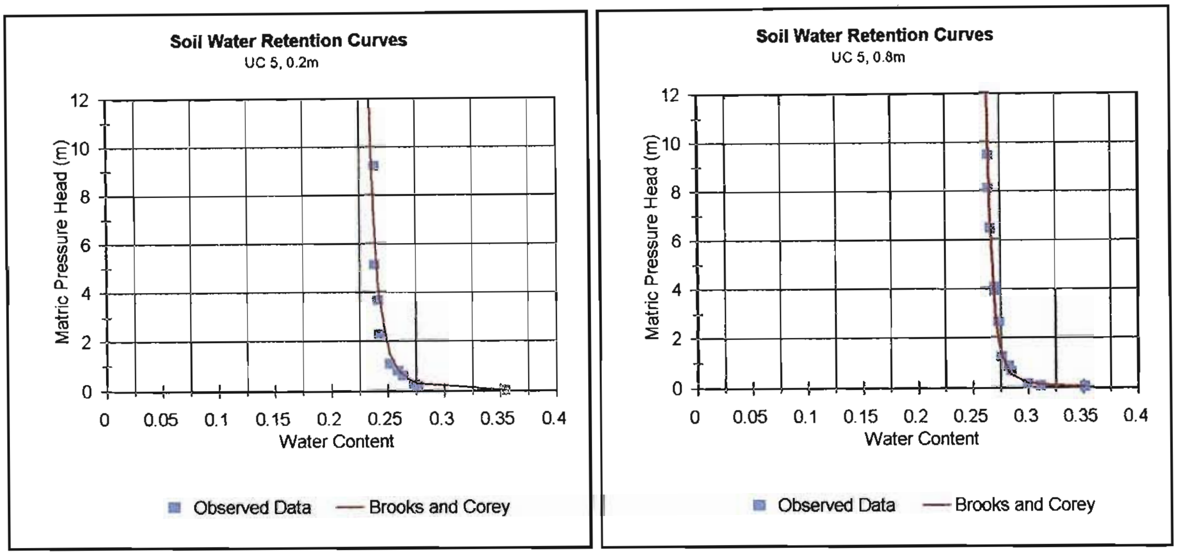


Figure 6.3 WRC at nest UC5 showing an increased retentivity with depth

The hydraulic conductivity at nest UC5 is shown in Figure 6.3 and is lower than on the crest of the hillslope. The graphs tend to show a flat slope with a low hydraulic conductivity, implying a uniform pore size distribution. A high pore size distribution is evident at nests UC8 in Figure 6.4 below, as seen by the steep graph slope between the matric pressure heads relative to that of UC5. The conductivities are also relatively high, indicating freely drained soils at the crest and the midslope with macropores present. These observations agree with the porosity data which generally decrease downslope towards the marsh, indicating that the downslope soils tend to have higher water retentions and are not as free draining as on the crest, as seen in Appendix D.

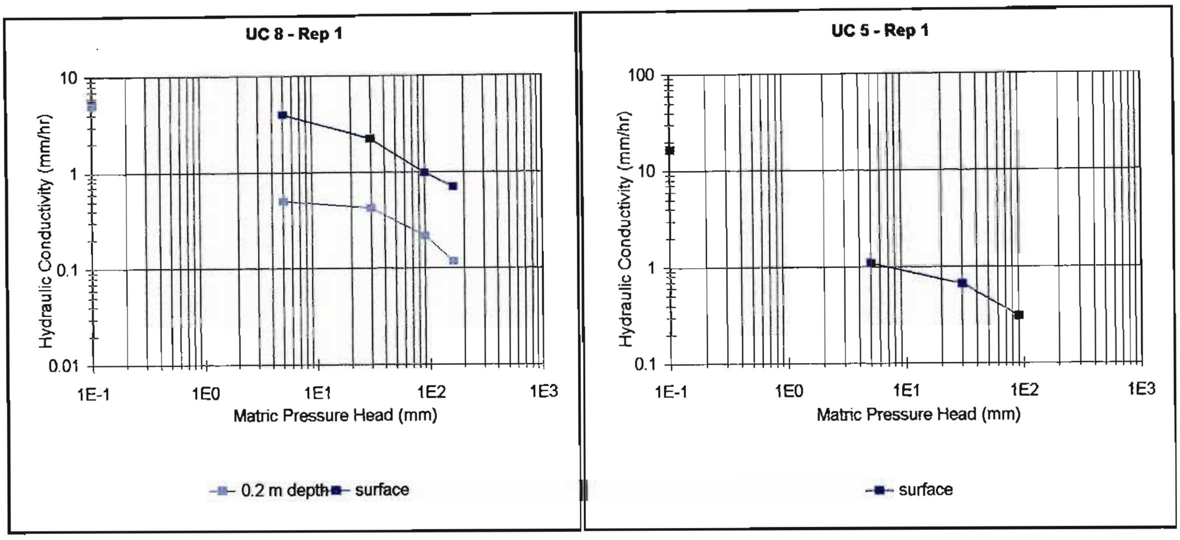


Figure 6.4 Hydraulic conductivities at nests UC8 and UC5

Transect 3, in the lower catchment area, runs from the top of the hillslope at nest 1, down past nest 4 and the Molteno rock outcrop, through the marsh to the stream and not up the opposite hillslope. This is because data have shown that the subsurface processes on the opposite hillslope are similar to those observed on transect 3. The soil's characteristics for nest 1 to nest 4 were determined in detail by Esprey (1997) and only a brief review will be discussed in this section. Esprey (1997) reported that there was a general decrease in the hydraulic conductivity with depth at nests 1 to 4. Large macropores were evident on the surface soils as indicated by the fact that a large amount of water drains from the soils at a low matric pressure. The high clay content at depths deeper than 1.5 m accounts for high water retention in the soil and the curves show a slow desorption of water (Esprey, 1997).

Below the rock outcrop at nest 5 and nest 6, saturated conditions exist resulting in a fluctuating marsh. Tension infiltrometer and double ring tests could not be done at these sites and the auger hole method (*cf.* Section 5.2.2) was used to calculate the saturated hydraulic conductivity (K_s).

Table 6.1 show results of the conductivities determined using the auger hole method where the surface soils were saturated.

Table 6.1 Saturated hydraulic conductivities determined using the auger hole method

Auger hole method	Nest 5	Nest 6
	K_s (mm.h^{-1})	K_s (mm.h^{-1})
Repetition 1	22.9	11.0
Repetition 2	8.5	19.0
Average	15.7	15.0

The anomalies between the repetitions could be attributed to the fact that they were done on different days while the groundwater levels were in different states of flux. Since the flow of water into the auger hole is three-dimensional, the flow properties could be different in either direction and the hole may extend through layers of different hydraulic conductivity (Amoozegar and Warrick, 1986). Despite the different readings, the average values are somewhat lower than those above the bedrock outcrop, but still compare favourably with the values obtained using tension infiltrometer and double ring tests above the rock outcrop.

The surface bulk densities obtained by the corer method from below the rock outcrop along transect 3 are shown in Appendix E. The bulk densities show a clear trend moving away from nest 5 towards the stream. There is a steady increase from 1 340 kg.m^{-3} between nests 5 and 6 to 1 540 kg.m^{-3} between nest 7 and the stream. This results in a corresponding decrease in the soil porosity which implies a low water retention and freely drained soils. This factor is considered to be of paramount importance in terms of runoff production, as these soils allow for free drainage of subsurface water into the stream, and hence a rapid response to rainfall events.

Hydraulic conductivities are shown in Figure 6.5. It can be seen that the hydraulic conductivity decreases with depth (as seen by the relatively flat curve shown by repetition 1), implying a high sand percentage and thus relatively high conductivities. The saturated hydraulic conductivities, measured by double ring infiltrometry, of the surface soils are an order of magnitude higher than the unsaturated hydraulic conductivity, measured by tension infiltrometry, which indicates the presence of macropores in the surface layers.

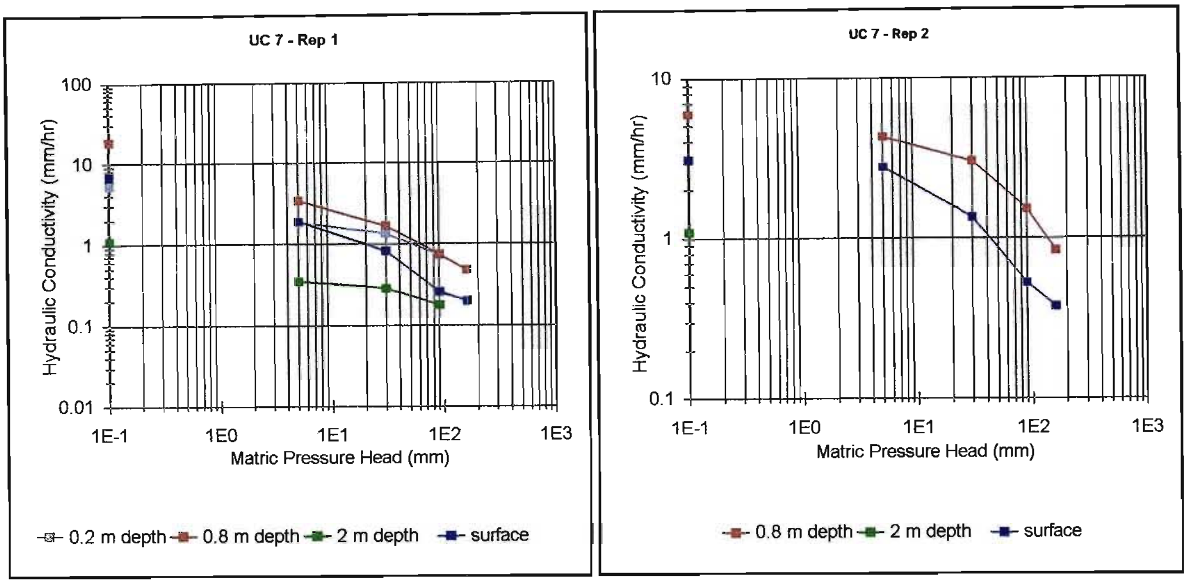


Figure 6.5 Hydraulic characteristics at nest 7 in the lower catchment area

Soil physical and hydraulic properties have been discussed for the three transects at Weatherley. It can be seen that the soils at Weatherley are highly variable in nature and composition with respect to their location on a hillslope. The upper catchment area appears to have coarse fragmented soils on the crests of the hillslopes which allow for free draining conditions and low water retention. The marshy soils that are prevalent at the toes of the hillslopes tend to show high WRC. This results in high AMC and rapid surface runoff. The lower catchment display complex soil physical properties above the rock outcrop with perched water tables existing due to layers of differing conductivities. Below the rock outcrop, freely drained soils with high conductivities exist along the stream, which allows for a higher component of subsurface flow contributing to the runoff hydrograph than the upper catchment.

These properties are essential to the understanding of subsurface processes and their effect on hillslope runoff. They also allow for important soil parameters to be determined for modelling purposes. The following section shows the results from the tensiometer, piezometer and weir monitoring network at the Weatherley experimental catchment.

6.1.2 Monitored Results

Results from the monitoring network are now presented. These include data from the controlled tensiometry experiment, tensiometers, piezometers, weirs and a pilot tracer study.

6.1.2.1 Controlled Tensiometry Experiment

Figures 6.6 to 6.8 below shows the results from the controlled tensiometry experiment conducted at the Ukulinga experimental farm at the University of Natal, Pietermaritzburg. The results from this experiment aided the interpretation and understanding of the tensiometer data obtained from the Weatherley experimental catchment.

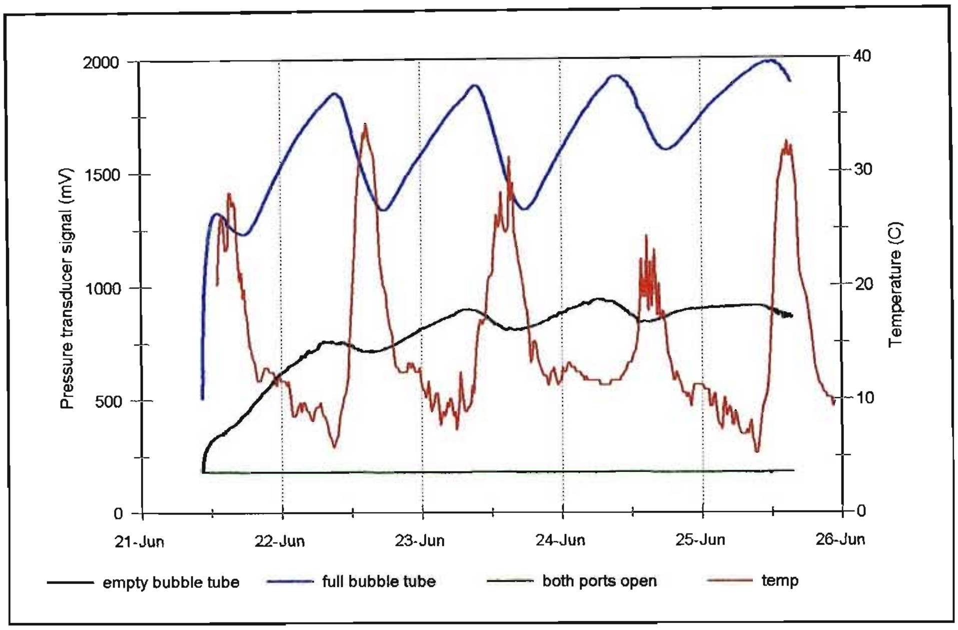


Figure 6.6 Tensiometers in the outdoor drum with a constant soil moisture

In Figure 6.6, there is a clear fluctuation in the tensiometer signal in both the full and the empty bubble tubes, despite the water content of the drum remaining constant. On analysing the temperature data it can be seen that the fluctuations are temperature related with the tensions dropping rapidly at midday and rising at midnight. Reasons for these diurnal fluctuations are due to the expanding and contracting air pockets in the water or the bubble tube.

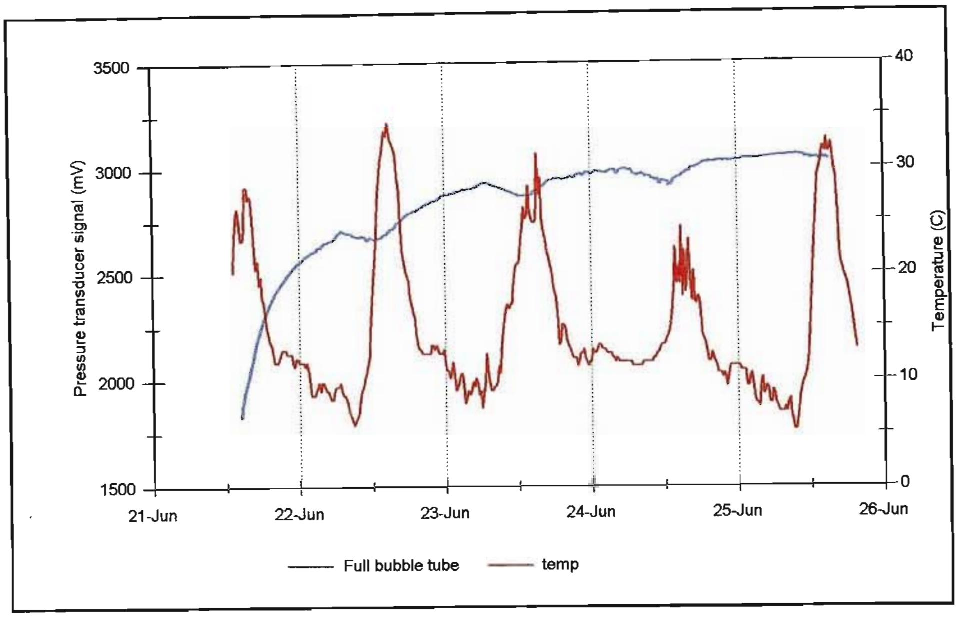


Figure 6.7 Tensiometer in soil next to the drum outdoors

The amount of water in the bubble tube also seems to influence the degree of fluctuation. The empty bubble tube fluctuates less than the full bubble tube due to the expansive properties air being greater than that of water, hence the effect of pressure on the transducer is greater in the full bubble tube. In Figure 6.7, the fluctuations of the tensions in the ground soils are less profound than those observed in the drum due to the ground providing some insulation to the temperature effects on the tensiometer signal.

Results from the drum in the controlled temperature environment (Figure 6.8) do not show any significant fluctuations at an almost constant temperature. There is also only a minute difference in the voltage signals between the empty and full bubble tube, indicating that only diurnal temperature fluctuations have an effect on the tensiometer signals in the field.

These results provided valuable insight into interpreting and understanding the tensiometer data at Weatherley, especially since the catchment's microclimate has an unpredictable nature, with rapid changes in both temperature and soil moisture occurring daily.

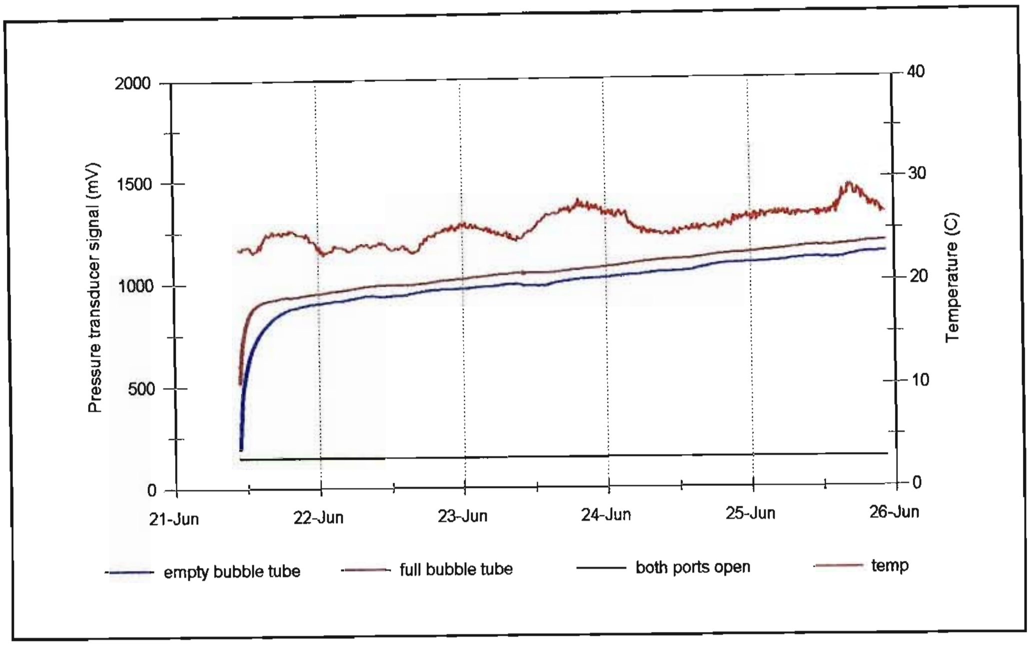


Figure 6.8 Tensiometers in controlled temperature environment.

6.1.2.2 Tensiometer and Piezometer Data

Owing to the large volumes of data and for the sake of brevity, only data from selected nests along the hillslope transects will be presented and used in showing the important processes that occur on the hillslopes in the catchment. Automated tensiometers recording the soil matric pressure (S.M.P.) at twelve minute intervals as well as daily rainfall values are shown in Figures 6.9 to 6.17.

At nest UC1, on the hillslope crest, prior to the event on 31 December 1998, the surface soil is slowly drying out (as indicated by the increase in S.M.P.) due to the lack of rainfall during the previous few days. When the first rain of the event falls (53 mm on 31 December 1998), the surface soils respond rapidly and approach saturation point as seen by the sudden drop in the S.M.P. of the soil to zero (Figure 6.9). This trend is dominant throughout the catchment since the surface soils are generally more sandy than deeper soils which tend to have a higher clay content (Esprey, 1997). Another reason for this rapid response is the presence of macropores and pipes in the surface soils.

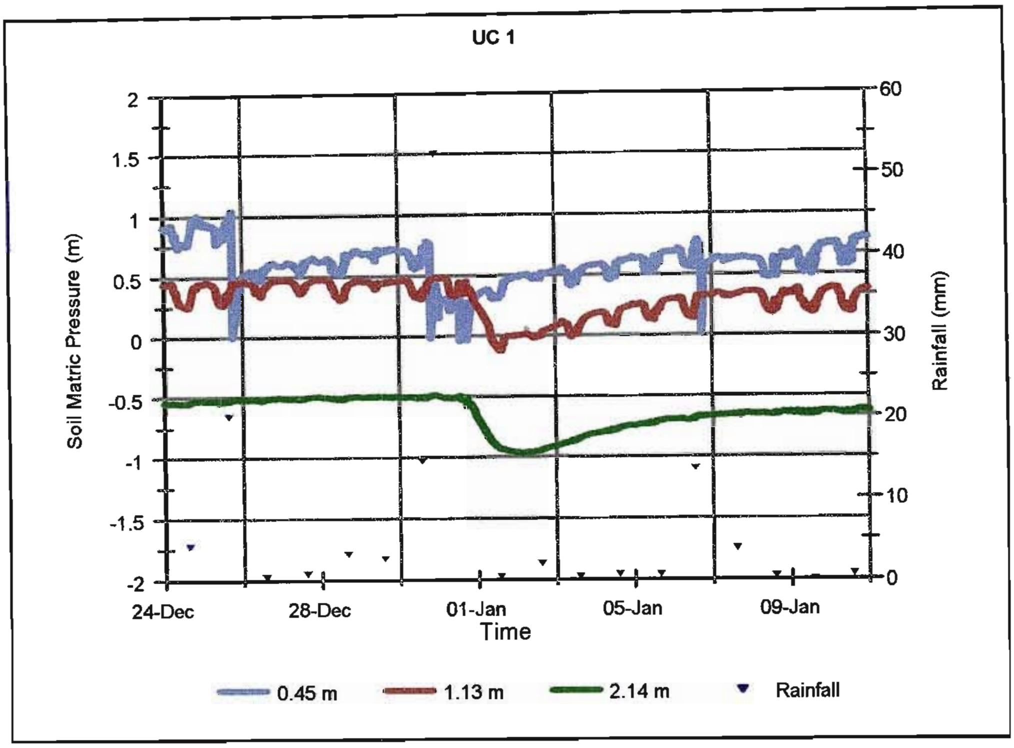


Figure 6.9 S.M.P.s from UC1 in the upper catchment

There are many visible cracks and animal burrows in these soils and this also contributes to this rapid wetting up of the surface soils as well as the rapid lateral flows down the slope. Deeper soil (1.13 m) also approaches saturation (0 m of S.M.P.), but the S.M.P. only starts to drop some hours after the initial rainfall event at a much slower rate, indicating that there is a lack of macropore flow in this layer. The soil at 2.04 m also shows a delay in responding to the event as the wetting front continues to move down the soil profile. The S.M.P. only stops dropping some twenty four hours after the rain commences. This indicates that there is significant infiltration and deep percolation to the bedrock in the upper reaches of the hillslope as a high intensity event such as this (5 mm/h) would normally produce more runoff and not allow infiltration to a depth of 2 m. When the S.M.P. drop below zero, a phreatic surface exists above the level of the tensiometer ceramic and thus ponded conditions exist at this depth. At nest UC3, near the toe of the hillslope in the upper catchment weir, the response to a rainfall event is again rapid (Figure 6.10), and can be attributed to macropores and animal burrows in the upper soil layers causing rapid lateral flow. Water was observed to gush out of a 15 mm pipe continuously for 38 hours after an event. Both the shallow and deeper soils appear to be saturated before the event with the deeper soil's S.M.P. only dropping slightly during the event. This is due to the vicinity of nest UC3 to the stream and marshy area. Hence nest UC3 shows mainly seasonal fluctuations rather than event fluctuations.

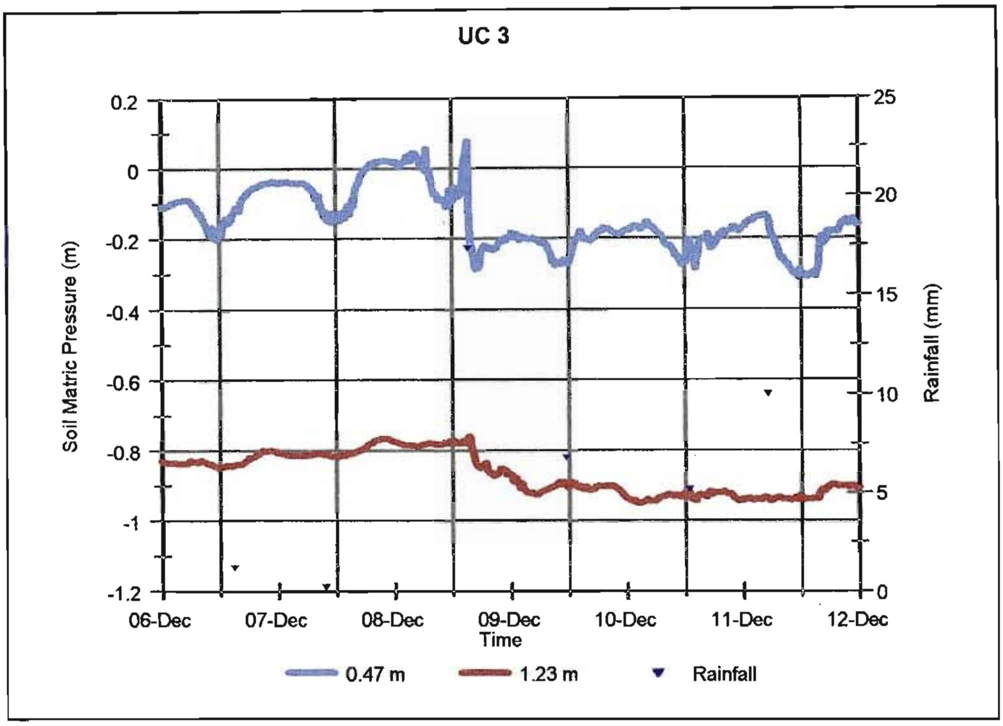


Figure 6.10 S.M.P.s from UC3 near the weir in the upper catchment

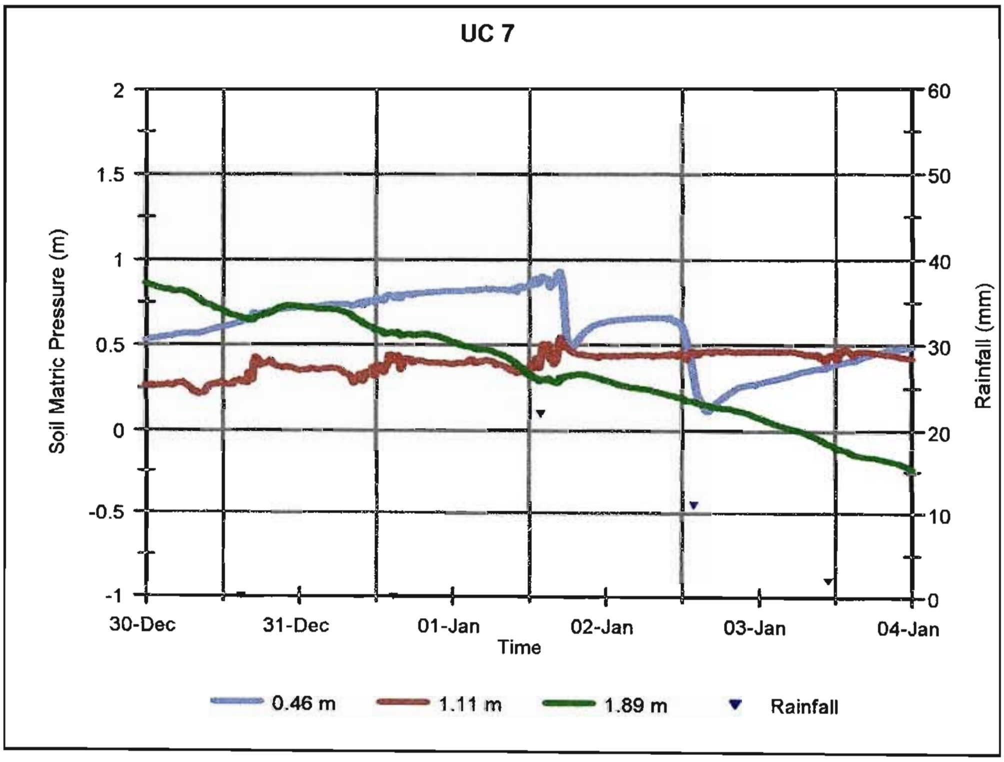


Figure 6.11 S.M.P.s from UC7 on a midslope in the upper catchment

At nest UC7 on the midslope section of transect 3, the surface soils show the usual rapid response to both events on 1 and 2 January 2000, despite the first event having double the amount of rainfall as the second event (Figure 6.11). The middle soil horizon (1.11 m) is not affected by either of the events. This can be attributed the macropores contributing to the rapid wetting up and drying out of the surface soils, but at the same time allowing the water to by-pass the middle horizons and flow directly to the deep horizon (1.89 m).

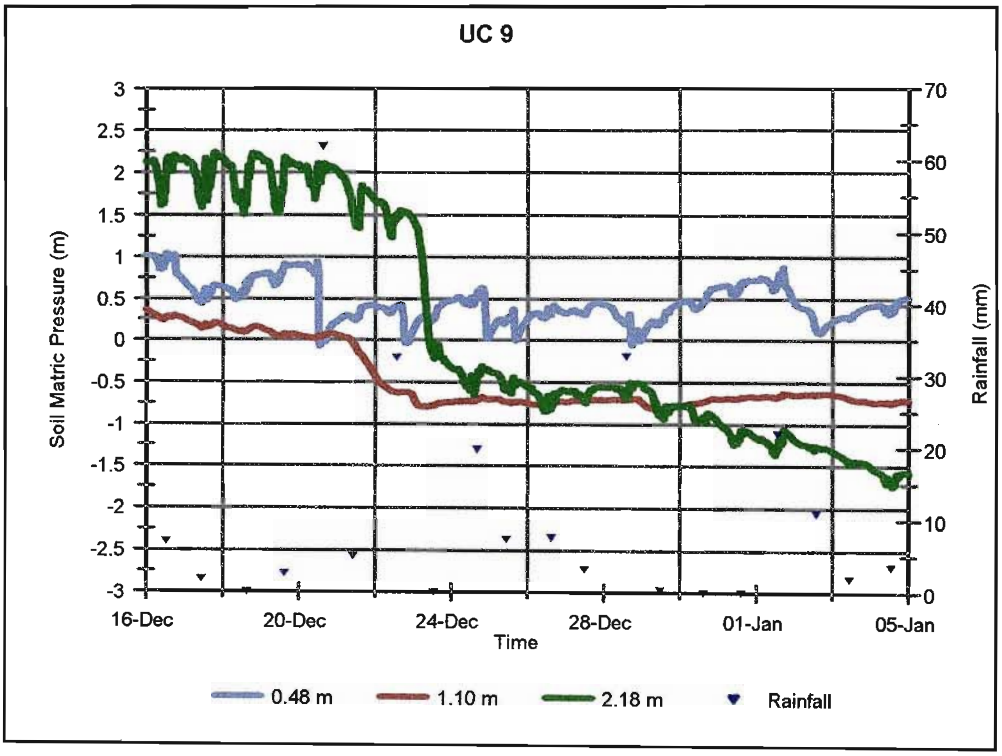


Figure 6.12 S.M.P.s from UC9 on the dolerite dyke in the upper catchment

At nest UC9, on a dolerite dyke in the upper catchment, surface soils appear to respond rapidly to events that have extremely large amounts of daily rainfall (e.g. 64 mm on 20 December 1999). Events that produce lesser amounts of rainfall (e.g. 23 mm on 2 January 2000) induce a slower response in the surface soils. Since the nest is situated on a dolerite dyke, the high percentage of coarse rock fragments in the surface soils which are present due to erosion of the rock outcrop above, allows for higher infiltration rates into the deeper soil horizons. The soils also dry out rapidly after events as seen by the fact that the surface layer only approaches saturation and do not actually display a positive hydrostatic pressure which occurs when the water table rises above the ceramic in the soil. This may be explained by the fact that infiltration is enhanced in this loosely bound fragmented soils. This is evident in the fact that the bulk densities at UC9 were found to be high and the water retention of the soil low (*cf.* Section 6.1.1).

The deep soil horizon (2.18 m) was initially drier than surface soils before the 20 December 1999 event which could be explained by the fact that interflow along bedrock is present and the high percentage of coarse material allowed for the drainage of the deep soil, leaving it in a drier state (as seen by the high S.M.P.) than the surface and near surface soils. Both the deep horizons eventually reach saturation point as the wetting front moves down the soil profile after the event.

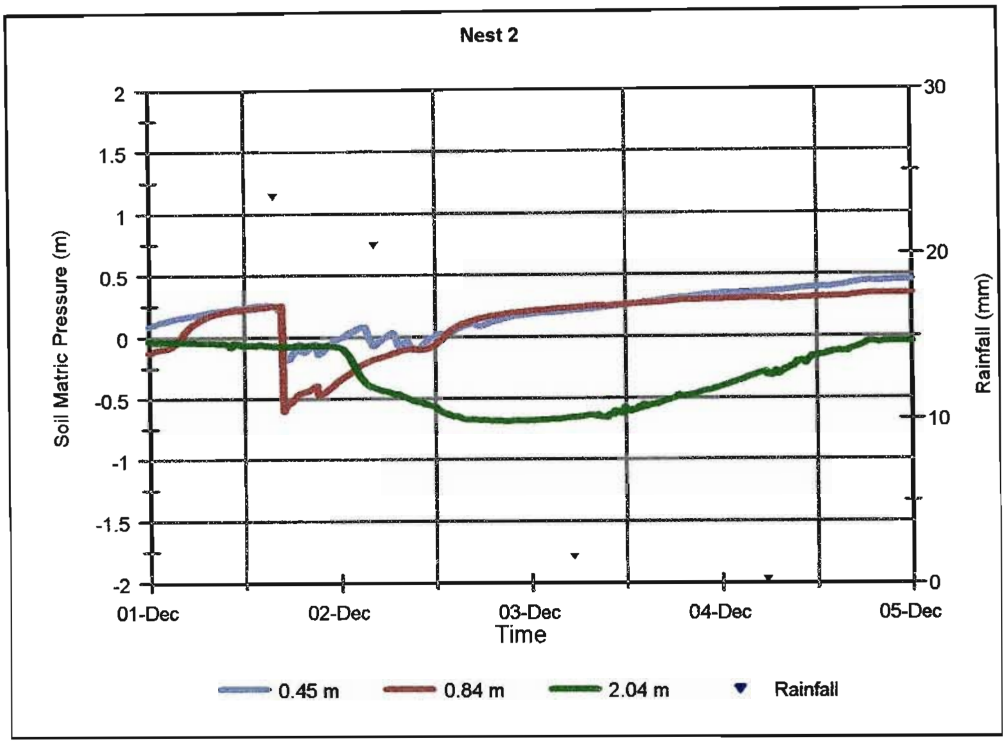


Figure 6.13 S.M.P.s from nest 2, midway down a hillslope section in the lower catchment

Nest 2 in the lower catchment shows similar response characteristics to UC1 in the upper catchment. There is a rapid response to the rainfall event up to a depth of 0.84 m as indicated by there rapid drop in the S.M.P.s. The deep horizon (2.04 m), however, only responds twelve hours after the event with a very gentle drop in S.M.P. over time, indicating once again that there is deep percolation to the bedrock. This behaviour also indicates the absence of macropores below a depth of approximately 1 m. The deep percolation to the bedrock is of significant importance in certain parts of the catchment as it contributes to groundwater ridging in areas of shallow soil. In areas where the bedrock intercepts the surface, the deep percolation and interflow that occurs in the upper hillslope reaches is exfiltrated out of the soil and becomes return flow. An example of these processes can be observed at nest 4 as shown in Figure 6.14

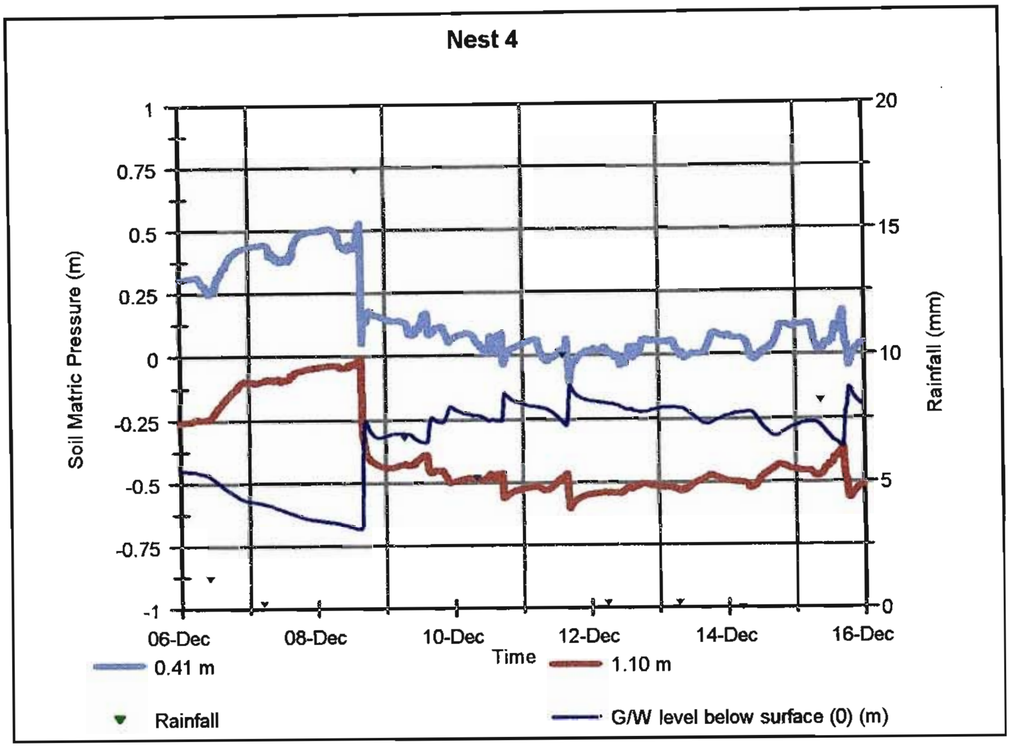


Figure 6.14 S.M.P.s from nest 4, at the toe of a hillslope section, above the rock outcrop in the lower catchment

At nest 4, above the Molteno rock outcrop in the lower catchment, both soil horizons (0.41 m and 1.10 m) respond rapidly to the rainfall event on 8 December 1999. There is, however, a noticeable absence in the drying out of the soils after the cessation of rainfall as indicated by the S.M.P's remaining saturated and the groundwater level remaining approximately 0.2 m below the surface, despite the fact that there is very little or no rainfall for eight days after the event. The lower horizon (1.10 m) shows a positive hydrostatic pressure, indicating the existence of a phreatic surface above the ceramic tip. This phreatic surface can be attributed to subsurface water which is generated on the upper section of the hillslope. The accumulation flow from the upper section flows down the hillslope along the bedrock as subsurface interflow. Upon reaching the shallow soil at nest 4, the soil becomes saturated and hence the accumulation flow exfiltrates out of the soil and becomes surface water once again. This water from return flow then discharges over the rock outcrop and contributes to the groundwater at nest 5, below the Molteno outcrop. Although a high percentage of the water cascades over the rock outcrop as surface flow, observations at nest 5 suggest that seepage through the bedrock also occurs and that subsurface flow also contributes to the groundwater at nest 5. This is evident in Figure 6.15 below.

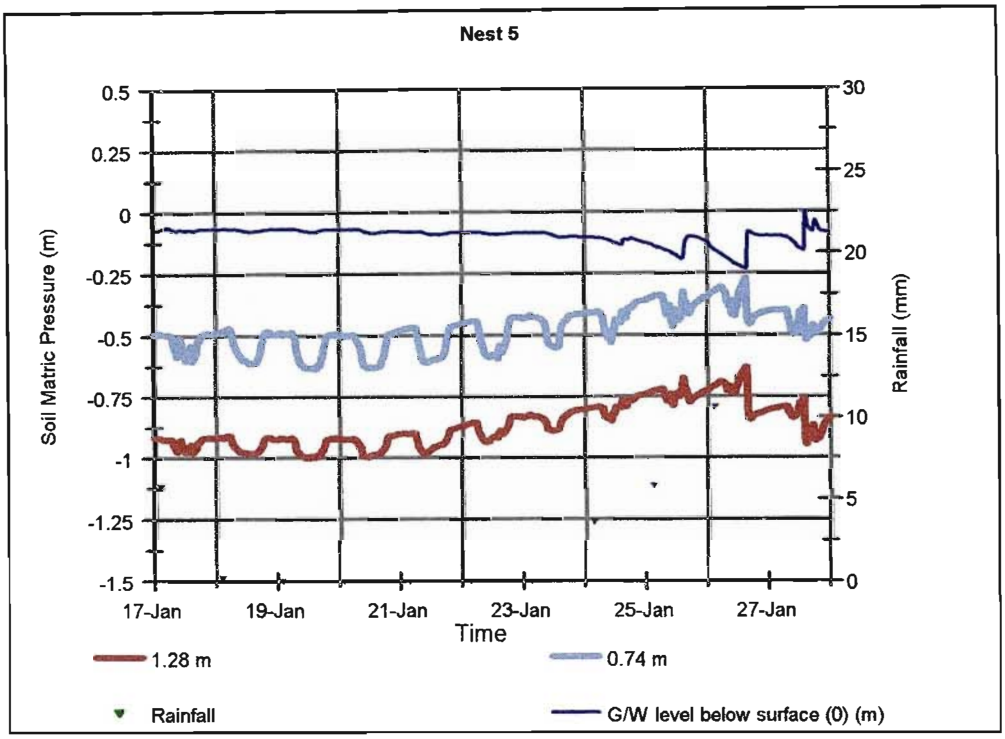


Figure 6.15 S.M.P.s from nest 5, below the rock outcrop in the lower catchment

Both the soil horizons show a positive hydrostatic pressure, indicating the presence of the water just below the ground level (the ground level is also represented by the 0 m soil matric pressure on the graph). The groundwater level just below the surface and remains so during the week without rainfall from the 17 to 25 January 2000. The fact that the soil only starts drying out after seven days without rainfall and that the groundwater levels remain just below the soil surface, suggests that, since return flow cascading down the rock outcrop would have ceased a few days after the event, subsurface flow from above the rock outcrop may seep through the bedrock and contribute to the groundwater levels in the marshy areas.

Of particular interest is the fact that there appear to be many small fluctuations (rapid rises and drops in S.M.P.s) in both the soil horizons (0.74 m and 1.28 m). This can be attributed to evapotranspiration or diurnal fluctuations that affect the tensiometers (*cf.* Section 6.1.2.1).

At nest 6, which is situated in the marshy area, the soil is constantly saturated and only rarely shows a positive S.M.P. of above 0.05 m. The S.M.P. at the surface horizon (0.32 m) shows a rapid response to rainfall, but also show a similarly rapid drying up response, indicating that the water is rapidly discharged into the marshy soils which then feed the stream.

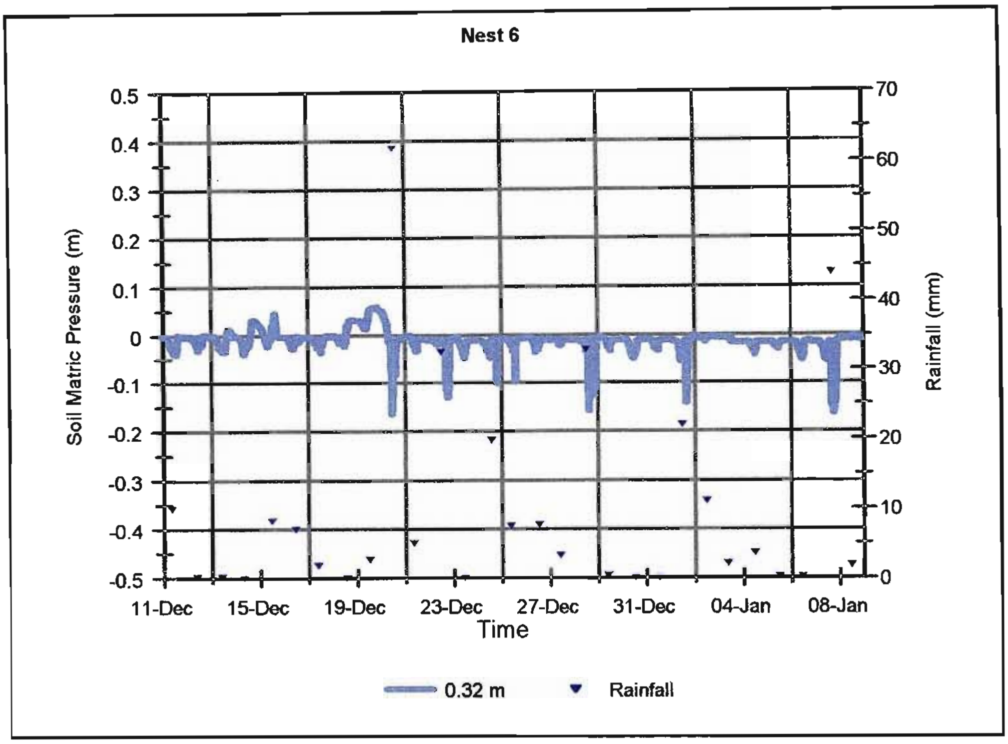


Figure 6.16 S.M.P.s from nest 6, in the marshy area of the lower catchment

Figures 6.9 to 6.16 have shown most of the subsurface processes that occur on hillslopes in the Weatherley catchment. These processes have been identified by referring to individual and different events that have occurred during the data collecting periods. In order to study the soil water status of the hillslope as a whole, the three hillslope transects have been presented in Figures 6.17 to 6.23, showing lines of equal soil matric pressures as well as groundwater levels below the surface. The transects response to different events and their influence on the catchment runoff are now discussed.

Two rainfall events have been chosen to show the overall transects soil water dynamics. The first event (Event 1) was a low intensity event which occurred between the 8 and 11 December 1999, where 39.2 mm of rainfall fell over a period of 80.6 hours. The second event (Event 2), a high intensity event, occurred on the 7 January 2000, where 43.8 mm of rainfall fell over a period of 6.5 hours.

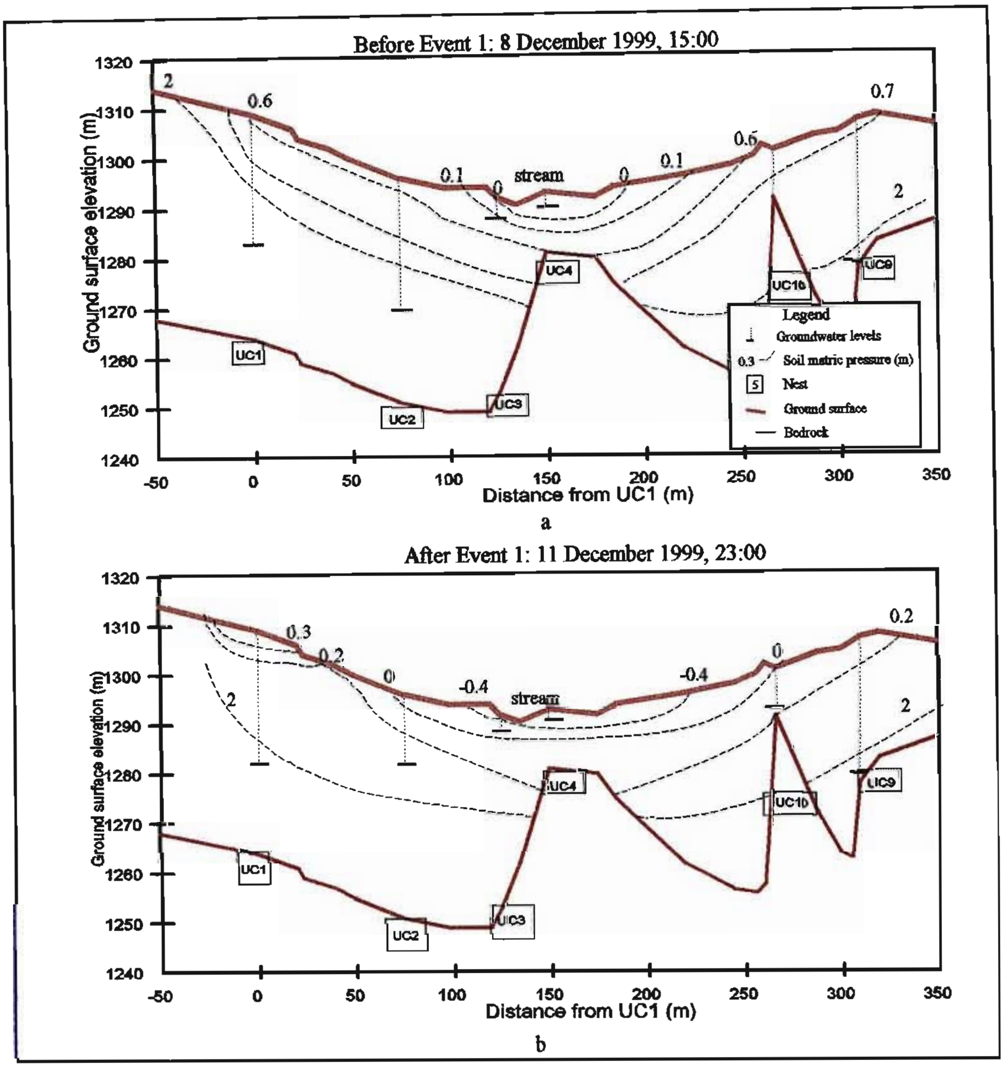


Figure 6.17 S.M.P contours (m) in transect 1 at (a), before Event 1 (15:00, 8 December 1999 and (b), after Event 1 (23:00, 11 December 1999). Depth to bedrock is exaggerated 10 times

Transect 1, in the upper catchment, runs from nest UC1, on the crest of the hillslope, down through the stream and up the opposite hillslope to nest UC9. It shows relatively dry soils on the crests of the hillslopes prior to Event 1 which is indicated by the high S.M.P. at UC1 and UC9. The toe of the slopes in the valley shows the soil to be in a state of saturation. This is attributed to the fact that a stream flows between nests UC3 and UC4. A marshy area exists in this region as seen by the fact that the S.M.P.s show the soils to be in a constant state of saturation. After the event, the surface soils display a distinct wetting up, although saturated conditions only extend from the stream up to the midslope near UC 2 and UC10 and are confined to the near surface soils only. The crests become relatively moist compared to before the event. There is little infiltration into the deep horizons on the crests and midslopes as seen by the high S.M.P at 1.8 m below the surface. The groundwater levels do not seem to be affected by the event. These conditions may be attributed to the fact that this event did not yield enough rain to allow for deep infiltration. Lateral rather than vertical flow through macropores and pipes in the surface soils may also have caused the water to flow directly into the marsh rather than infiltrate into the deep soils on the hillslope crests. Towards the toe of the hillslope from nests UC2 and UC10, the soils alongside the stream and marsh become saturated and the groundwater levels rise and intercept the surface, allowing exfiltration directly into the stream.

Transect 2, also from the upper catchment area, dissects transect 1, and runs from nest UC8 on the crest of the hillslope down to the weir as seen below in Figure 6.18. At nest UC8 on the crest of the hillslope in transect 2 , shallow soils exist due to the Molteno rock outcrop. Since the rock displays highly eroded and fragmented characteristics, the nest does not display the same subsurface processes that exist at nest 4 in the lower catchment (*cf.* discussion on Figure 6.9). This can be seen by the high S.M.P. that exists at nest UC8 prior to the event. Nest UC7 is characterised by deep soils as seen by the fact the bedrock depth is 4.5 m below the surface. The soil profile becomes increasingly wetter with depth down the profile at nest UC7. The bedrock thus acts as a subsurface "reservoir" by trapping the water that flows as subsurface flow along the bedrock from nest UC8 as well as any infiltration from the surface. Tensiometer data for nest UC6 were not obtained for these events due to faulty equipment and data. Below nest UC7 as one approaches the marsh and weir, the soils wet up progressively, with the groundwater table rising to intercept the surface in the vicinity of the weir. After the event, the entire transect has become saturated as indicated by the drop in S.M.P.s near the surface. Of interest is the rapid wetting of the entire soil profile that takes place on the crest of the hillslope. The shallow soils and broken bedrock allow water to infiltrate the area around nest

UC8 rapidly. Subsurface water then flows towards nest UC7 and causes the groundwater level to rise rapidly as ponded conditions occur on the bedrock. Gravitational subsurface flow is responsible for the movement of this water towards nest UC6 and the marsh.

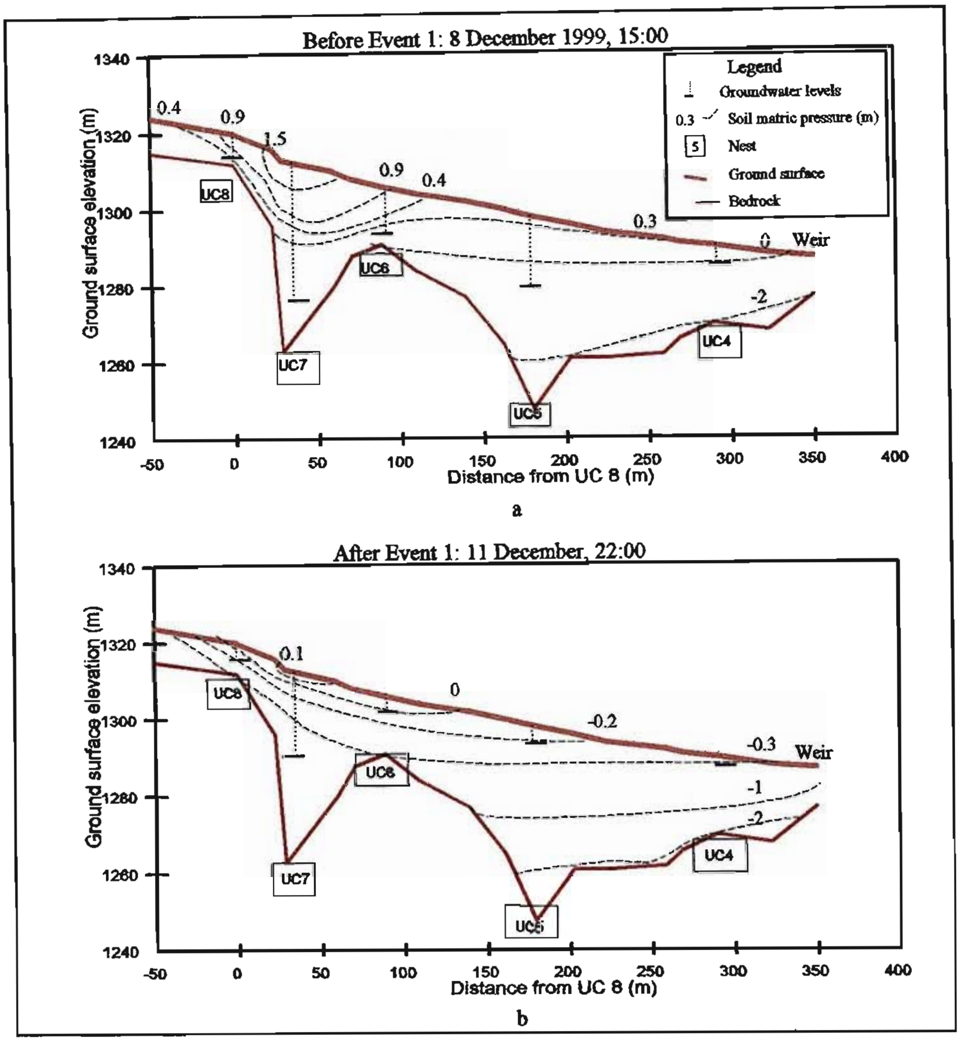
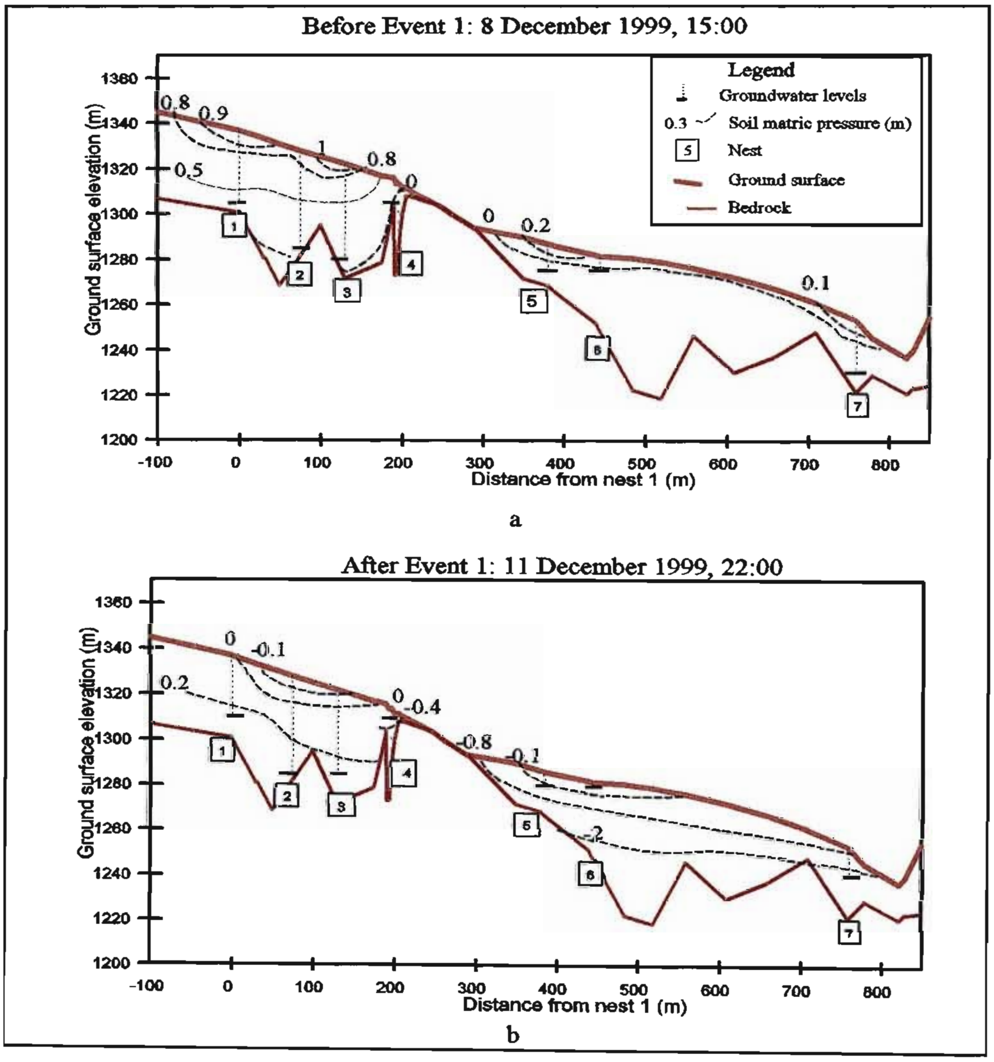


Figure 6.18 S.M.P. contours (m) in transect 2 at (a), before Event 1 (15:00, 8 December 1999) and (b), after Event 1 (23:00, 11 December 1999). Depth to bedrock is exaggerated 10 times

Since the marsh area has a constantly high soil moisture content, with the groundwater levels constantly in the vicinity of the surface soils down to a depth of one metre, the surface soils also display a rapid response to the event as the groundwater level rises to intercept the soil surface from as high up the slope as nest UC6.

In discussing the response of transect 3, in the lower catchment area, to the event it is important to note that the transect only extends from the crest of the hillslope at nest 1 down to the stream because the processes on the opposite hillslope are similar to those observed on transect 3 in the way that, for example, the position of the Molteno rock outcrop between nest 10 and nest 9 causes similar responses to the outcrop observed at nest 4 and nest 5.


Before Event 1: 8 December 1999, 15:00

After Event 1: 11 December 1999, 22:00

Figure 6.19 S.M.P. contours (m) in transect 3 at (a), before Event 1 (15:00, 8 December 1999) and (b), after Event 1 (23:00, 11 December 1999). Depth to bedrock is exaggerated 10 times

Along the entire length of transect 3 above the Molteno rock outcrop, soils appear to be dry on the surface and get slightly more moist down the profile towards the bedrock. An exception occurs at nest 4 where a phreatic surface exists just below the surface as seem by the S.M.P.

and groundwater level. Groundwater levels at the other nests upslope are all reflecting the dryness of the soils as seen by their depth below the soil surface.

After the event, the surface soils to a depth of just over a metre show saturated conditions. Of significance in this scenario is the dry soils (high S.M.P.) at a depth of 2 m below the surface and the fact that the groundwater levels have showed very little or no response to the event. This can be attributed to the same reasons as at nest UC1 and UC2 on transect 1, the amount of rain falling during the event was not enough to cause deep percolation. Lateral rather than vertical flow through macropores and pipes in the surface soils may also have caused the water to flow down the slope as lateral subsurface flow prior to infiltration into the deep soils by vertical flow. Since macropores were only present in the soil surface to a depth of approximately 1 m (Esprey, 1997) and the soils below that depth seem to have lower hydraulic conductivities (*cf.* Figure 6.9), the water moves laterally through the surface soils. Evidence of this lateral flow downslope can be seem in the fact that a positive hydrostatic pressure exists at the surface of nest 4, indicating the accumulation flow from the hillslope above is present. At nest 2 and nest 3, the groundwater levels remain in the vicinity of the bedrock at approximately 2.5 m below the surface while saturated conditions exist up to a depth of approximately 1 m. This indicates the presence of a perched water table.

Below the Molteno rock outcrop towards the stream, the soils are relatively moist before the event and the groundwater table is close to the soil surface. Owing to the high antecedent soil moisture (ASM), the effect of even a low intensity event like this results in an instantaneous and dramatic decrease in S.M.P's accompanied by an associated rise in the already high groundwater levels. Water is discharged directly into the stream during these saturated conditions.

Some general concluding remarks about the response of the catchment to low intensity events are that the hillslope processes allow for the rapid wetting up of the surface soils only (due to the presence of macropores). At the toe of the hillslopes and in/near the marsh area, response is very rapid due to high ASM. Discharge into the streams is therefore direct and continuous. The low intensity events also seem to aid the formation of localized perched watertables without contributing directly to deep groundwater tables. Lateral flow in the surface soils contribute to the draining of these perched watertables. Although not show in these data, low intensity events of high rainfall volumes do result in water recharging the groundwater levels.

The response of the catchment to a high intensity event is considerably different to that of a low intensity event and is shown in Figures 6.20 to 6.22 below.

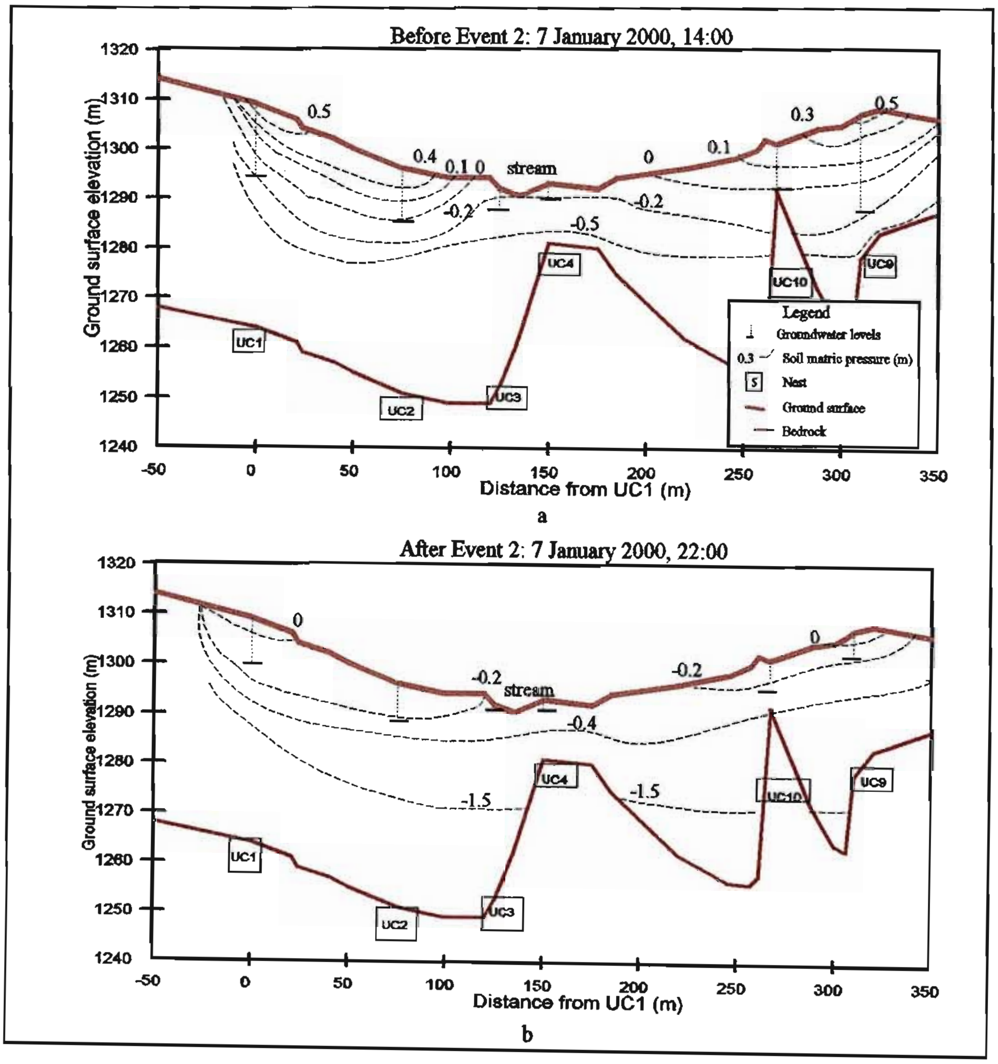


Figure 6.20 S.M.P. contours (m) in transect 1 at (a), before Event 2 (14:00, 7 January 2000) and (b), after Event (22:00, 7 January 2000). Depth to bedrock is exaggerated 10 times

The transect appears to be distinctly wetter prior to the event 2 than it was before event 1. The soils, albeit wetter, show similar trends to those describing the transect before event 1. During the high intensity storm (event 2), the transect rapidly wets up at the onset of rainfall. Of significance in this event is the fact that there is deep percolation to the deep soils below a depth of 2 m. The groundwater level in the crest of the hillslope respond to this percolation by rising to within 1 metre of the surface. The toe of the hillslopes become saturated rapidly and thus most of the water entering the stream is by rapid surface stormflow.

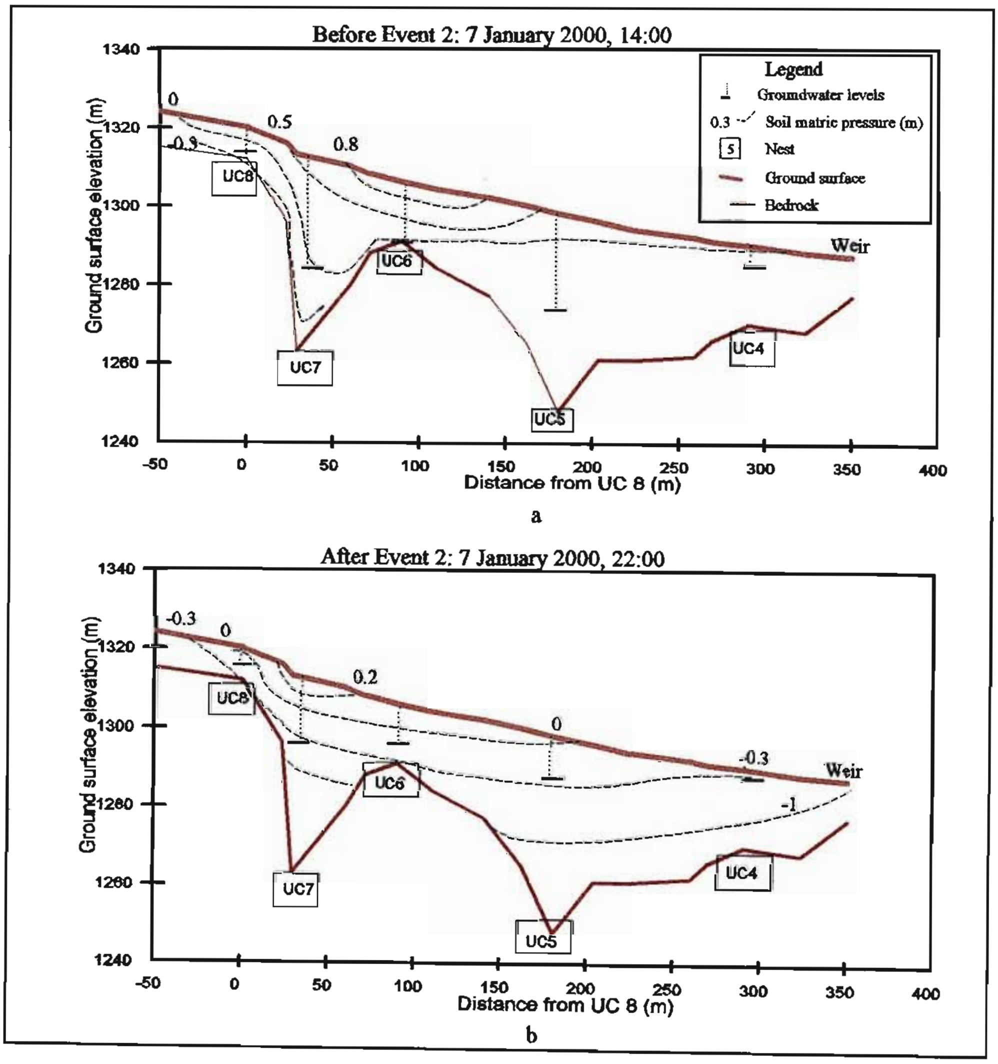
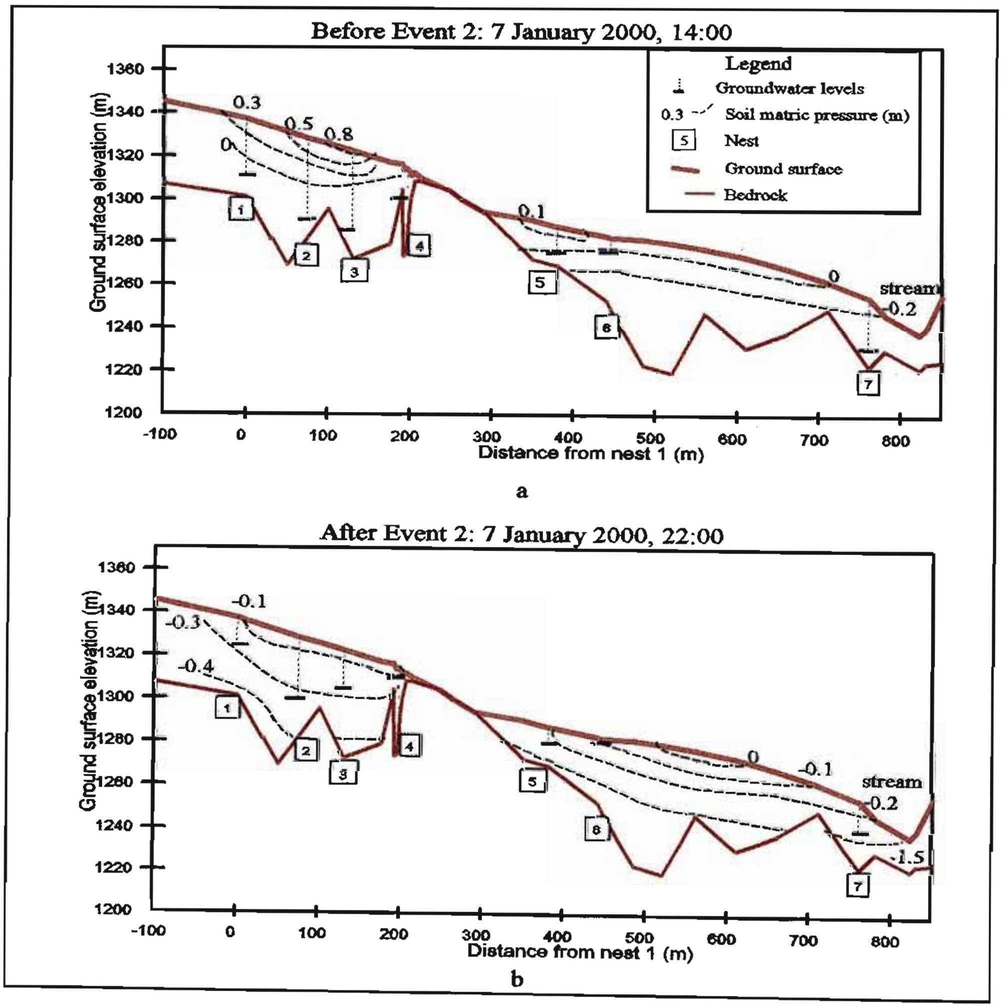


Figure 6.21 S.M.P. contours (m) in transect 2 at (a), before Event 2 (14:00, 7 January 2000) and (b), after Event (22:00, 7 January 2000). Depth to bedrock is exaggerated 10 times

At nest UC8, the soils are saturated prior to the event. Water cascading into the "reservoir" causes ponding on the bedrock as indicated by the groundwater level. The surface soils along the midslope remain relatively dry and saturated conditions exist at the toe of the hillslope near the weir. After the event, the transect wets up rapidly. The soil surface at nest UC7, however, does not reach saturation. A number of explanations can be given for this. The intensity of the event is very high and leads to rapid runoff rather than infiltration. The bedrock topography causes subsurface flow to flow into the deep reservoir, thus draining water from the upslope nest UC8 away from the surface soils at nest UC7. The nest is also situated on a steep gradient which allows for rapid runoff rather than infiltration into the soil. Seasonal fire breaks are also burned around nest UC7 which may also lead to an increased water repellency of the soils. The deep soils contribute to runoff as subsurface flow emerges in the toe of the hillslope in the vicinity of nest UC4 and the marsh area.


Before Event 2: 7 January 2000, 14:00

a

After Event 2: 7 January 2000, 22:00

b

Figure 6.22 S.M.P. contours (m) in transect 3 at (a), before Event 2 (14:00, 7 January 2000) and (b), after Event (22:00, 7 January 2000). Depth to bedrock is exaggerated 10 times

Transect 3 in the lower catchment the hillslope above the Molteno rock outcrop is showing dry soil conditions. Below the rock outcrop towards the marsh, the presence of the groundwater table near the surface accounts for the relatively moist soils. After the event, the entire transect is saturated and the groundwater levels have risen distinctly. Ponded conditions occur on the bedrock and accumulation flow causes subsurface water to exit out of the soil at nest 4 and cascade over the Molteno rock outcrop. This water also contributes to the already saturated conditions that exist below the rock outcrop. Of significance in this event is the absence of the perched water tables that were present at nest 2 and nest 3 during event 1. The amount of water infiltrating the soils is more than event 1, leading to vertical flow down to the bedrock rather than lateral flow.

The response of the catchment to the high intensity event differs significantly to that of the low intensity event. The deep soils tend to wet up more readily in a high intensity event due to the presence of macropores and pipes and a much higher volume of water being available for infiltration. This results in ponding on the soil surface which, in turn, allows for any excess water to enter the macropores or pipes from the surface and move through the soil at a high velocity and low tension. The groundwater responds to the high intensity event on the crest of the hillslopes due to this wetting up of deep soils and ponded conditions are common along the bedrock. Since saturated conditions usually prevail shortly after the onset of rainfall, a large amount of runoff is generated and flows directly into the streams.

The marsh is seen as a dominant factor that influences the runoff at Weatherley. It allows for direct runoff into the stream and acts as "bridge" for water between the hillslope and the stream by allowing for rapid surface storm flow to reach the stream with minimum infiltration and also by allowing subsurface flow from groundwater tables to enter the stream directly. The groundwater tables on the crest and midslope have a very influential effect on the marsh areas as they determine the rate at which water will flow down the hillslope and into the marsh.

Since not all the piezometer tubes were automated, manual readings were conducted on a monthly basis at all the piezometers at Weatherley. Figure 6.23 shows the seasonal variations of the groundwater tables at Weatherley and their influence on the marsh areas. The maps do not represent altitude or contour effects. Depth to the water tables were extrapolated between the nests with piezometers using inverse distance weighing, and thus only data shown along the transects are a true representation of the depths to the water tables.

The depths to the water table represented at areas without piezometers are a result of the extrapolation. The depths to the water tables vary considerably between seasons on the crest of the hillslopes. During the wet month (January 2000) the crests have a constantly high water tables with the depths rarely dropping below 1.8 m below the surface. This ensures constant seepage of subsurface flow into the marsh and stream. The dry month (July 1999) shows a noticeable increase in the depths to water tables on the crests and midslopes, with the depth to the water tables dropping to 2.4 m on some of the hillslopes. This causes the marsh area to recede during these winter months, sometimes by as much as 15 m on either side. Appendix F contains depth to water tables for selected months during 1999.

Now that a clear idea of the subsurface processes on the hillslopes at Weatherley catchment has been gained and how they interact with each other and affect the hillslopes response to different rainfall events, runoff data from the upper catchment and lower catchment weirs are presented and discussed.

6.1.2.3 Runoff Data

The two automated Crump weirs record runoff data from the upper and lower catchment areas continuously. The response of the catchment to event 1 is shown in Figure 6.24. At the onset of rainfall, both the upper weir and the lower weir respond to the event at the same time. This hydrograph behaviour may be attributed to the marsh area that exists alongside the streams near the weirs which causes any rain falling on or near the stream and marsh area to be contributed directly to the streamflow with minimal delay. Another interesting point to note is the fact that both weirs have very similar peak discharge rates although not discharge volumes. The runoff co-efficient (R.O.C.), the fraction of precipitation falling on the catchment that becomes runoff, are similar. For event 1, the upper catchment R.O.C. was 0.12 and the lower catchment had a similar value of 0.14. The reason for this may be the fact that after the

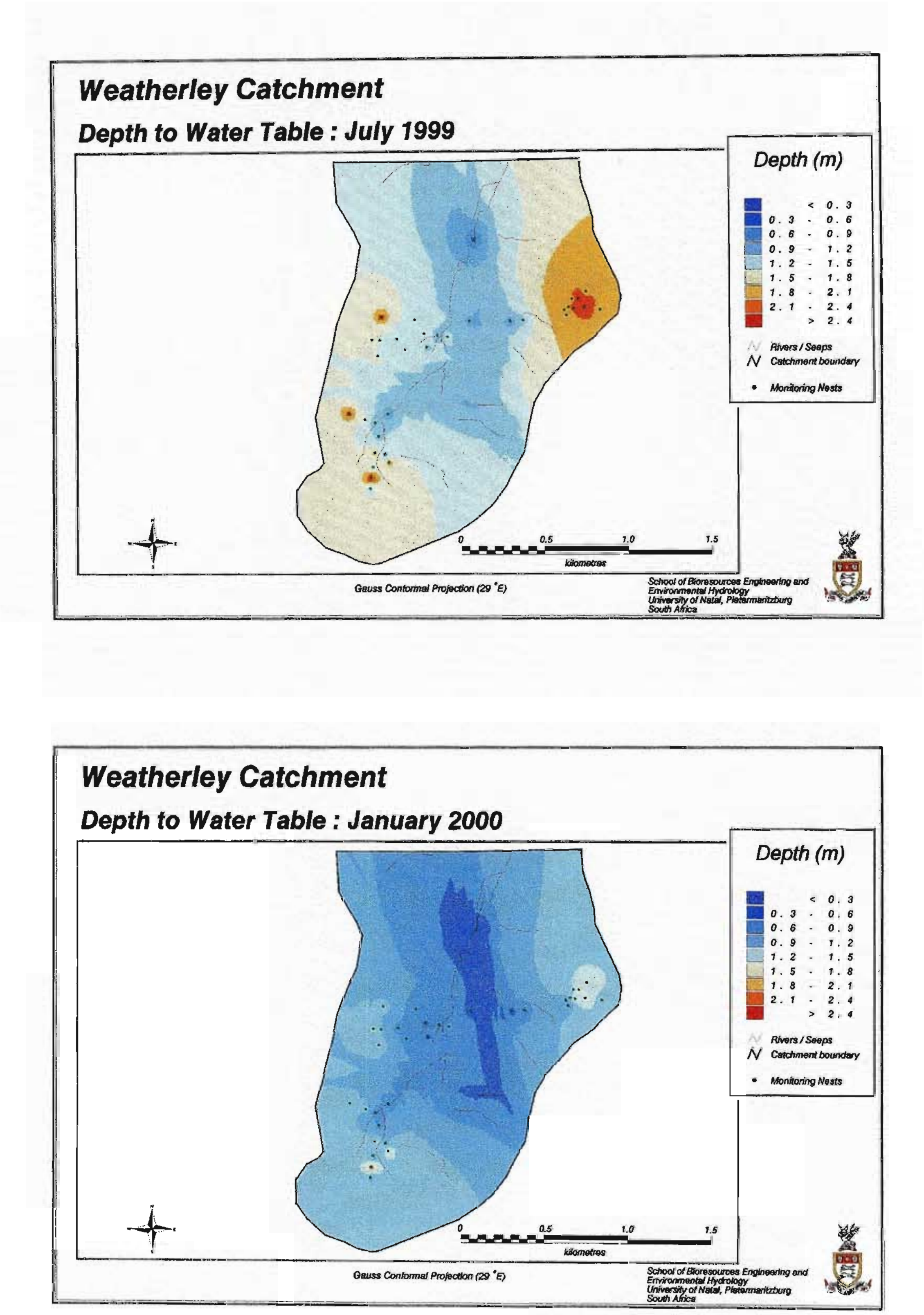


Figure 6.23 Depth to water tables showing seasonal fluxes of the marsh

initial rains stop falling, there is a sudden decline or dip in the rising limb of both the lower and upper weirs (Figure 6.25) shows the first few hours of event 1 on a smaller scale for clarity). This is caused by the cessation of direct contributions to the stream from rainfall and runoff from around the marsh.

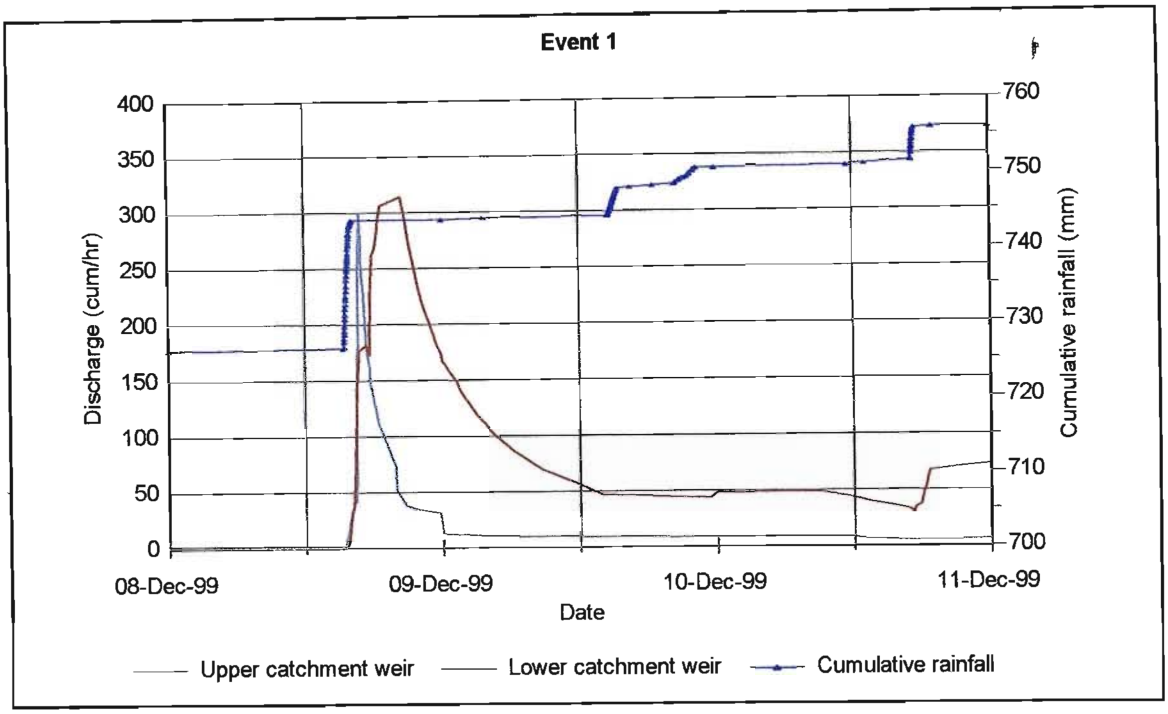


Figure 6.24 Observed runoff from the weirs for Event 1

Water flowing from the marsh and surrounding hillslope soils, however, continues to flow into the stream after the cessation of the rainfall, causing the limb to continue rising until the peak is reached. Since the R.O.C.s are similar, the peak discharge rates (although not volume) are also similar. There is also a slight delay in peak discharge between the upper and lower weirs, and the amount of runoff from the lower catchment is five times greater than that produced in the upper catchment. This is attributed to the fact that the lower catchment area as well as its marsh area are five times those of the upper catchment. The rainfall over the next three days does not cause any increase in the discharge rates but rather prolongs the receding limbs decline and cause a slow continuous discharge of water from the catchment. These hydrograph characteristics can be associated with the saturated conditions that occur at the toe of the hillslopes near the stream and marsh areas in the catchment which ensures a slow but steady release of water into the stream from subsurface flow. The observed runoff data from the high intensity event is shown in Figure 6.26, reflecting distinctly different characteristics to those observed during the low intensity event.

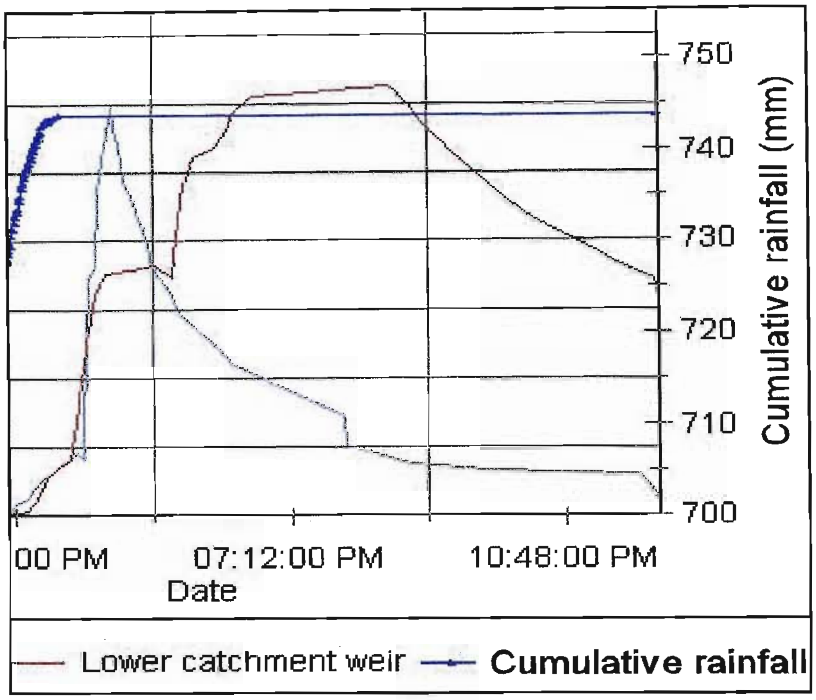


Figure 6.25 The first few hours of Event 1 showing the sudden decline or dip in the rising limb of both the upper catchment and lower catchment weirs

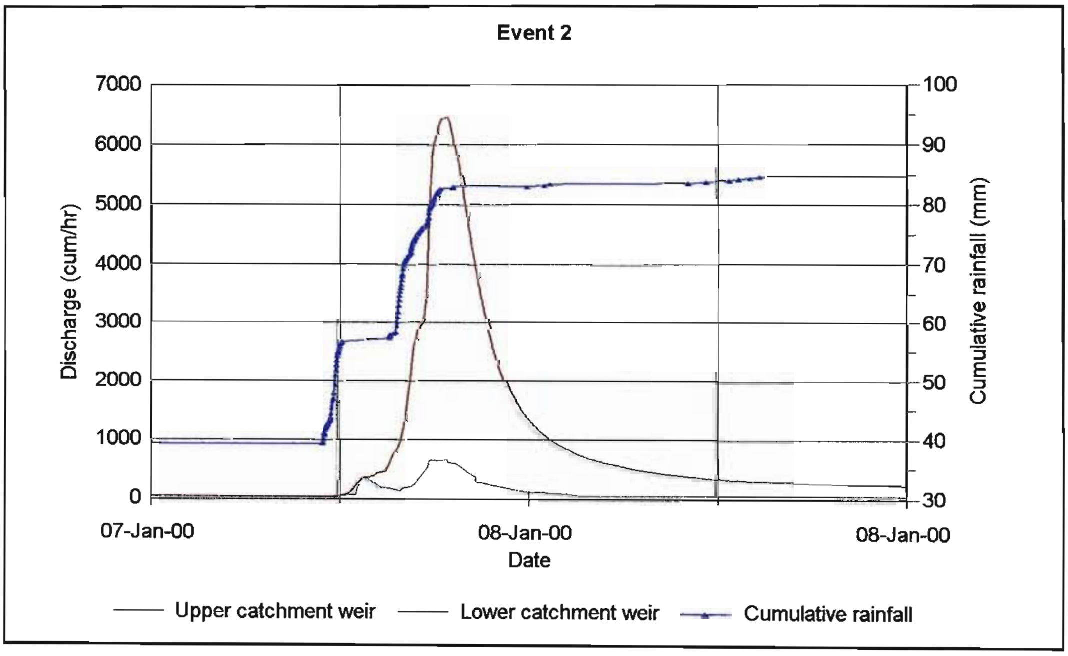


Figure 6.26 Observed runoff from the weirs for Event 2

Most noticeable of these characteristics is that the upper catchment weir shows two distinct discharge peaks. This characteristic is caused by the cessation of the rainfall for short period of time during the event, before commencing again a few hours later. The sudden decline of the rising limb of the upper catchment weir prior to the secondary peak indicates that there is mainly runoff contributing to the upper catchment's hydrograph. This is evident in the fact that there is no continuous release of water into the stream from the saturated soils or marsh area as observed after the cessation of rainfall during the low intensity event. Since runoff generally only commences after the surface soils become saturated, these observations indicate that the surface soils reach a state of saturation faster in a high intensity event than a low intensity, thus lending credence to the tensiometer observations discussed earlier in this chapter.

The R.O.C. s for the lower and upper catchment are 0.21 and 0.34 respectively, indicating that there is a much higher percentage of rainfall that reaches the stream as runoff in the lower catchment. After the cessation of rainfall, the receding limb declines rapidly, indicating a higher percentage of runoff just after the cessation of rainfall. In general, the high intensity event produces a peak flow an order of magnitude higher than the low intensity event.

6.1.2.4 Pilot Tracer Experiment

The experiment took place on a small hillslope section in the upper catchment. The tracer injection took place after a 3 day rainfall event in October 2000, which left the site saturated. Return flow was seen to emerge from pipes at the toe of the experimental section indicating that saturated conditions prevailed. Results from the sampling are shown in Figure 6.27. The results of the piezometer intensities include a 5 day period where no samples were extracted due to the lack of personnel. From the results it can be seen that the concentrations of tracer are very low in all but two samples at piezometer 3. Although there are small peaks between 24 hours and 48 hours and also between 120 hours and 144 hours after the injection respectively, moving downslope from piezometer 1 to piezometer 3, there is considerable doubt as to whether these are caused by Uranine due to their low concentrations. Accurate detection of the Uranine concentration was hindered by the fact that all the samples had a high sediment content, and even after filtering these samples, strong background fluorescence was detected in the samples. There is clearly an absence of a breakthrough curve in both the piezometer and streamflow samples and the varying intensities do not show any significant pattern. There appears to be a distinct peak at piezometer 3, seventy one hours after the tracer was injected and it can be speculated that since water was observed gushing out of numerous pipes and holes at the toe of the hillslope, lateral movement from pipe flow caused preferential flowpaths to transport the tracer to only one piezometer downslope, bypassing the others.

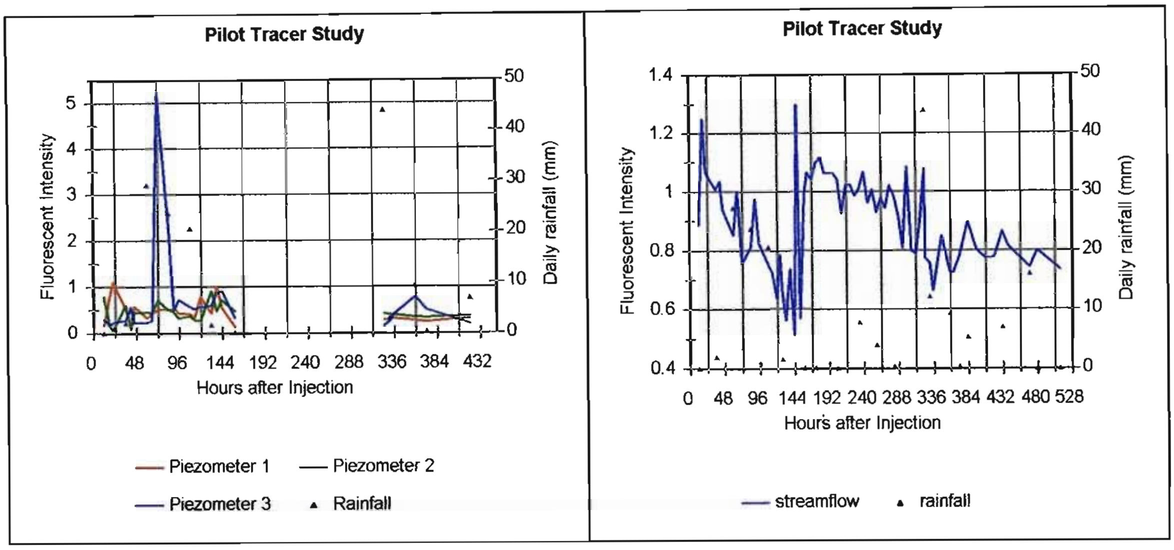


Figure 6.27 Results from the pilot tracer study showing piezometer and streamflow flourescent intensities

This experiment highlights important considerations that need to taken into account before commencing further tracer studies in the future. Tracer sorption into the soils need to be estimated as it was hypothesised that the low concentrations may have been a result of absorption by soil particles. The proximity of the experiment to the marsh may also have resulted in dispersion of the tracer with the marsh's dynamic flux. The volume of tracer used needs to be increased. It is also recommended that more than one tracer type be used in order to compare different breakthrough curves. *In-situ* analysis of at least one of the tracer concentrations needs to be done in order to be able to adjust the sampling frequency at each site accordingly as the macropore and pipes may have resulted in the tracer flowing directly into the stream rapidly.

In conclusion, the experiment did not provide any significant information regarding the runoff generation and subsurface flow characteristics on a hillslope.

6.2 Modelling results

Results from the model simulations are now discussed. Information regarding input menu and parameters can be found in Appendix G. The Contributing Hillslope Sections Approach *(cf.* Section 3.2) was used in applying the *HILLS* model to the upper catchment area of the Weatherley catchment since it is a small catchment with localised gullies and seeps that play an important role on the hillslope hydrology. By applying this approach, the hillslopes could be divided up into a number of segments and each segment modelled separately. This is advantageous in a catchment that has a high degree of heterogeneity with regard to its hillslope characteristics.

In simulating the upper catchment area at Weatherley, two hillslope segments were determined that were considered representative of the upper catchment areas hillslopes. The first segment, segment 1, is 200 metres long and runs downslope next to transect 1 in the upper catchment (Figure 5.2). Segment 1 and its hillslope characteristics were estimated to represent approximately 25 percent (0.075 km^2) of the upper catchment's area of 0.325 km^2. Segment 2, which is 520 metres long, runs downslope next to transect 2 in the upper catchment and its hillslope characteristics are representative of 75 percent (0.25 km^2) of the upper catchment's area. Runoff from the two segments were area weighted and these values combined to give the total simulated runoff from the upper catchment area. The main differences between segment 1 and segment 2 can be seen in the input menus which are shown in Appendix G. Apart from the topography and general soil physical and hydraulic properties being different, the segment parameters do not vary significantly from each other. One difference is the anisotropy factor, FISOT, which relates the horizontal and vertical conductivities of the soils. The FISOT parameter on segment 1 has been set so that there is a slightly more pronounced horizontal conductivity than at segment 1, as segment 1 has a steeper slope and many visible pipes and macropores which allow for lateral flow in the surface layers. Figure 6.28 shows the simulated and observed runoffs for event 2. The simulated hydrograph appears to respond in a similar manner to that of the observed hydrograph. The shape of the peaks, however appear to be sharper than the observed peaks indicating that the segments are responding at a faster rate than observed in the catchment.

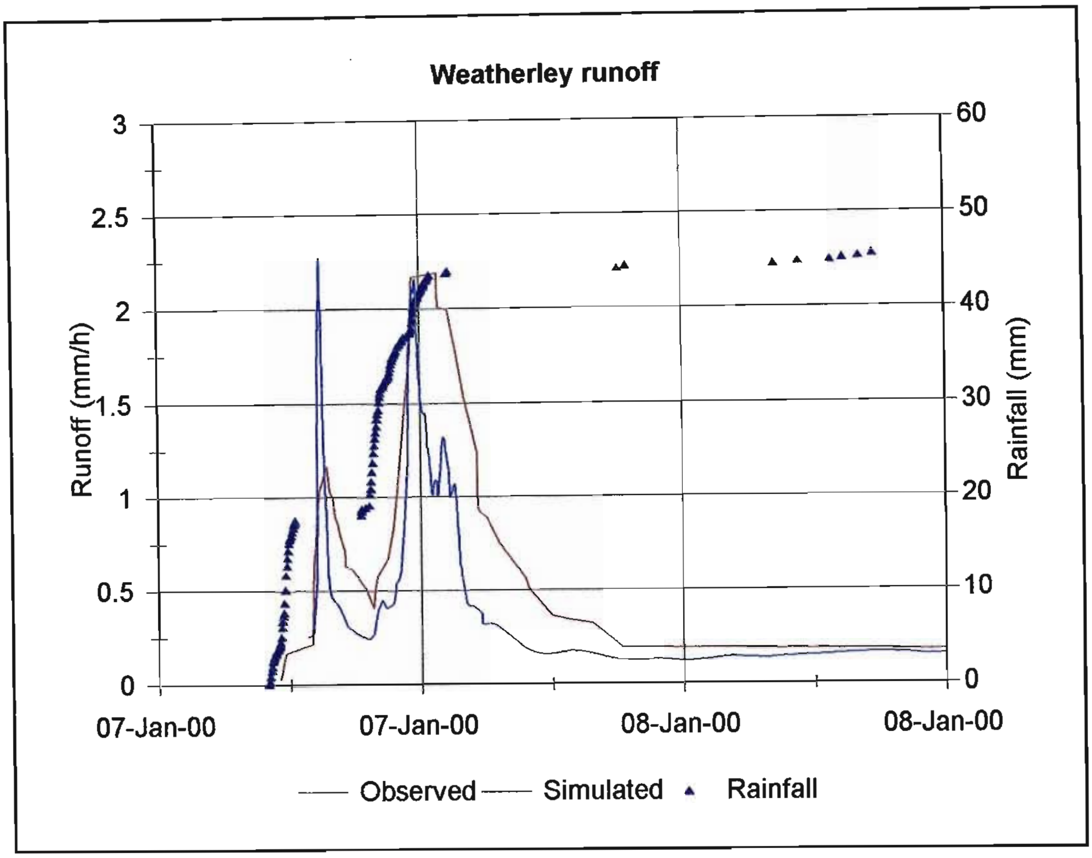


Figure 6.28 Simulated vs observed runoff generated from the upper catchment area during Event 2 on the 7 January 2000

The reason could be that the *HILLS* model assumes that water in the unsaturated zone only moves in a vertical direction at the rate specified by the vertical conductivity, K_u (*cf.* Figure 4.1), and saturated flow only occurs once the depth to the soil bedrock interface has become saturated, and does so at the rate specified by the horizontal conductivity (K_h). In reality, the upper catchment has numerous macropores and pipes which allow for the rapid infiltration into the deep soils (*cf.* discussion of Figure 6.20). Since there is no macropore flow option in the *HILLS* model, the simulation produces steep and sharp runoff peaks that characterise rapid runoff from a high intensity event. The absence of infiltration into the soils due to macropore flow is also evident in the fact that the receding limb of the simulated runoff (Figure 6.29) does not show the slow release of subsurface flows into the marsh and stream as seen in the observed runoff. The cumulative observed and simulated runoff's for the event are shown in Figure 6.33. Accurate results are obtained from the total volume of runoff simulated using the *HILLS* model as seen by the fact that on the 10 January at midday, 12.2 mm.h^{-1} was simulated compared to the observed volume of 11.9 mm.h^{-1}. The shape of the cumulative runoff graph also shows that the simulation does not account for initial infiltration into the soils, but shows rapid runoff from the hillslope into the marsh. The observed results show a slow desorption of water out of the soils into the marsh and stream. The fact that the total volume of runoff simulated is similar to the total observed runoff three days after the event once the receding hydrograph limbs had reached equilibrium shows that the model performs satisfactory at the Weatherley catchment.

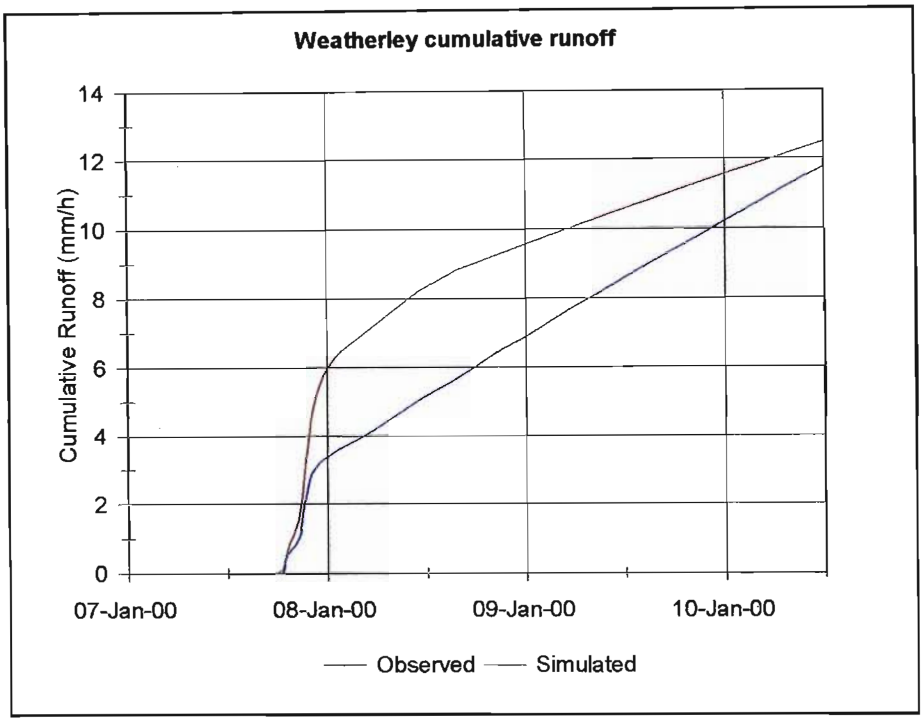


Figure 6.29 Simulated vs observed cumulative runoff generated from the upper catchment area during Event 2 on the 7 January 2000

This chapter has presented and discussed the results from extensive fieldwork and monitoring networks at the Weatherley catchment. These results have given a clear and concise interpretation of the hillslope processes that occur. Using this understanding, the hillslope's runoff was simulated. The results show that catchment runoff can be accurately simulated using hillslope hydrological processes provided a clear understanding of the sub-surface processes at the hillslope scale is achieved. The next chapter presents concluding remarks on this study.

7. SUMMARY AND CONCLUSIONS

A hillslope is subject to highly complex subsurface processes that are seldom fully understood by catchment modellers. These subsurface processes and their interactions with each other are often a major factor affecting a small catchment runoff response. Owing to the importance of hillslope subsurface processes, a number of models that use these processes to simulate catchment runoff have been developed over the years. An attempt was made to group these different runoff models according to the approach they used in modelling the hillslope.

Relative merits and shortcomings of theses modelling approaches were discussed. It was concluded that there is no universally acceptable method or approach to modelling a catchment's runoff using subsurface processes as each catchment is unique and the approach adopted accordingly. In adopting an approach, a clear understanding of the subsurface processes needs to be gained prior to using a model to simulate small catchment runoff.

With a clear understanding of how the hillslope processes affect the catchment response, methods of determining the hillslope subsurface processes were devised. These included a comprehensive monitoring network of tensiometers, piezometers and Crump weirs. In addition to this, soil physical and hydraulic characteristics were determined from in field and laboratory experiments. These experiments included the use of tension infiltrometers and double ring infiltrometers to determine unsaturated and saturated hydraulic conductivities respectively. Where these tests could not be performed due to saturated conditions, the auger hole method was used. Soil physical characteristics (bulk densities and porosity) and WRC were determined in the laboratory using the corer method and the controlled outflow cell method respectively.

With the methodology on how to determine the subsurface processes and the monitoring network setup, a hillslope model using subsurface processes as its main component to simulate small catchment runoff was chosen. A recently updated version of the *HILLS* numerical hillslope model (Hebbert and Smith, 1996) was used.

The main hillslope subsurface processes, their interactions and their effect on the small catchment runoff at the Weatherley catchment have been identified and described. A high degree of spatial heterogeneity exists in the soil profiles at the Weatherley catchment. Different soil forms result in different physical and hydraulic characteristics along the hillslopes. Different conductivity values were measured in repetitions as close a 1 metre apart. The key findings can be summarised as follows.

1. Despite being highly heterogeneous, with deviations from the general observations occasionally being observed, the general soil physical and hydraulic characteristics followed similar trends at each of the hillslope transects. There was a general decrease in hydraulic conductivities with depth down a profile corresponding to an increased clay content.

2. The unsaturated hydraulic conductivities decreased down the hillslopes towards the toe of the slope and marsh areas. The crests of the hillslopes all tended to have a high sand content resulting in high bulk densities and freely draining soils.

3. In most cases, the saturated conductivities were an order of magnitude higher than the unsaturated conductivities on or just below the surface soils, thus indicating the presence of macropores in the surface layers of the soil.

4. Where a high degree of coarse unconsolidated material was observed in the field (UC9, UC8 and nest 7), the hydraulic conductivities and WRCs showed a high pore size distribution which allows for rapid drainage of water from the soils at a low tension.

5. The soil's water holding capabilities tended to increase with depth down the profiles as indicated by the WRCs. A noticeable exception occurred at UC9 where the water retention capability was found to be low near the bedrock, resulting in rapidly drained soils. A general increase in the soil water holding capability down the slope towards the marsh was observed, as indicated by the WRC. This, coupled with the fact that high porosity values were obtained in the marsh areas, leads to the conclusion that the marsh

area has a high water content which is present throughout the year and is a dominant factor in affecting the catchment response to rainfall events.

6. The marsh area in the lower catchment showed a deviation from the general trend with the bulk densities increasing downslope towards the stream from below the rock outcrop at nest 6. The increasing bulk densities towards the stream indicated a higher sand content in the soil component. The presence of macropores causes rapid draining soils in the vicinity of the stream, which allows for rapid flows from the marsh area into the stream.

Before tensiometer data were analysed, a controlled tensiometry experiment was conducted in order to assess the accuracy of the tensiometers, especially with regard to different amounts of water in the bubble tubes as well as the effect of temperature on the tensiometers. The results from this experiment show that the tensiometer readings are prone to diurnal fluctuations that result in the minute air bubbles in the tensiometer expanding and contracting due to temperature and direct sunlight effects.

The tensiometer data reflected the general consensus obtained from soil characteristics experiments. Tensiometer responses to rainfall events were rapid and allowed for the rapid wetting up of the soils. Flow accumulation at the toe of the hillslopes occurred due to ponded conditions on the bedrock. This accumulated flow often resulted in saturation wedges forming and causing water to be exfiltrated out of the soil as return flow. High intensity events producing large volumes of rainfall caused the soils to wet up rapidly on the crests and midslopes due to macropore and pipe flows. This, in turn, led to the rapid recharging of groundwater tables and a high degree of runoff. A low intensity event did not allow the deep soils to wet up as much nor contribute to the groundwater tables in the crests and midslopes, but rather caused the surface soils to a depth of 0.2 m to reach saturation and aid in the formation of perched water tables. Lateral flow would then drain water from the perched water tables. Tensiometer data from the marsh areas show a constantly saturated or near saturated state throughout the year. Subsurface flows from the hillslopes and groundwater tables also ensured that the marsh was constantly saturated. Consequently, regardless of the intensity of the event, water falling onto or nearby the marsh was rapidly transferred into the stream as storm runoff. When the groundwater tables on the crest and midslopes receded, the marsh was seen to recede correspondingly.

The runoff data from the two Crump weirs showed that the catchment has a rapid response to a rainfall event. A low intensity event produced similar R.O.Cs for both the upper and lower catchment areas, resulting in similar peak discharges. A low intensity event allowed for a slow continuous release of water into the stream from the marsh while a high intensity event produced results associated with a rapid overland flow. The R.O.Cs of the high intensity event showed that there is a higher rate of runoff in the lower catchment compared to that of the upper catchment, indicating that the upper catchment soils have higher infiltration rates and better soil water holding capabilities. This is consistent with the findings of Hickson (1999).

Owing to the poor recovery of the plume signal, results from the pilot tracer study do not provide any significant information regarding the subsurface fluxes at the Weatherley catchment, but rather serve as a foundation on which to base further tracer studies.

The initial simulated results from the *HILLS* models have shown that simulating small catchments runoff with hillslope process observations may be achieved, provided the modeller has a sound knowledge of the hillslope processes and the model accommodates these processes adequately. Using parameters derived from intensive monitoring, the *HILLS* model was used in an initial modelling exercise to simulate runoff from the upper catchment area. The Contributing Hillslope Sections Approach was used and involved using two segments from the upper catchment to simulate the runoff. The segments were the area weighted and the simulated runoff combined and compared to the observed runoff. Although the simulation was accurate in terms of accumulated runoff, the hydrograph shapes did not reflect the initial infiltration that occurs due to macropores in the presence of a high intensity event. Since the model lacks a macropore component, the rainfall resulted in sharp and steeply ascending and receding limbs of the hydrograph which characterises rapid runoff from a high intensity event.

These results can be improved by allowing for more infiltration into the soil by adding a macropore function to the model.

In the light of proposed afforestation at the Weatherley catchment, this dissertation has set out to provide a sound understanding of the processes that occur at Weatherley. Continued research of this kind during and after afforestation of the catchment will provide an invaluable source of knowledge pertaining to the effects of afforestation on localised small scale processes in the northern parts of the Eastern Cape Province.

8. RECOMMENDATIONS FOR FUTURE RESEARCH

Research work conducted at the Weatherley experimental catchment by Esprey (1997) as well as the work presented in this dissertation provides a comprehensive and detailed account of the subsurface processes that occur at Weatherley as well as how these processes affect the small catchment's runoff. The catchment runoff was successfully simulated using hillslope hydrological process observations. In the light of the foreseen afforestation at Weatherley, recommendations for future research include the following:

- Monitoring of the current sites in both the upper and lower catchment areas during and after afforestation should be continued in order to assess the effect of land use change on the local subsurface processes.

- A full scale tracer study should be conducted using more than one tracer in order to fully assess the effects of macropore and pipe flow on the soil water dynamics.

- A more detailed WRC analysis along the remaining transectsmust be completed in order to determine any anomalies in the presented results.

- Automatic piezometers in at least one full transect in the upper catchment area are required so that the continuous groundwater fluxes in both the upper and lower catchment can be compared and their influence on the resulting hydrograph assessed.

- Sediment yield analyses on samples of streamflow at the lower catchment weir should be conducted to assess the impacts of afforestation on the catchment's sediment yield.

- The *HILLS* model should be refined with regard to providing a macropore and variability of hydraulic property component to the model and

- The *HILLS* model should be used to predict the effects of land use change on the small catchment runoff during and after afforestation.

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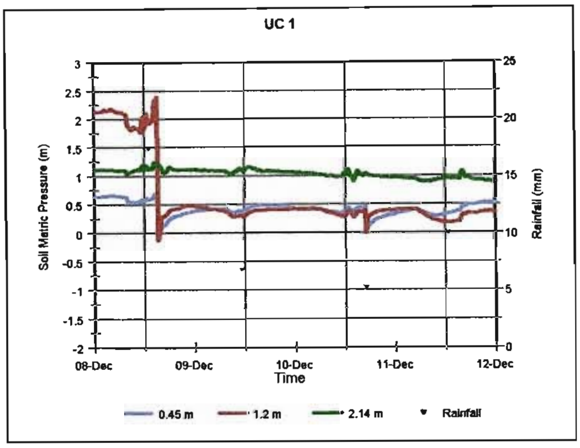
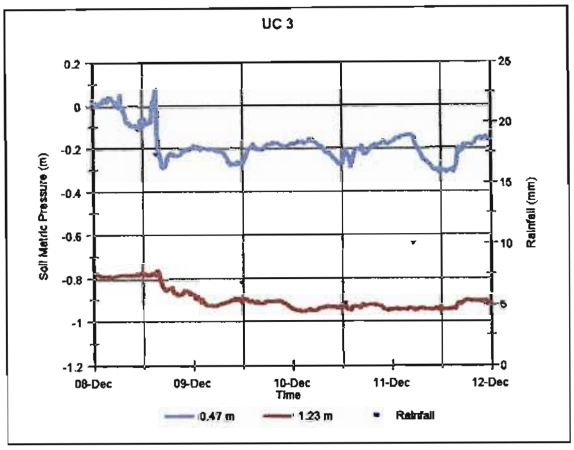
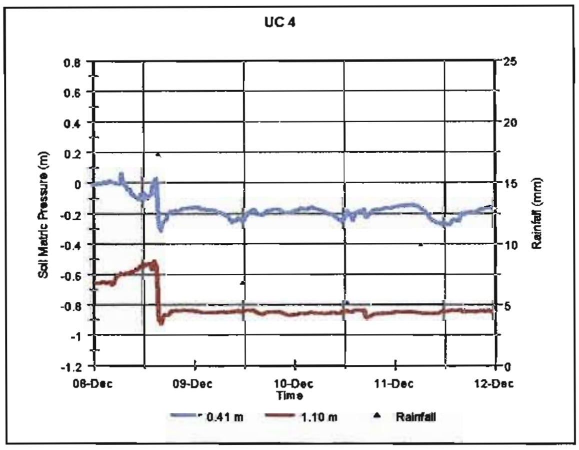
APPENDIX A

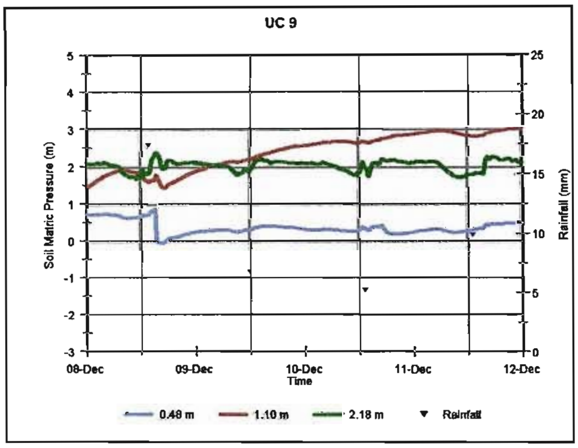
Appendix A contains tensiometer data for transects 1 to 3, 8 - 11 December 1999.

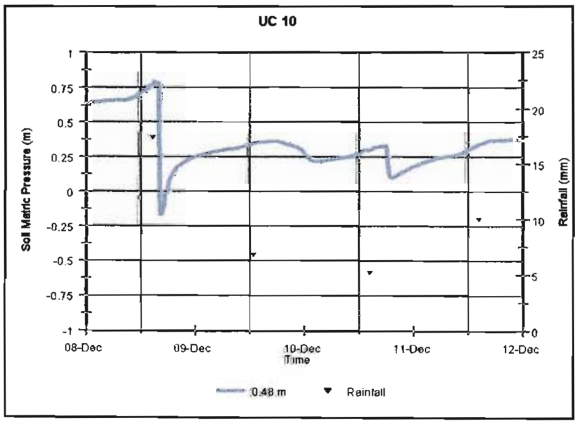
Tensiometer data from Transect 1.



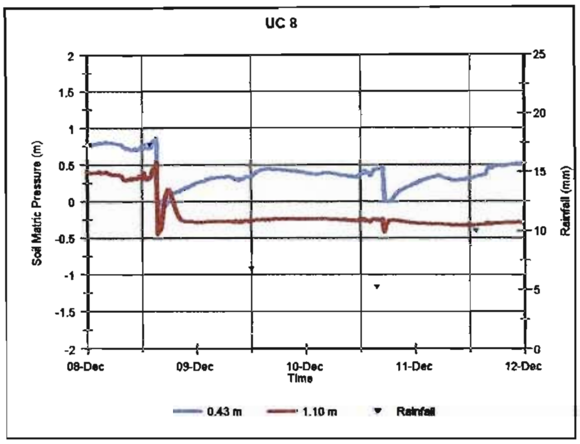


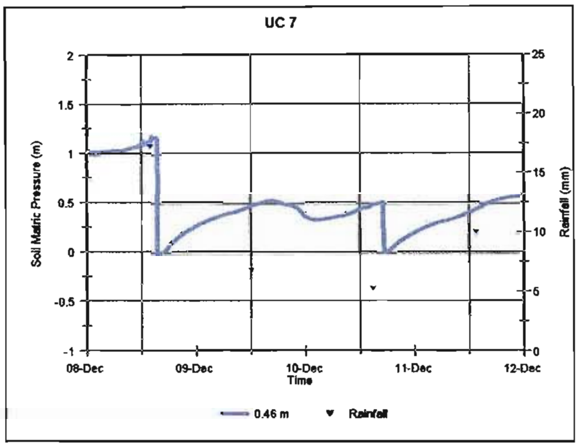


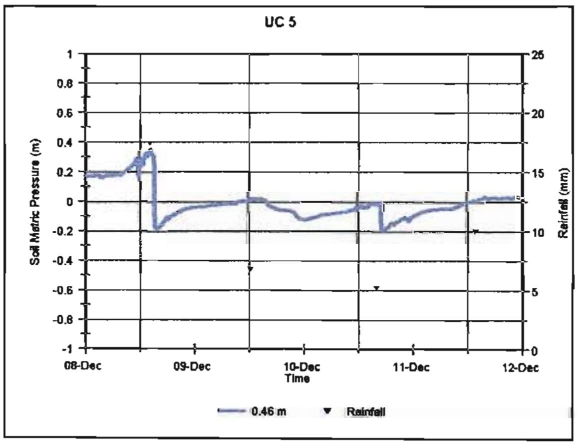


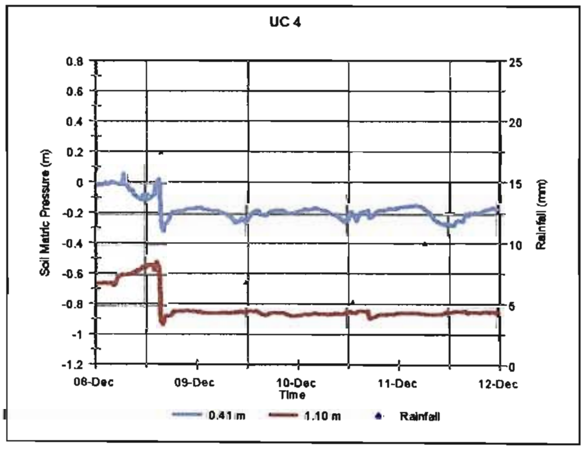


Tensiometer data from transect 2.

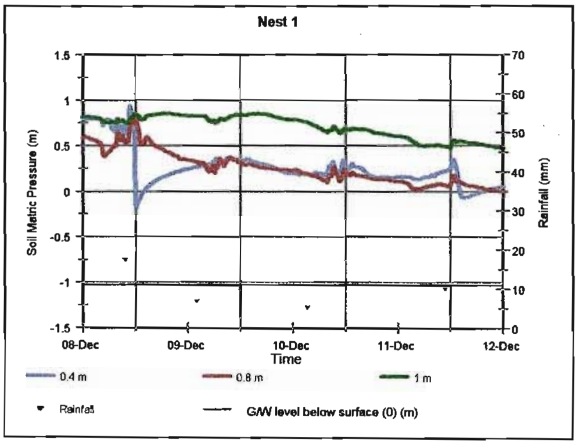


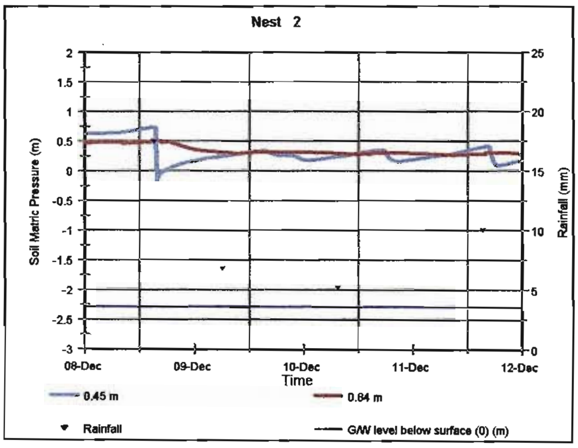


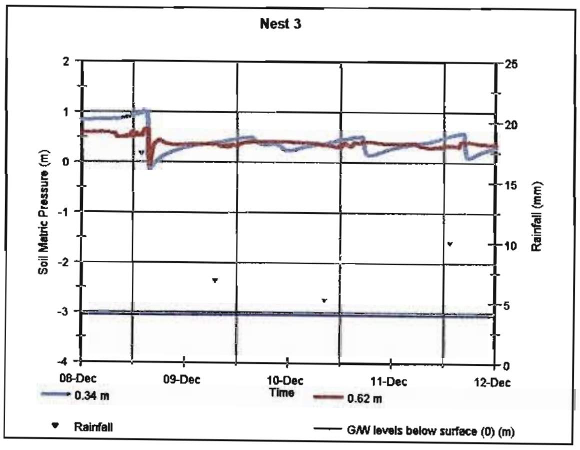


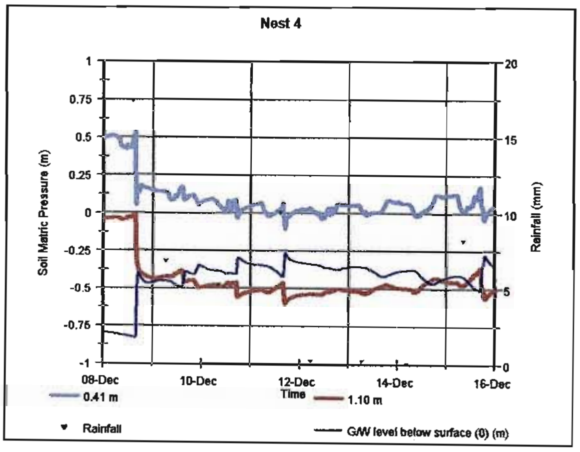


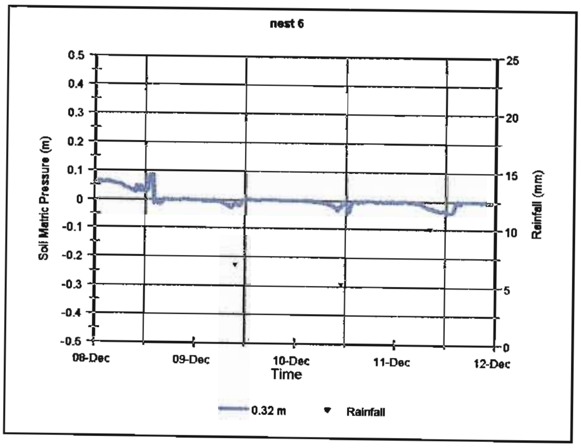
Tensiometer and automated piezometer data for transect 3.







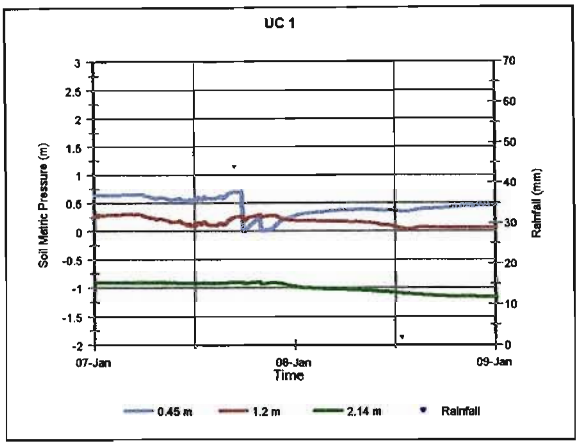


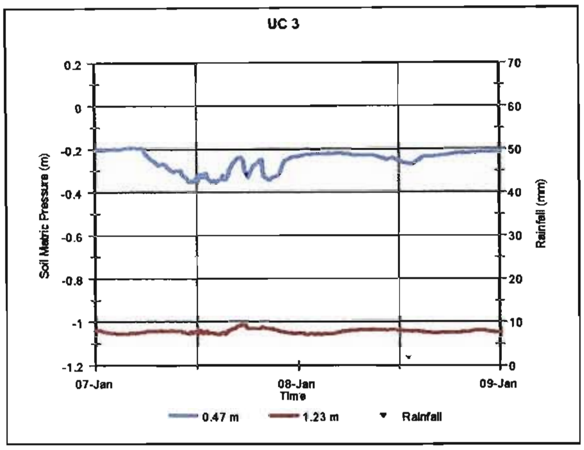


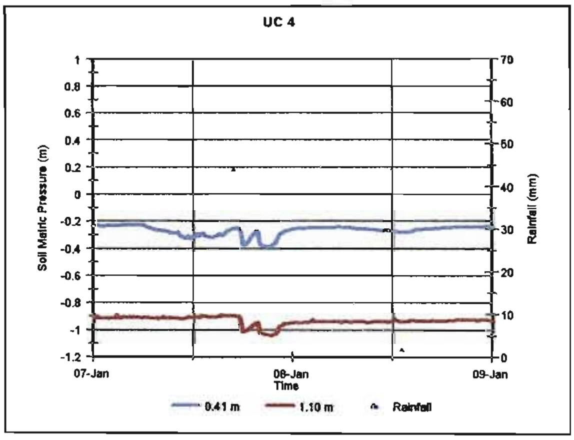
APPENDIX B

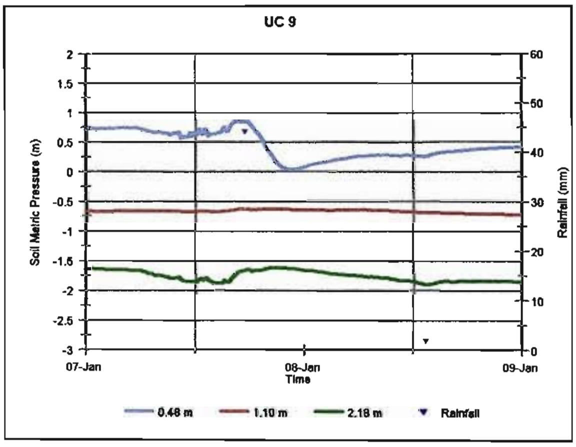
Appendix B contains tensiometer data for transects 1 to 3, 7 January 2000.

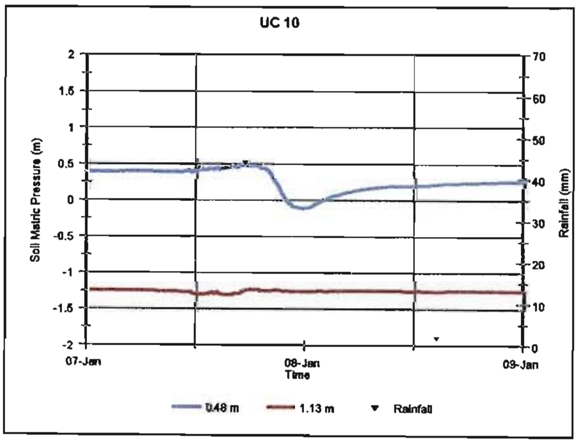
Tensiometer data from transect 1



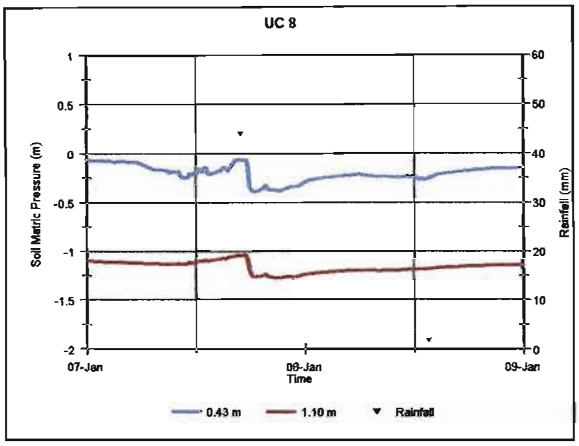


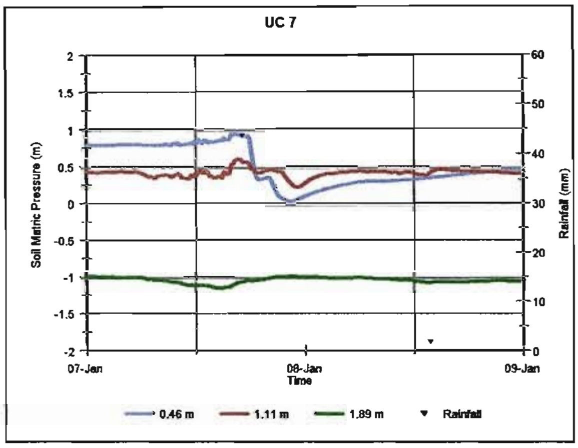


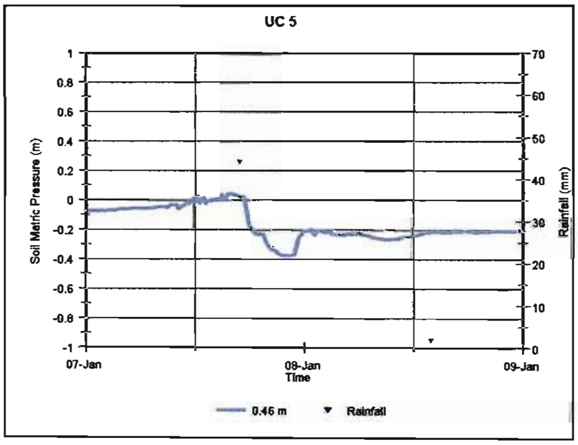


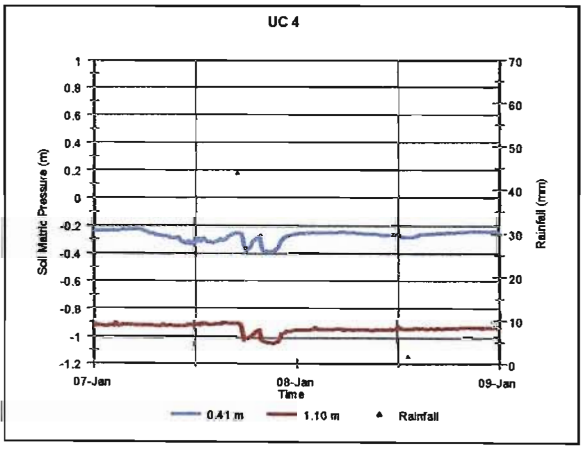


Tensiometer data from transect 2.

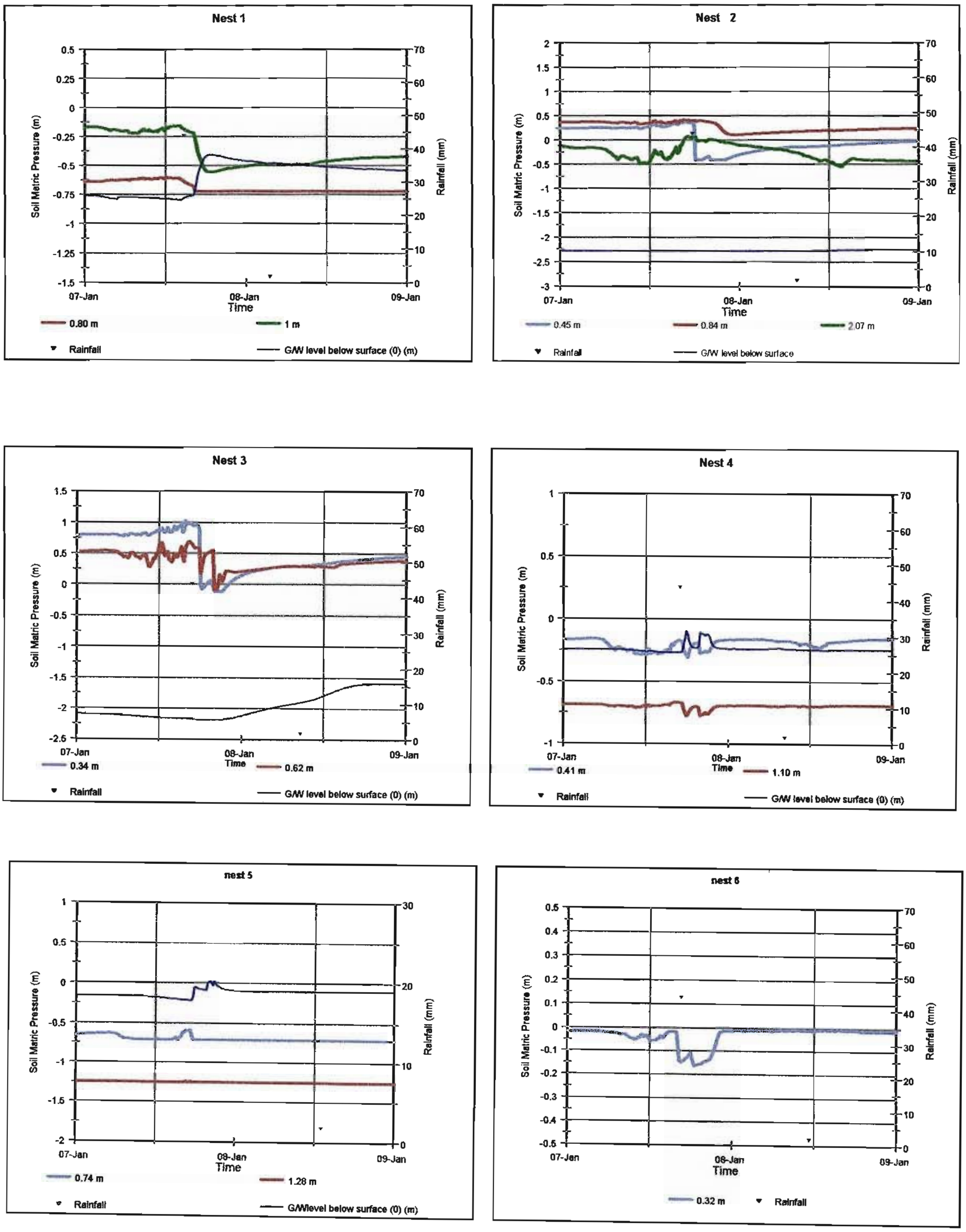






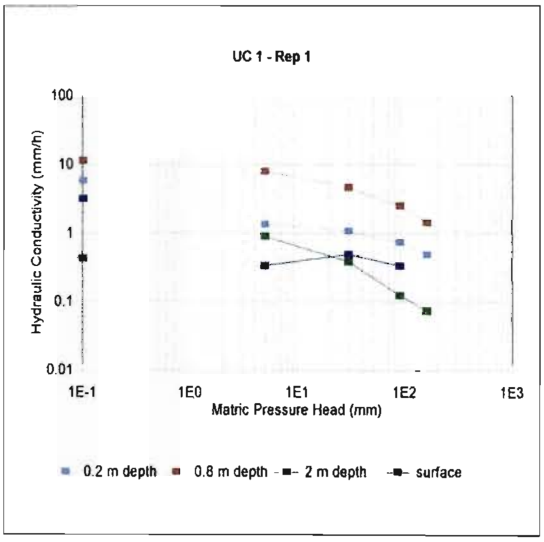


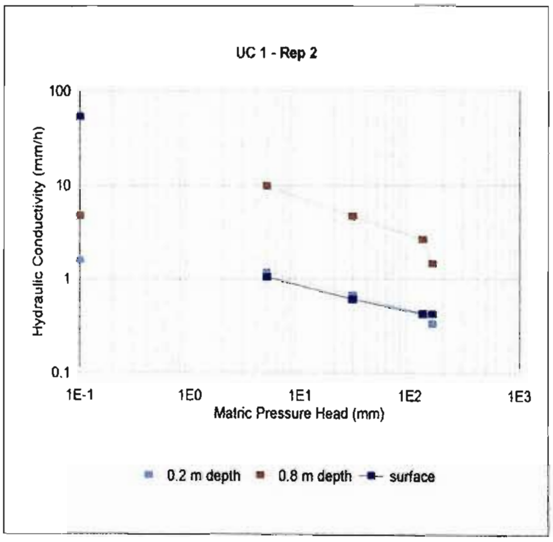
Tensiometer and automated piezometer data for transect 3.

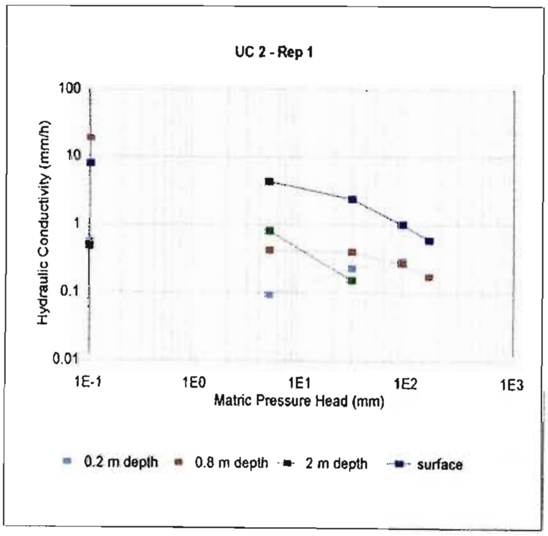


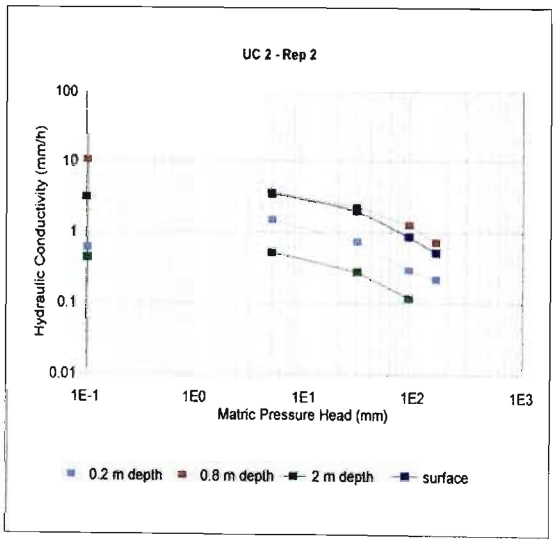
APPENDIX C

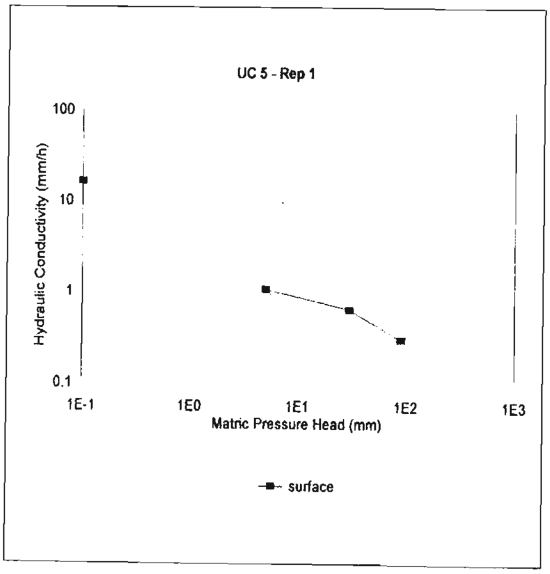
Appendix C: soil hydraulic characteristics data. Unsaturated hyraulic conductivity is shown on the line graph and the saturated hydraulic conductivity is shown on the y-axis

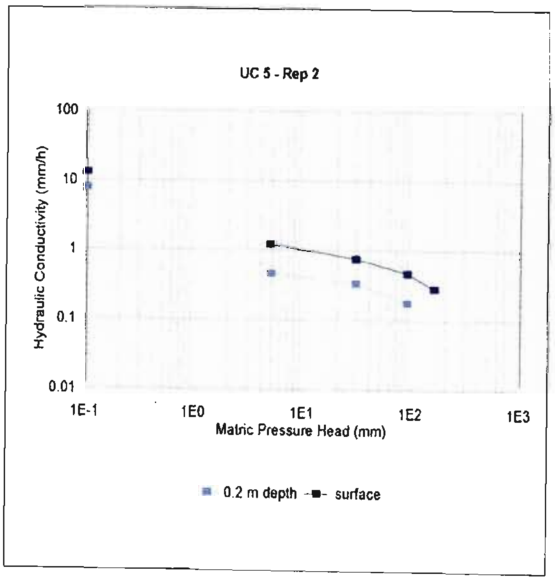


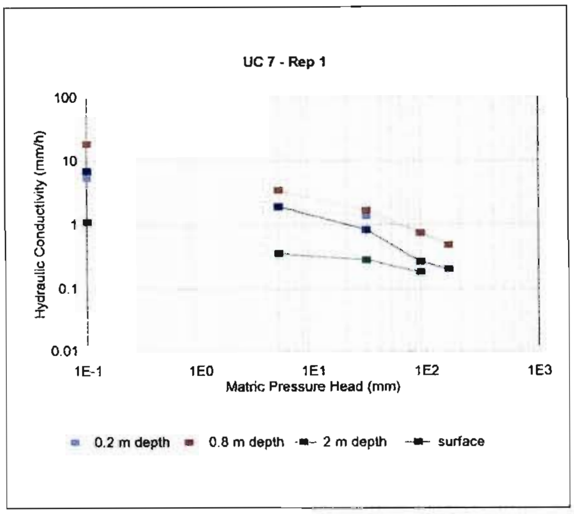


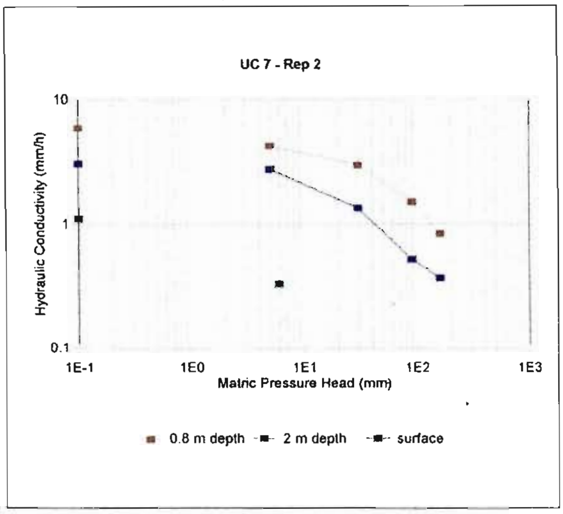


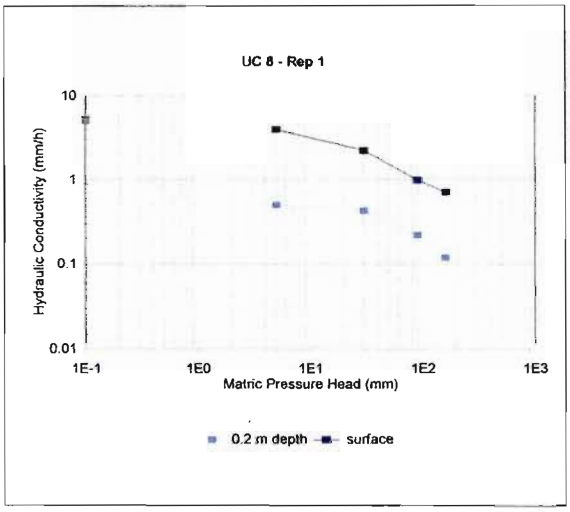


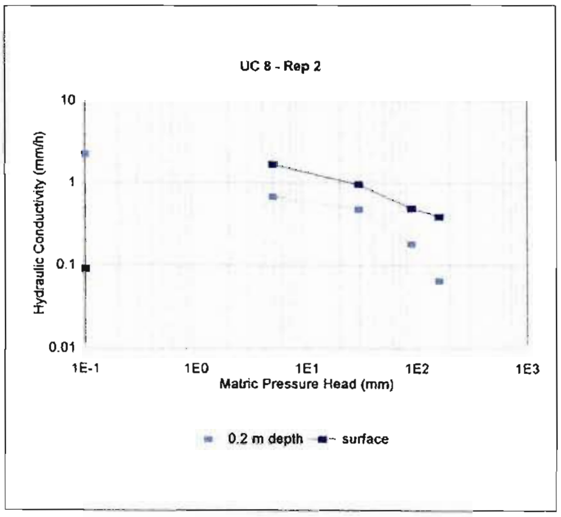


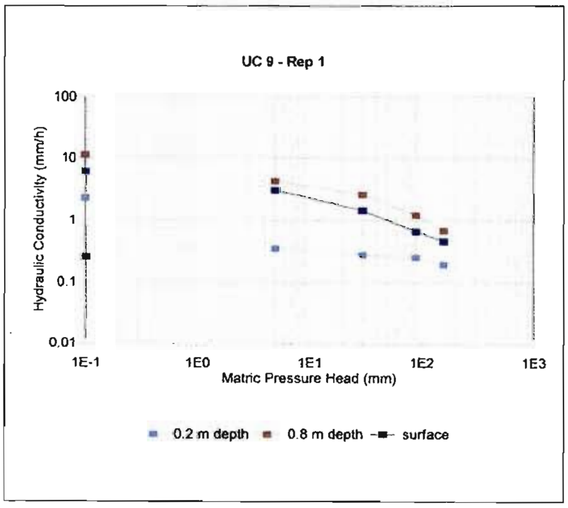


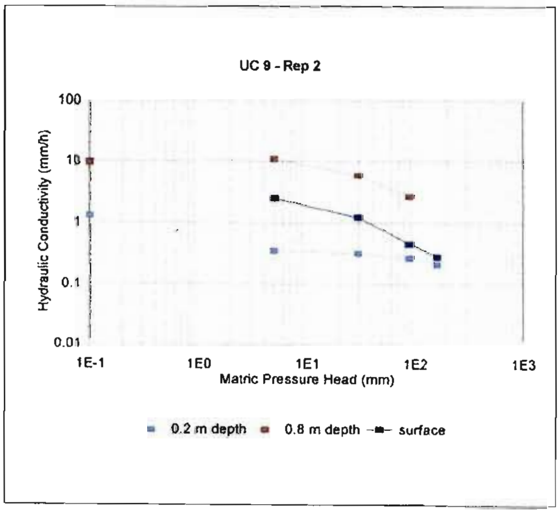

UC 7 - Rep 1
Hydraulic Conductivity (mm/h)
100
10
1
0.1
0.01
1E-1
1E0
1E1
1E2
1E3
Matric Pressure Head (mm)
0.2 m depth
0.8 m depth
2 m depth
surface

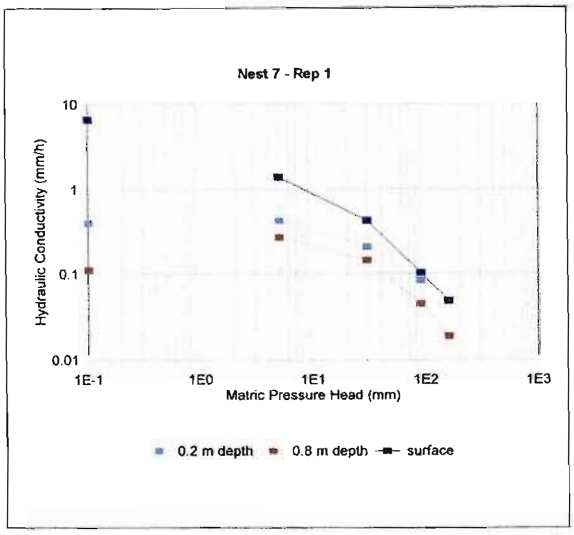

UC 7 - Rep 2
Hydraulic Conductivity (mm/h)
10
1
0.1
1E-1
1E0
1E1
1E2
1E3
Matric Pressure Head (mm)
0.8 m depth
2 m depth
surface

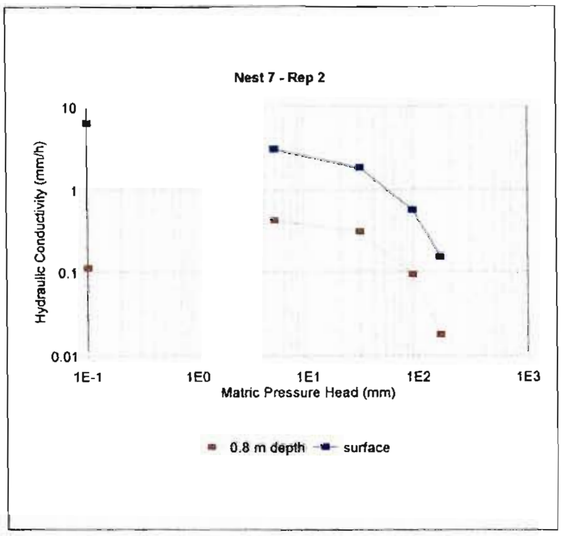

UC 8 - Rep 1
Hydraulic Conductivity (mm/h)
10
1
0.1
0.01
1E-1
1E0
1E1
1E2
1E3
Matric Pressure Head (mm)
0.2 m depth
surface

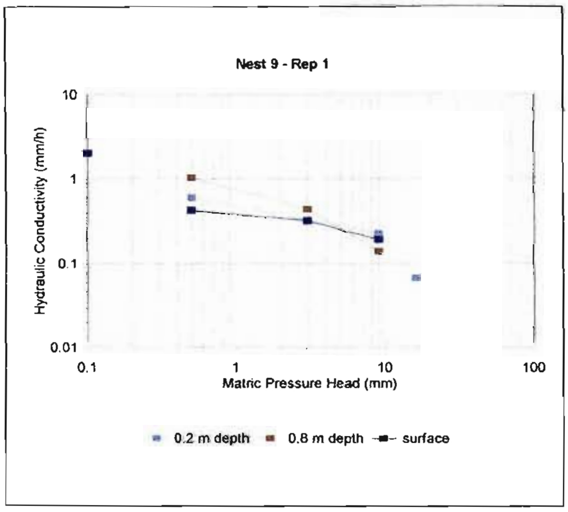

UC 8 - Rep 2
Hydraulic Conductivity (mm/h)
10
1
0.1
0.01
1E-1
1E0
1E1
1E2
1E3
Matric Pressure Head (mm)
0.2 m depth
surface

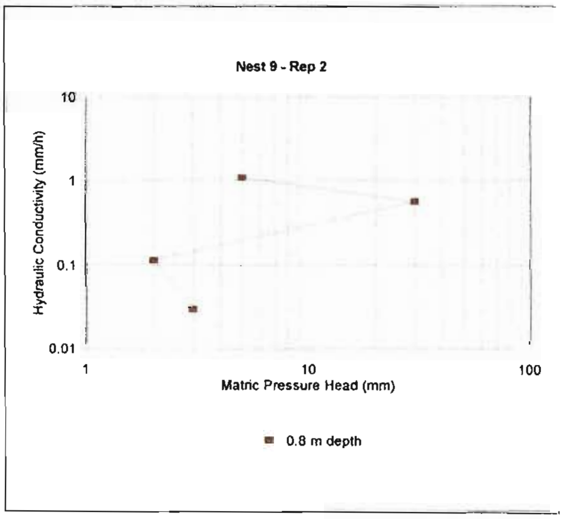

UC 9 - Rep 1
Hydraulic Conductivity (mm/h)
100
10
1
0.1
0.01
1E-1
1E0
1E1
1E2
1E3
Matric Pressure Head (mm)
0.2 m depth
0.8 m depth
surface

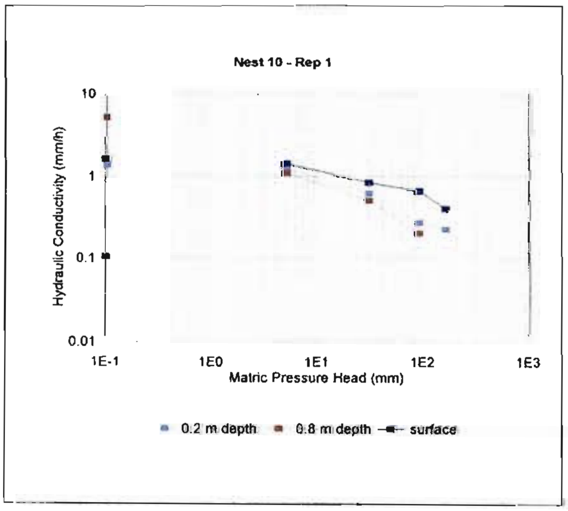

UC 9 - Rep 2
Hydraulic Conductivity (mm/h)
100
10
1
0.1
0.01
1E-1
1E0
1E1
1E2
1E3
Matric Pressure Head (mm)
0.2 m depth
0.8 m depth
surface

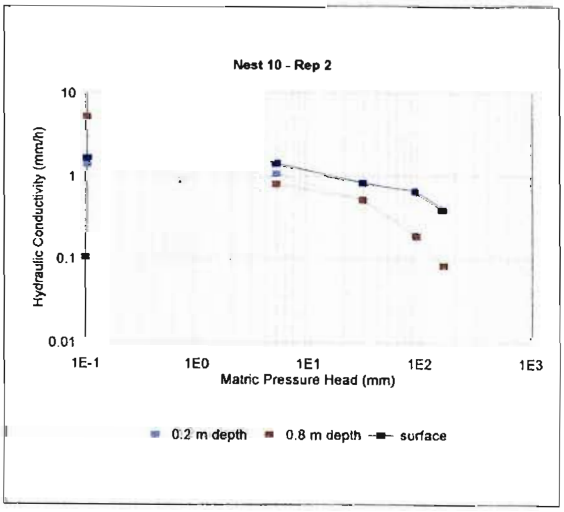

Nest 7 - Rep 1
Hydraulic Conductivity (mm/h)
10
1
0.1
0.01
1E-1
1E0
1E1
1E2
1E3
Matric Pressure Head (mm)
0.2 m depth
0.8 m depth
surface


Nest 7 - Rep 2
Hydraulic Conductivity (mm/h)
10
1
0.1
0.01
1E-1
1E0
1E1
1E2
1E3
Matric Pressure Head (mm)
0.8 m depth
surface


Nest 9 - Rep 1
Hydraulic Conductivity (mm/h)
10
1
0.1
0.01
0.1
1
10
100
Matric Pressure Head (mm)
0.2 m depth
0.8 m depth
surface

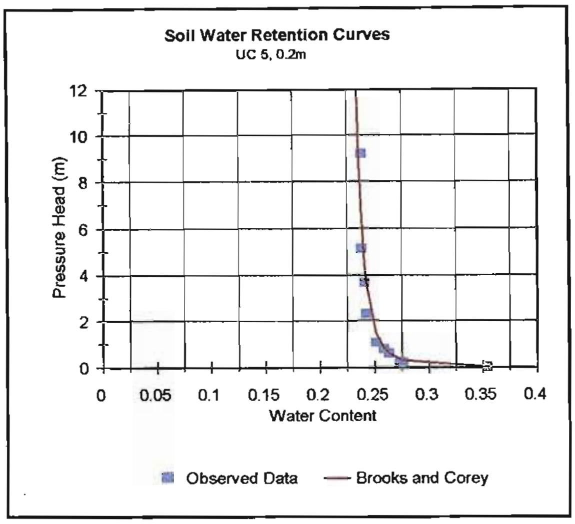

Nest 9 - Rep 2
Hydraulic Conductivity (mm/h)
10
1
0.1
0.01
1
10
100
Matric Pressure Head (mm)
0.8 m depth

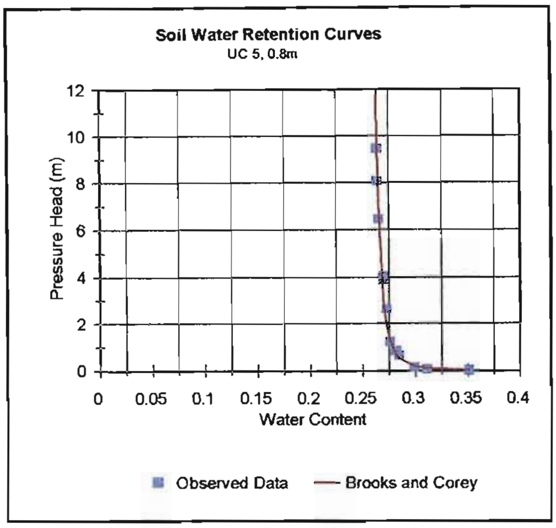

Nest 10 - Rep 1
Hydraulic Conductivity (mm/h)
10
1
0.1
0.01
1E-1
1E0
1E1
1E2
1E3
Matric Pressure Head (mm)
0.2 m depth
0.8 m depth
surface

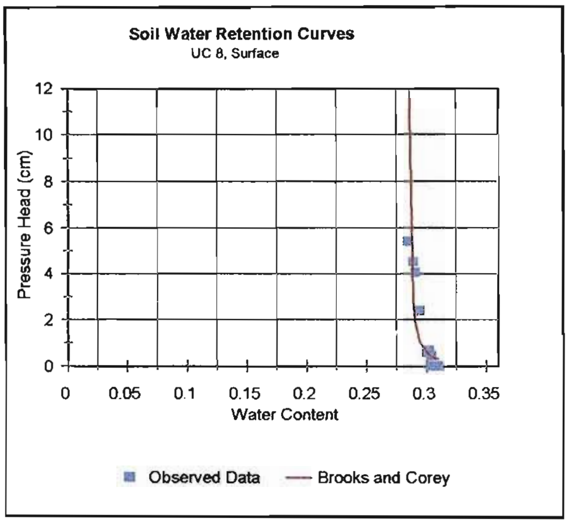

Nest 10 - Rep 2
Hydraulic Conductivity (mm/h)
10
1
0.1
0.01
1E-1
1E0
1E1
1E2
1E3
Matric Pressure Head (mm)
0.2 m depth
0.8 m depth
surface

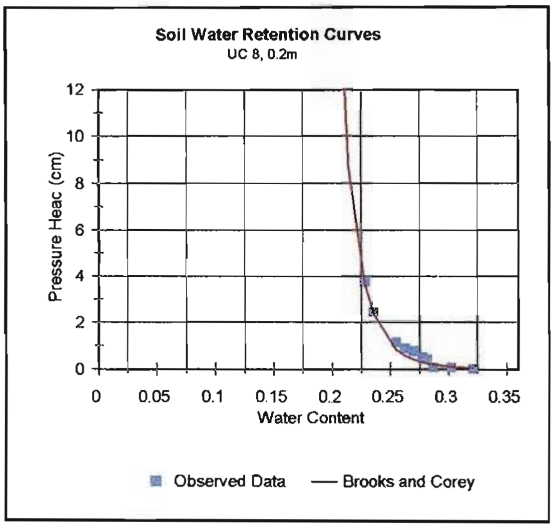
APPENDIX D

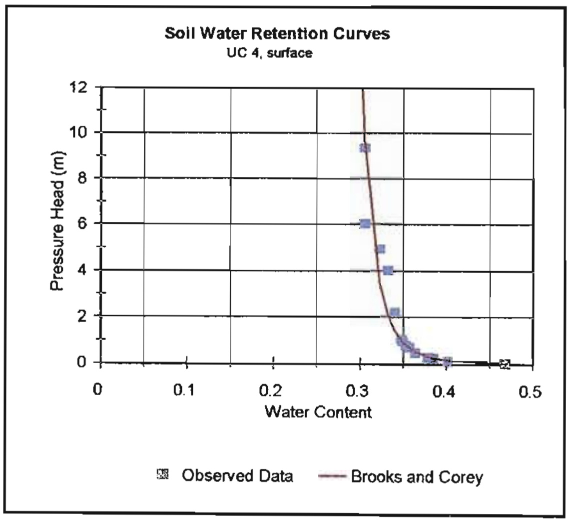
Appendix D contains water retention characteristic graphs with Brooks and Corey (1964) curves fitted to the data.

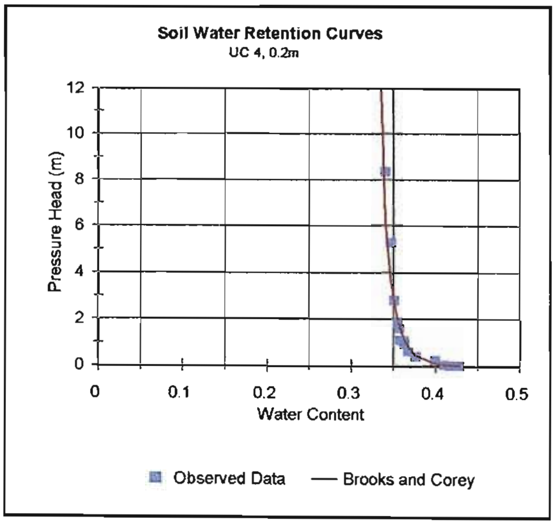


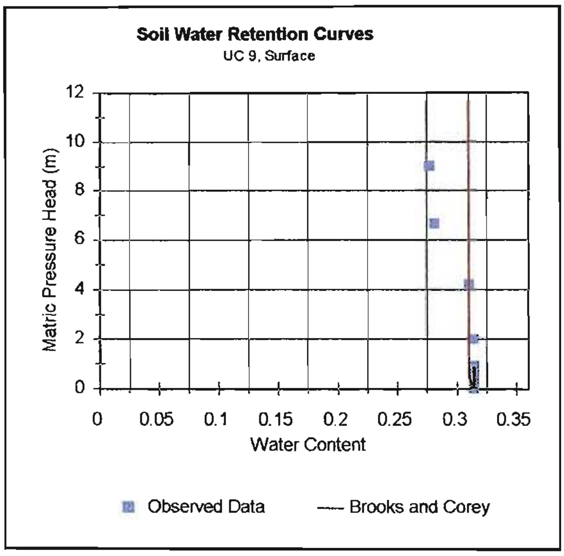


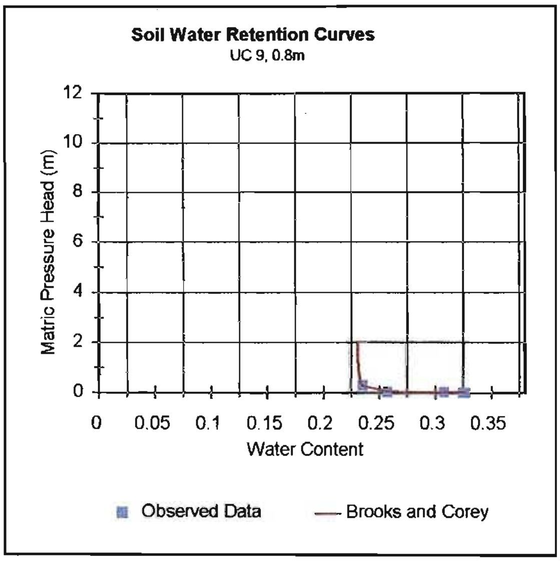









Soil Water Retention Curves
UC 9, Surface
Matric Pressure Head (m)
12
10
8
6
4
2
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Water Content
Observed Data
Brooks and Corey


Soil Water Retention Curves
UC 9, 0.8m
Matric Pressure Head (m)
12
10
8
6
4
2
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Water Content
Observed Data
Brooks and Corey

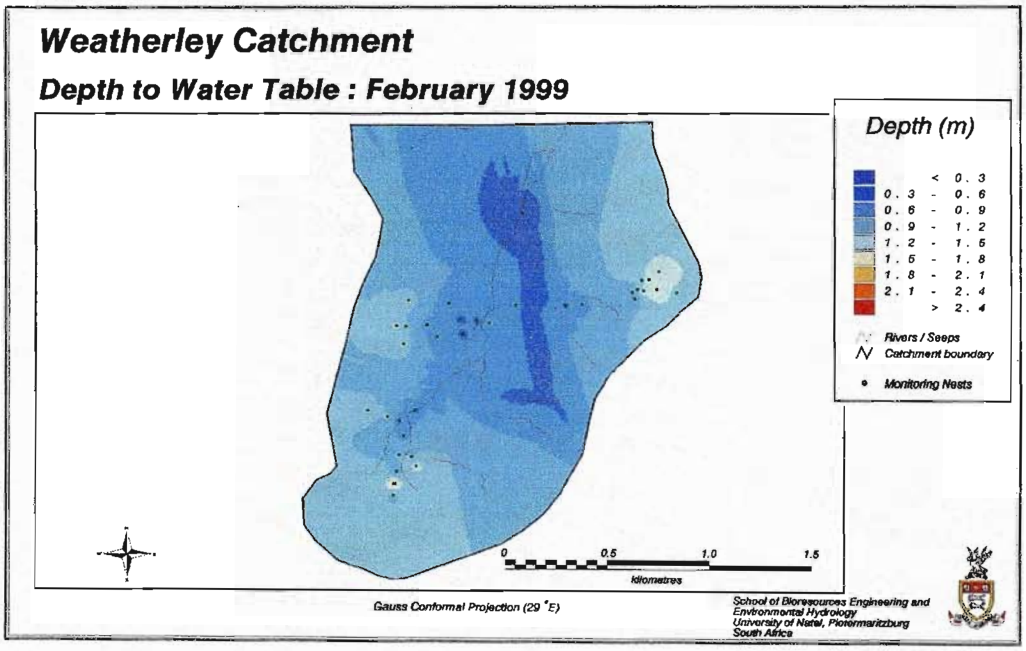
APPENDIX E

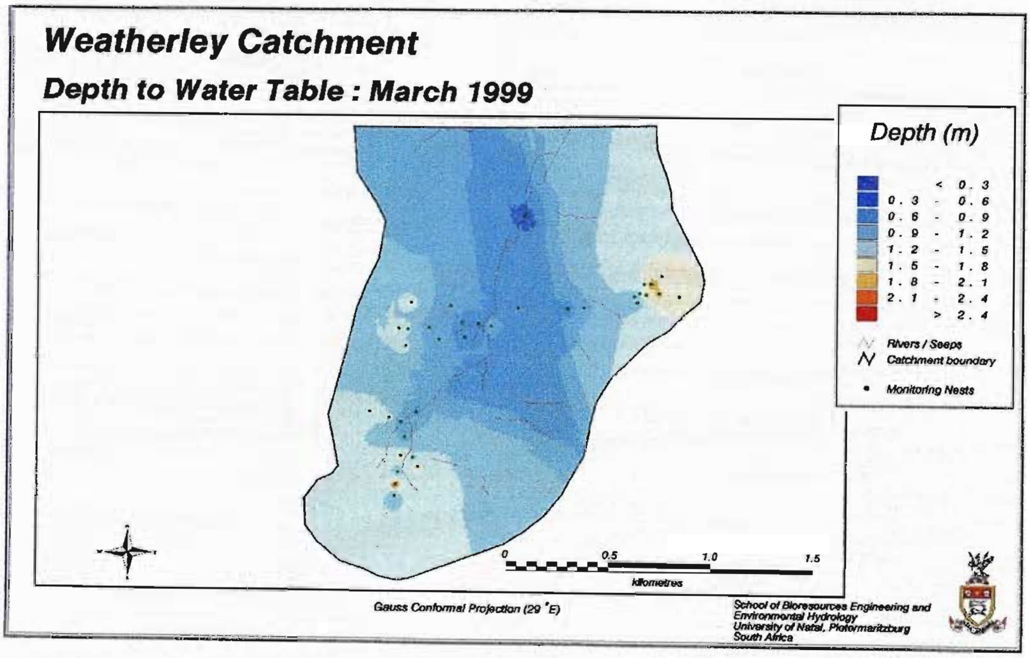
Appendix E contains bulk densities derived from the corer method as well as the outflow cell method from selected sites at Weatherley.

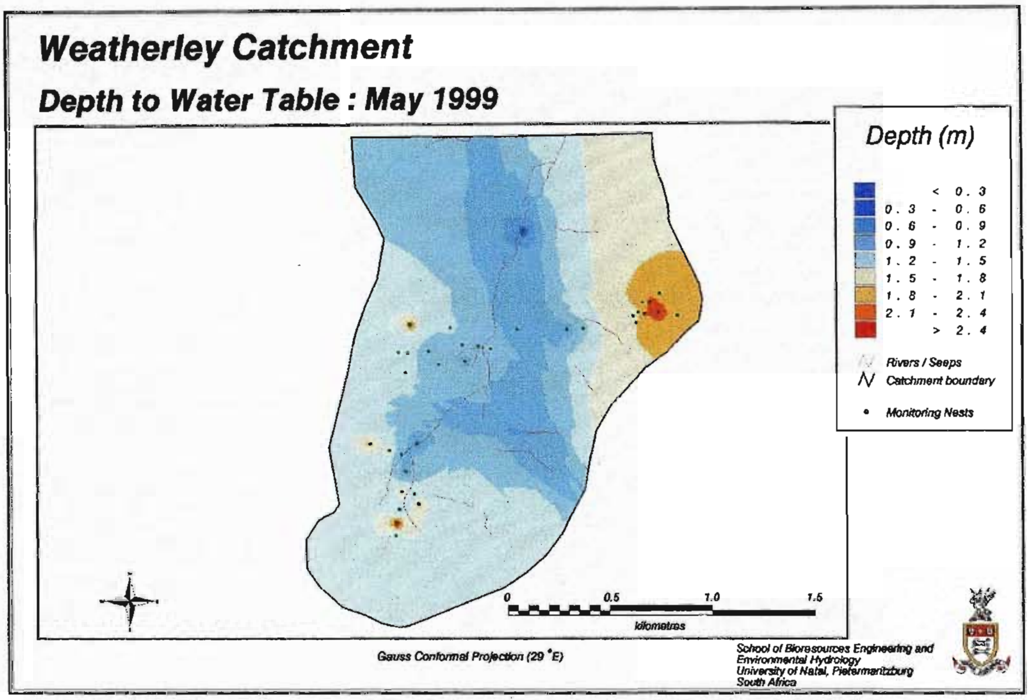
Site	Location/depth	Corer Method		Outflow method	
		ρ_b (kg/m^3)	ϕ	ρ_b(kg/m^3)	ϕ
A	Surface between uc1 & uc2	1.57	0.408		
B	Surface between uc5 & uc4	1.19	0.551		
D	Surface between nests 5 & 6	1.34	0.494		
E	Surface between nestsv6 & 7	1.41	0.468		
F	Surface between nests 6 & 7	1.46	0.449		
G	Surface between nest 7 & stream	1.54	0.419		
H	Surface between nests 8 & 9	1.34	0.494		
I	Surface between nests 9 & 10	1.35	0.491		
UC4	Surface			1.411	0.468
UC4	0.2 m			1.517	0.428
UC5	0.2 m			1.712	0.354
UC5	0.8 m			1.721	0.351
UC8	Surface			1.680	0.366
UC8	0.2 m			1.799	0.321
UC9	Surface			1.817	0.314
UC9	0.8 m			1.783	0.327

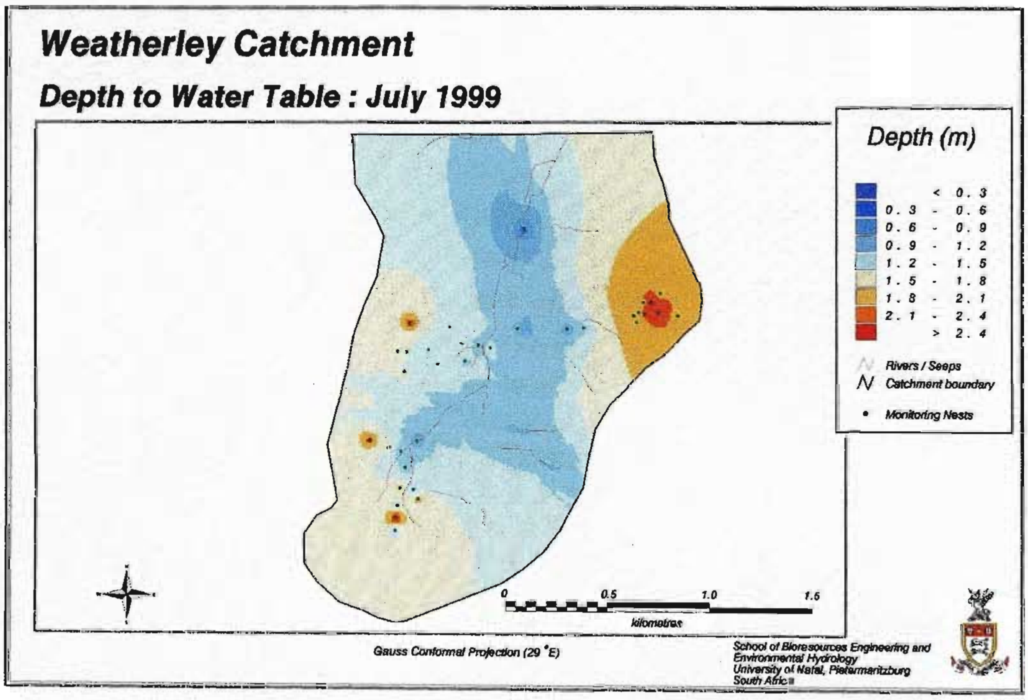
APPENDIX F

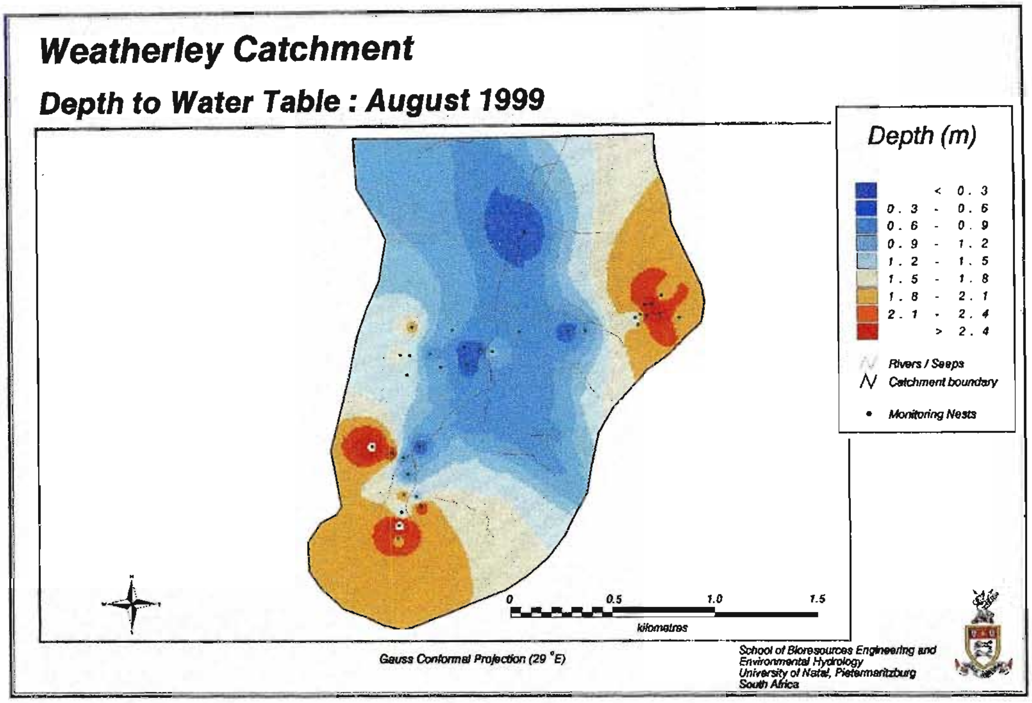
Appendix F contains depths to water tables at the Weatherley catchment for selected months during 1999. Data is missing for the months of January, April, June and November.

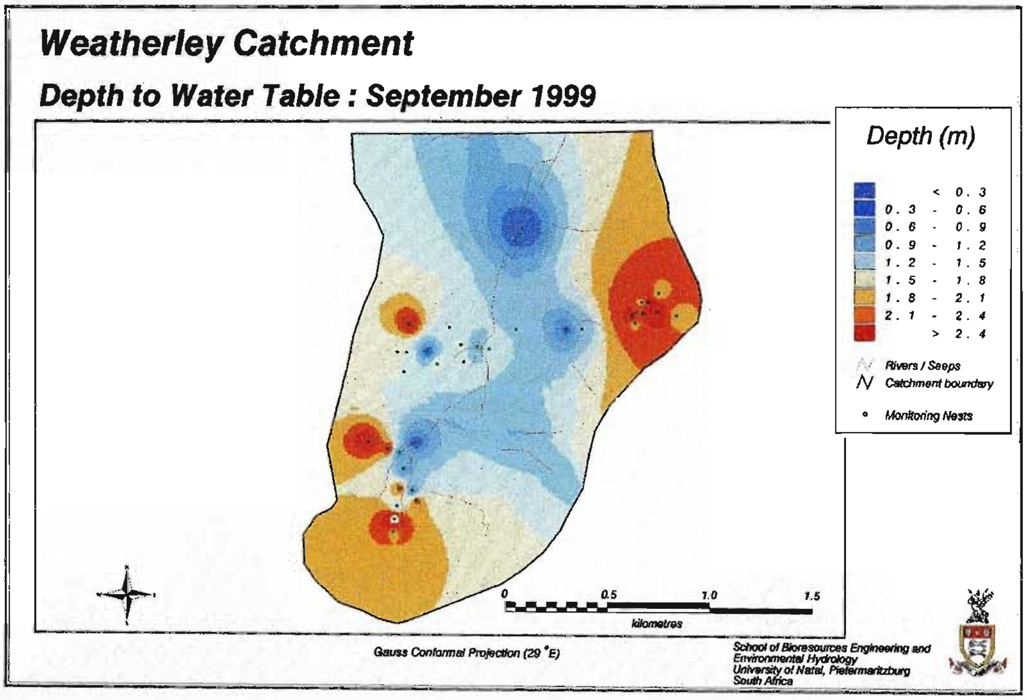


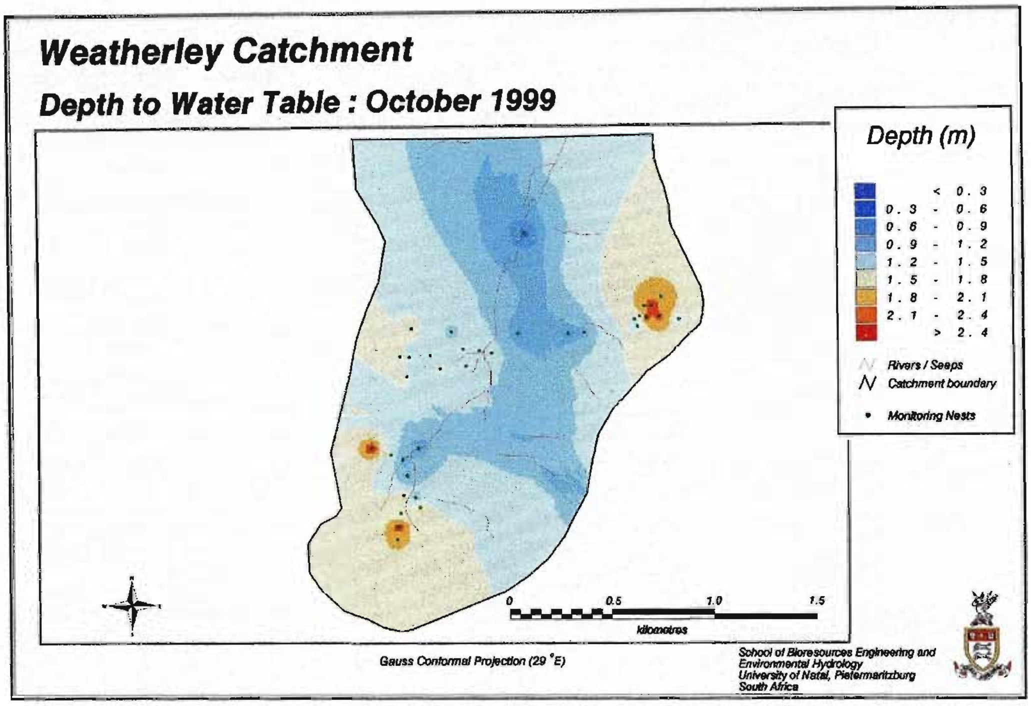


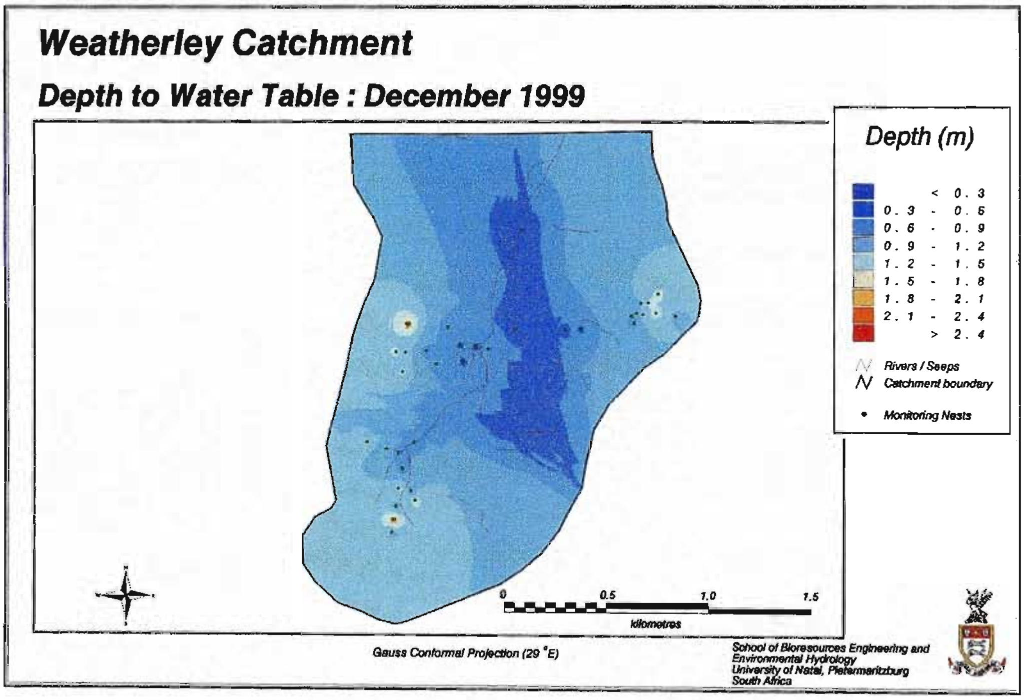

Weatherley Catchment
Depth to Water Table : May 1999
Depth (m)
< 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
> 2.4
Rivers / Seeps
Catchment boundary
Monitoring Nests
0
0.5
1.0
1.5
kilometres
Gauss Conformal Projection (29 °E)
School of Bioresources Engineering and
Environmental Hydrology
University of Natal, Pietermaritzburg
South Africa


Weatherley Catchment
Depth to Water Table : July 1999
Depth (m)
< 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
> 2.4
Rivers / Seeps
Catchment boundary
Monitoring Nests
0
0.5
1.0
1.5
kilometres
Gauss Conformal Projection (29 °E)
School of Bioresources Engineering and
Environmental Hydrology
University of Natal, Pietermaritzburg
South Africa


Weatherley Catchment
Depth to Water Table : August 1999
Depth (m)
< 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
> 2.4
Rivers / Seeps
Catchment boundary
Monitoring Nests
0
0.5
1.0
1.5
kilometres
Gauss Conformal Projection (29 °E)
School of Bioresources Engineering and Environmental Hydrology
University of Natal, Pietermaritzburg
South Africa


Weatherley Catchment
Depth to Water Table : September 1999
Depth (m)
< 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
> 2.4
Rivers / Seeps
Catchment boundary
Monitoring Nests
0
0.5
1.0
1.5
kilometres
Gauss Conformal Projection (29 °E)
School of Bioresources Engineering and Environmental Hydrology
University of Natal, Pietermaritzburg
South Africa


Weatherley Catchment
Depth to Water Table : October 1999
Depth (m)
< 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
> 2.4
Rivers / Seeps
Catchment boundary
Monitoring Nests
0
0.5
1.0
1.5
kilometres
Gauss Conformal Projection (29 °E)
School of Bioresources Engineering and Environmental Hydrology
University of Natal, Pietermaritzburg
South Africa


Weatherley Catchment
Depth to Water Table : December 1999
Depth (m)
< 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
> 2.4
Rivers / Seeps
Catchment boundary
Monitoring Nests
0
0.5
1.0
1.5
kilometres
Gauss Conformal Projection (29 °E)
School of Bioresources Engineering and Environmental Hydrology
University of Natal, Pietermaritzburg
South Africa

APPENDIX G

Appendix G contains input menus used in the *HILLS* model. Below is an example of a section of the *HILLS* rainfall input file.

Rainfall

Start: Dec ' 99,1521 HRS (8 12 99 1521)

Start	Year	Month	Day	Time	Rainfall
1	2000	1	7	1731	0.2
2	2000	1	7	1732	0.2
3	2000	1	7	1733	0.6
4	2000	1	7	1734	0.6
5	2000	1	7	1735	0.4
6	2000	1	7	1736	0.6
7	2000	1	7	1737	0.2
8	2000	1	7	1738	0.2
9	2000	1	7	1739	0.2
10	2000	1	7	1740	0.2
11	2000	1	7	1741	0.2
12	2000	1	7	1743	0.2
13	2000	1	7	1744	0.2
14	2000	1	7	1745	0.2
15	2000	1	7	1746	0.2
16	2000	1	7	1747	0.2
17	2000	1	7	1748	0.6
18	2000	1	7	1749	1.0
19	2000	1	7	1750	0.6
20	2000	1	7	1751	0.6
21	2000	1	7	1752	0.4
22	2000	1	7	1753	1.0
23	2000	1	7	1754	1.4
24	2000	1	7	1755	1.6
25	2000	1	7	1756	1.0
26	2000	1	7	1757	0.8
27	2000	1	7	1758	0.8

An example of the input menu from hillslope segment 1 used in simulating the Weatherley catchment runoff.

```
Upper catchment segment1
 LATEST UPDATE: 10 July 2000
KHOUT  KSUBF  UNITS  JPRNT  JIMIOS  JIDEP  HINIT
  1       0       1      2       0       0      0
 IQP  IPR  JPLO  JPROF  JCHAN  JBAL  JEVAP  JSALT  JLIN
  1     1     1     1       0       1      0       0      0
  DS  NDX  DXL  DRAT  SURF   YU   YB  HOUT  DWDX
 200.  40   0.2   1.5   .130    2.9   0.9  .20     0.0
  CPC  PHI  SWmx  SWmn  ALAM   CF  QINIT  TINC
 0.3    0.45   0.95    0.10     1.8   0.26  0.07    0.5
  NCK    PU     PL    QGW    FISOT  CFHD  CSKL
   1      0.09  0.004  -0.003   5.0     1.20  0.000
  DTR  ALPHA  TEMP  RFMAN   CVF  ITERMX
  0.1       0.6    20.0   0.5      0.01    50
 Nodes N1, N2 at which GW depths are followed in output:
 10  38
 NGP (no. locations for profile slope and depth)
  4
 XHL(I),YHL(I),SHL(I) for NGP
 0        2.9     0.110
 50       2.5     0.160
 150      1.8     0.100
 200      0.9     0.100
  CIN  CPRK   CGW    CRO  INITIAL Concentrations, IF JSALT > 0
 0.0    0.0   0.1   0.0
 TEV  ZROOT  PSIC  PSIM (Profile evap control parameters)
  3.      0.4     0.10    15.
12 monthly mean pan Evap. values:
 8.1  7.9  5.8  3.3  2.2  2.1  2.3  2.4  3.4  4.1  5.8  8.1
The following are only read for catchment simulation option:
NOPL
  1
ACAT   CHRF   CHSL   C1   C2
75000   .01     .006     1.    1.
NGC(No. of channel slope data pairs following)
```

An example of the input menu from hillslope segment 2 used in simulating the Weatherley catchment runoff.

```
 Upper catcment segment1
 LATEST UPDATE: 10 July 2000
KHOUT  KSUBF  UNITS  JPRNT  JIMIOS  JIDEP  HINIT
  1       0       1      2        0        0      0
 IQP  IPR  JPLO  JPROF  JCHAN  JBAL  JEVAP  JSALT  JLIN
  1     1     1     1        0       1       0       0      0
  DS  NDX   DXL  DRAT  SURF    YU    YB   HOUT  DWDX
  520.  40    0.2    1.5   .113      2.9    0.9   .20       0.0
  CPC   PHI   SWmx   SWmn   ALAM    CF   QINIT   TINC
   0.3   0.45   0.95     0.10     1.8     0.26     0.08   0.5
  NCK     PU      PL     QGW     FISOT  CFHD   CSKL
   1      0.085   0.004  -0.002     2.0     1.20    0.000
  DTR  ALPHA  TEMP  RFMAN    CVF   ITERMX
  0.1      0.6      20.0     0.5        0.01       50
 Nodes N1, N2 at which GW depths are followed in output:
 10  38
 NGP (no. locations for profile slope and depth)
  4
 XHL(I),YHL(I),SHL(I) for NGP
 0          2.9       0.113
 50         2.5       0.100
 150        1.8       0.100
 200        0.9       0.113
  CIN   CPRK    CGW    CRO   INITIAL Concentrations, IF JSALT > 0
 0.0     0.0     0.1     0.0
 TEV  ZROOT   PSIC   PSIM (Profile evap control parameters)
  3.      0.4         0.10    15.
12 monthly mean pan Evap. values:
8.1  7.9  5.8  3.3  2.2  2.1  2.3  2.4  3.4  4.1  5.8  8.1
The following are only read for catchment simulation option:
NOPL
  1
ACAT    CHRF    CHSL    C1    C2
75000   .01     .006     1.    1.
NGC(No. of channel slope data pairs following)
```