A DESCRIPTION, QUANTIFICATION AND CHARACTERIZATION OF HILLSLOPE HYDROLOGICAL PROCESSES IN THE WEATHERLEY CATCHMENT, EASTERN CAPE PROVINCE, SOUTH AFRICA

Carl Freese
BSc Honours (Hydrology)
203505791

Submitted in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE IN HYDROLOGY

School of Agricultural, Earth and Environmental Sciences
University of KwaZulu-Natal
Pietermaritzburg

October 2013

ABSTRACT

Advances in hillslope hydrology have been numerous in the past two decades. However many of these advances have been highly site specific in nature, without identifying any means of linking processes across different spatial scales. Meaningful Prediction in Ungauged Basins (PUB) requires the understanding and observation of processes across a range of scales in order to draw out typical hydrological controls. Contempory tracer based methods of quantifying a combination of hillslope processes have identified hillslope geology as the main determinant in different catchment response types. A range of hillslope scale models have been developed in the last 20 years, using different levels of detail to simulate hillslope hydrological responses. Often the data heavy requirements of hillslope scale models make them impractical to apply at larger scales. While catchment scale models lack the ability to represent hillslope scale processes. In order to overcome this, a scale applicable model with the ability to represent hillslope and catchment dynamics is required to accurately quantify hillslope and catchment hydrological processes. This study aims to characterize typical hillslope soil type responses through inferring qualitative hillslope descriptions into a numerical catchment scale model allowing for lateral subsurface routing between adjacent soil horizons. Hydrometric and tracer observation are used to describe and quantify dominant hillslope hydrological processes. Simplifications of hillslope process descriptions are used to calibrate the model to represent the subsurface hillslope connectivity. Results show that hillslope scale hydrological process characteristics can be faithfully simulated with quaternary scale climate, land use and soils data, discriminating only between different hillslope soil types. The simplification of hillslope soils into three distinct groups allows for the further derivation of dimensionless descriptors of hillslope hydrological response using the Advection Dispersion Function. Slopes with shallower stratified soils showed rapid responses to rainfall in the soil water, while those with deeper soils and less horizontal stratification showed appreciably slower responses to rainfall, with older hillslope water dominating soil water for longer periods. This identifies soils as a dominant determinant in hillslope runoff characteristics. This allows for the characterization and ultimately a simplified classification of different hillslope soils and their response types, which is applicable at a range of scales.

DECLARATION

Work described in this document was carried out in the school of School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, for the purposes of a postgraduate degree, supervised by Prof. S. A. Lorentz and co-supervised by Dr P.A.L. le Roux. Field and analytical work contributed to an externally funded project in conjunction with the University of the Freestate and the Water Research Commission.

I hereby certify that work reported in this document is my own original and unaided work, except where due acknowledgement is made.

Signed: ________________________

Carl Freese

ACKNOWLEDGEMENTS

I would like to acknowledge the following individuals and institutions

Prof S.A. Lorentz for his guidance and supervision throughout this research process

Dr P.A.L le Roux for his guidance and supervision throughout this research process

Mr J.J Pretorius for assistance in catchment monitoring and isotope analysis

Mr J Ngaleka for catchment monitoring assistance

The Water Research Commission of South Africa for funding of the HOSASH project

My parents, Graeme and Sue Freese for their endless support and financial assistance

My fiancé, Kezia Fitzsimmonds for her constant inspiration and assistance with language and editing issues.

Staff and students at the school of Bioresources Engineering and Environmental Hydrology, University of KwaZulu Natal

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Advances in understanding hydrological processes have been abundant in the last two decades, particularly at the small headwater catchment scale. However, the fact that these studies largely comprise local transect measurements at contrasting research catchment locations, means that the estimation of dominant processes at scales larger than the gauged study area are difficult (McGuire *et al*., 2005). This is because of two major hindrances in the field of hydrology (Uhlenbrook *et al*., 2002);

1: Spatial and temporal complexity/variability of runoff process across scales
2: Current lack of tools to apply process understanding at ungauged sites.

Sivapalan (2003) points out that recent advances in hillslope hydrological process understanding have been abundant in recent years however, we have not improved our understanding of how hillslope hydrological processes relate to each other and to catchment responses. To represent heterogeneities across scales, models must be distributed and highly detailed. However, when scaling up from the hillslope to the catchment scale an extremely large amount of data is required to represent the heterogeneities, which is neither cost nor time effective. A theory for overcoming this hurdle, known as 'self-similarity', first conceptualized by L.F Richardson (Bloschl, 2001), and propagated by Sivapalan (2003) involves the identification of a common underlying thread linking conceptualizations across a range of scales. This method is applied with the aim of deriving a combined large-scale equation from first principles (Bloschl, 2001).Weiler and McDonnell (2003) add further insight by claiming that hillslope studies have focused heavily on 'idiosyncrasies', without purposeful integration toward revealing common processes

An integration of these two ideas is proposed in an extremely concise classification of hydrological responses into orders of magnitude and scale, much like those classification systems used in biology and science (Wagener and Sivapalan, 2007). The basis of this unifying theory is essentially an extension of the "Dunn diagram for runoff generation mechanisms" (Figure 1.1). This diagram relates the response of a catchment as a function of topography, vegetation, geology, soils etc. (Altinors and Oender, 2008).

Observation of these catchment response functions allows for the development of characteristic hillslope responses. However, these are inherently limited by the fact that they usually include the use of qualitative data. In the case of this study, quantitative relations are derived from qualitative point observations, in an attempt to characterise different soil and hillslope response types. Therefore, it must be stated that parts of this study include the use of qualitative observations for use in mathematical and hydrological modelling.

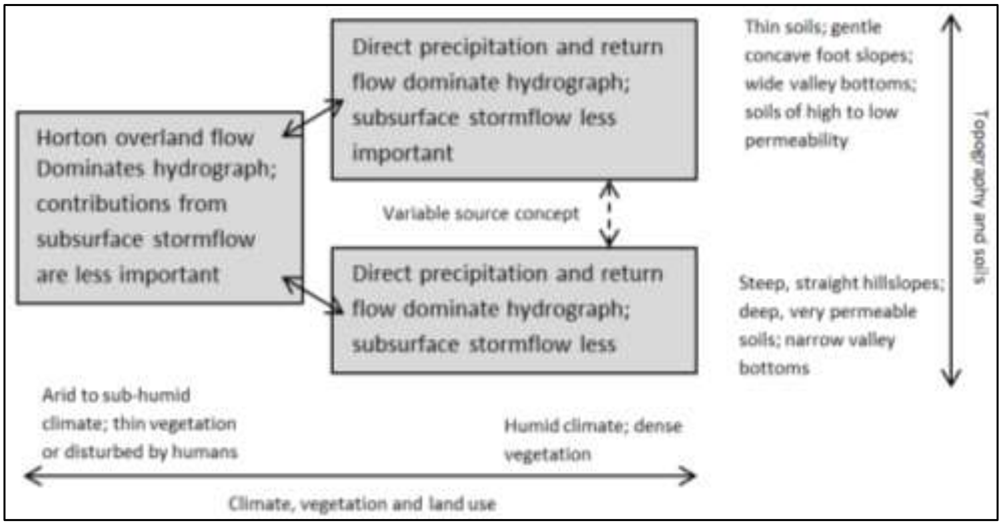


Figure 1.1 Dominant processes of runoff generation mechanisms at the hillslope scale (Wagener and Sivapalan, 2007)

The aim of this study is to provide a basis for classifying hillslope responses for use in catchment models through the following objectives:

- Define the hydrological process in two distinct hillslopes through hydrometric, geophysical and tracer observations;
- Develop typical response functions for discharge from the hillslopes;
- Integrate the response functions into a catchment model and;
- Evaluate the improvement afforded by the hillslope hydrology responses and recommend future direction for catchment response simulations using classed of hillslope responses.

The outline of the document includes:

- Literature review outlining different methods applied in the simplified representation of hillslope scale processes in the simulation of hillslope and catchment scale runoff.
- Methodology in which the integration of hillslope scale observations to a catchment scale model is theoretically developed.
- Results, which identify the dominance of different zones of hydrological connectivity along a hillslope transect and allow for the derivation of numerical descriptors of hillslope responses, which are applied in the parameterization of hillslope scale data for use in catchment scale runoff simulations.
- Conclusions, which outline the major findings of this study, focusing on the ability of the proposed methodology to perform representative simulations, parameterized with conceptual models.

2 LITERATURE REVIEW

This literature review assesses the commonly perceived steps in reaching a justifiable system of catchment hydrological response classification. The steps involved include description, quantification, characterization and classification of hydrological processes. Currently, the science of hydrology has not evolved sufficiently to yield a common means of hydrological response classification. While this literature review will not attempt to define a complete classification technique, it will focus on the application of detailed point scale observations at the hillslope scale to identify typical response types, applied to hillslope and catchment scale process modelling.

2.1 Description of Hillslope and Catchment Hydrological Processes

The quantification of hillslope hydrological processes must be underpinned by conceptual descriptions of catchment function, common across various spatial and temporal scales (McDonnell, 2003; Sivapalan, 2003). However many recent studies in processes hydrology have documented atypical processes which are localized in nature. While these studies may prove beneficial to the identification of small scale localized processes, no greater understanding of typical responses across scales is achieved (Weiler and McDonnell, 2004). In order to resolve such an issue, Weiler and McDonnell (2004) suggest a combination of qualitative and quantitative methods:

> "Numerical experiments with a model driven by collective field intelligence".

"Collective field intelligence" can be defined as ones familiarity of a study site based on qualitative observations. The ability of hillslope models to capture such qualitative observations is often hindered by the complexity of the mathematical functions required (Dunne, 1983; Sivapalan, 2003).

A bottom up approach will be applied in this study. Hillslope and catchment scale responses will be monitored in order to assess the impact of hillslope scale responses on the resultant catchment scale response. In order to determine the factors linking responses across scales a dominant or first order hydrological control, which links responses across scales, must be identified and monitored, such that the observations, qualitative and quantative, are representative at a range of different hydrological scales (Wagener and Sivapalan, 2007; van Tol, 2010).

2.2 Dominant Hillslope Hydrological Control

In any given landscape there are a number of separate hydrological processes occurring, which are all a function of dominant environmental factors. In order to characterize hydrological process relationships across scales, a common first order hydrological control must be identified. The common first order control has often been referred to as “the golden thread” which underlies characteristic hydrological responses at a range of different scales. Many studies over the preceding decades have identified soil physical and hydraulic properties as one of the main driving forces behind hillslope and catchment response. (Freer and McDonnell, 2002; Weiler and McDonnell 2004; Wagener and Sivapalan, 2007). This argument would appear logical as soil formation is a direct function of both climatic and geological factors, thus serving as a marker of both terrestrial and atmospheric patterns.

Hoover and Hursh (1943) found that peak discharge in the Coweta research catchment was heavily influenced by soil depth, topography and hydrologic properties at different elevations. A study by (Uhlenbrook and Didszun, 2004) identified six HRU’s based on the dominant hydrological behaviour of the soils. The six soil types accounted for ground water recharge, lateral flow and responsive (saturated/rock outcrop/settlement) soil types. In their findings the authors determined that the catchment disaggregation based on soil types allowed for the transfer of routines and data sets to ungauged sites, while preserving the three dimensional characteristics of a hillslope. In an attempt to explain preferential flows using a numerical model Weiler (2007) found that the mixing ratios of conservative tracers, and thus transient hillslope water, is highly dependant on soil depth. These studies all concluded that catchment and hillslope hydrological characterization should be heavily based on the hillslope scale hydrological soil properties.

With these examples in mind, it is worth recalling that soil properties are a function of parent material and climate, the combination of these factors determines specific soil physical and chemical characteristics. The combination of terrestrial and climatic parameters thus also influences the topography, vegetation and the consequent habitability of an environment by living organisms, Ashman and Puri (2005) express this relationship in the form of an equation where;

Soil Formation = f (climate, parent material, topography, organisms and time)

Soil formation is thus an integration of climate, topography, parent material, vegetation and land use. The soil matrix appears as an initial first order or dominant hydrological control in the partitioning of precipitation into various storages and releases (Schulze, 1995; Uhlenbrook and Roser, 2004; Uhlenbrook and Didszun, 2008). These functions of soil formation are also very significant in the hydrological cycle, developing simultaneously over time and leaving pronounced markers of water movement and storage in different soils (van Tol, 2010).

The nature of a first order hydrological control ultimately defines the manner in which different hillslope elements are hydrologically connected along a hillslope catena, defined by Weiler and McDonnell (2004) as:

"The main and essential process constraints on water and solute flux"

2.3 Why the Hillslope

The hillslope unit has been identified as the smallest possible elementary unit representing catchment scale runoff dynamics across different catchment sizes (McGuire and McDonnell, 2005). The hillslope unit characterizes a three-dimensional transect across the landscape as an environmental sequence traversing the range of altitudes. Hillslopes can be used to characterize the different environmental sequences such as geology, soils, land use and topography, to determine dominant response patterns resulting from different hillslope catena's (McGuire and McDonnell, 2005; van Tol, 2010). In this manner, the hillslope acts as an organizing principle, conserving mass and complementing the hydrological cycle.

There are a number of hillslope scale processes that ultimately contribute to hillslope discharge, Figure 2.1. However hillslopes do not all respond in an identical manner. At any one time, only certain hydrological processes are present on any single hillslope. This highlights the fact that hillslope runoff generation is a highly non-linear and spatially variable process that occurs above and below ground (Wood, 1990).

The presence of particular responses is dependent on slope characteristics such as; soil type, depth and distribution, climate, land use and topography, which occur at different spatial and temporal scales. Transitions between particular process zones may be abrupt or gradual depending on the dominant slope morphological forcing. Geological/topographical and land use transitions are typically spatially and temporally abrupt in occurrence (Ashman and Puri, 2005), whereas Climatic variations commonly occur gradually because of regional scale continental and oceanic atmospheric systems (Leibunbgut and Maloszewski, 2009). Abrupt transitions in geology and land use occur at a range of scales. Landscape transitions result in the discontinuity of subsurface flow mechanisms transporting hillslope water to the riparian soils (Wagener and Sivapalan, 2007).

2.4 Hillslope Hydrological Connectivity

Hillslope hydrological connectivity between hillslope elements has been defined in many ways over the past two decades. Possibly the most functional description of hillslope hydrological connectivity is the development of zones of continuous saturated soil water on mid and upslope areas, away from the riparian zone. Fluctuations of stored soil water in these zones results in a stream response. Hillslope hydrologic connectivity is also a function of antecedent moisture conditions, surface and bedrock topography, and slope shape. However a range of studies over the preceding decades have indicated that soil depth is the dominant factor in determining hillslope response and connectivity (Ocampo, 2006; Bracken and Croke, 2007; Detty, 2010; Jencso and McGlynn, 2010; Jensco, 2010; McGuire, 2010).

The ability to assimilate a range of processes into a conceptual understanding of an entire hillslope segment, made up of elements and their connections, allows for the identification of the first order hydrological control at any given scale of study (Sivapalan 2003; Wagener and Sivapalan, 2007).

2.5 Hillslope Hydrological Process Response Controls

There are a wide variety of hydrological hillslope processes that may occur at any location. The presence of certain processes is directly dependant on catchment characteristics. Figure 2.1 illustrates the various hillslope processes and responses that occur at the hillslope scale depending on catchment characteristics such as geology, soil, climate and vegetation. A brief description of studies carried out on the identification of flow generation mechanisms is given to highlight the fact that there are a number of various processes operating on any given hillslope, and a clear description and quantification of processes and their linkages is needed to understand the often complex response mechanisms of a hillslope.

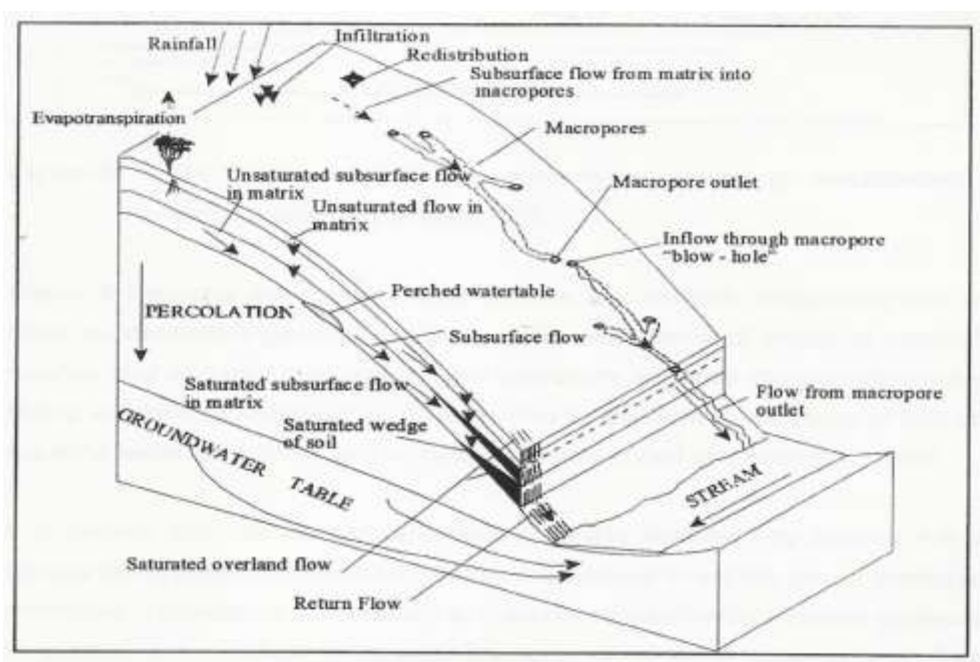


Figure 2.1 Hillslope response flow paths (after Anderson and Burt, 1990).

In a 2006 study of the hydrology of the Feshi catchment, Scotland, (Soulsby and Tetzlaff, 2006) used isotope tracer methods in conjunction with a GIS database, to define hillslope responses. One of the central aims of the study was to define responses in terms of spatial and temporal distribution of ground water, surface runoff and mean residence times. The descriptions of hillslope responses are illustrated in Figure 2.2. Subsurface hillslope processes were derived from the mapped catchment soils distribution as defined by the UK Hydrology of Soil Types (HOST) classification. The HOST Class system identified dominant hillslope processes at specific hillslope catena positions, allowing for the conceptualization of hillslope subsurface connectivity along the entire transect The study concluded that shorter residence times and negligible ground water contributions occur on hillslopes with shallow soils and bedrock. Longer residence times and increased ground water contributions were found on hillslopes with deep, freely drained soils. (Soulsby and Tetzlaff, 2006).

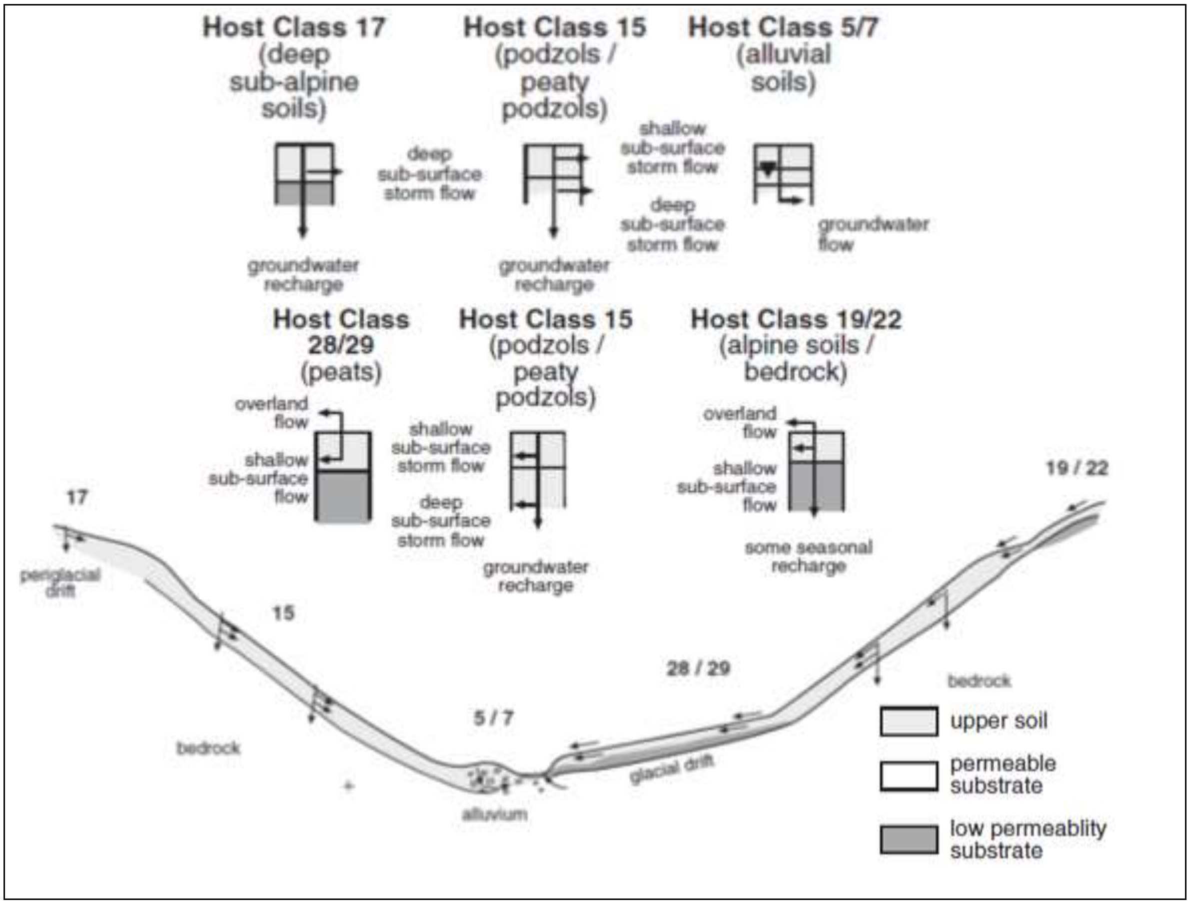


Figure 2.2 HOST Soil Class hillslope responses of the Feshi catchment (Soulsby *et al*., 2006).

The application of the HOST system in this instance allows for the determination of dominant zones of subsurface transport and recharge of soil water. The system classifies soils of the United Kingdom into 29 distinct groups based on hydrological characteristics. The HOST classes of soils have been calibrated against indices describing surface runoff and baseflow recharge potential, highly dependent on in situ soil characteristics.

While such a classification of hydrological processes is not yet available in South Africa, process studies identifying the dominant flow mechanisms along different hillslope transects have arrived at a commonly agreed framework for conceptualizing hillslope hydrological responses. Two such examples include the Weatherley (Figure 2.3) and W17 Zululand (Figure 2.4) catchments just below the eastern escarpment of South Africa. Both hillslopes are formed on sedimentary geologies facilitating the development of perched water tables in the soil, and subsequent lateral flows. This is as a result of the stratification in vertical soil permeability resulting in the development of vertically inhibiting soil layers, Figure 2.3 A, F and H, Figure 2.4 B and D. The terracing observed in Figure 2.3 D, causes the development of a perched water table, by creating a break in the hillslope near surface vertical connectivity. Similar to the formation of perched water tables directly downslope of intrusive formations shown in Figure 2.3 J to I (Lorentz, 2008), and Figure 2.4 E (van Zyl, 2003).

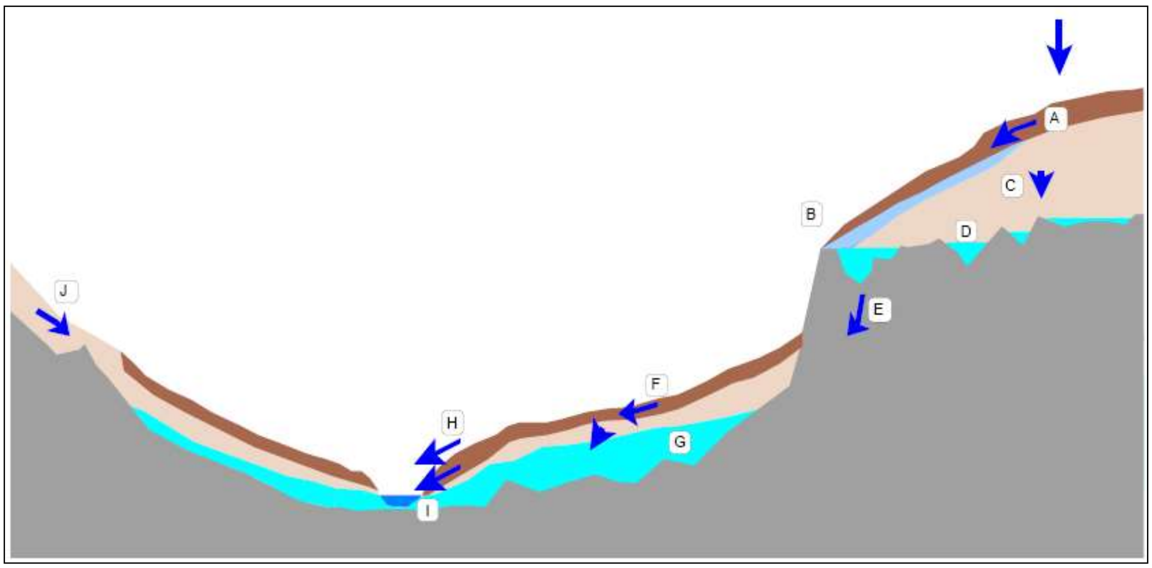


Figure 2.3 Weatherley hillslope hydrological process conceptual description (Lorentz, 2008)

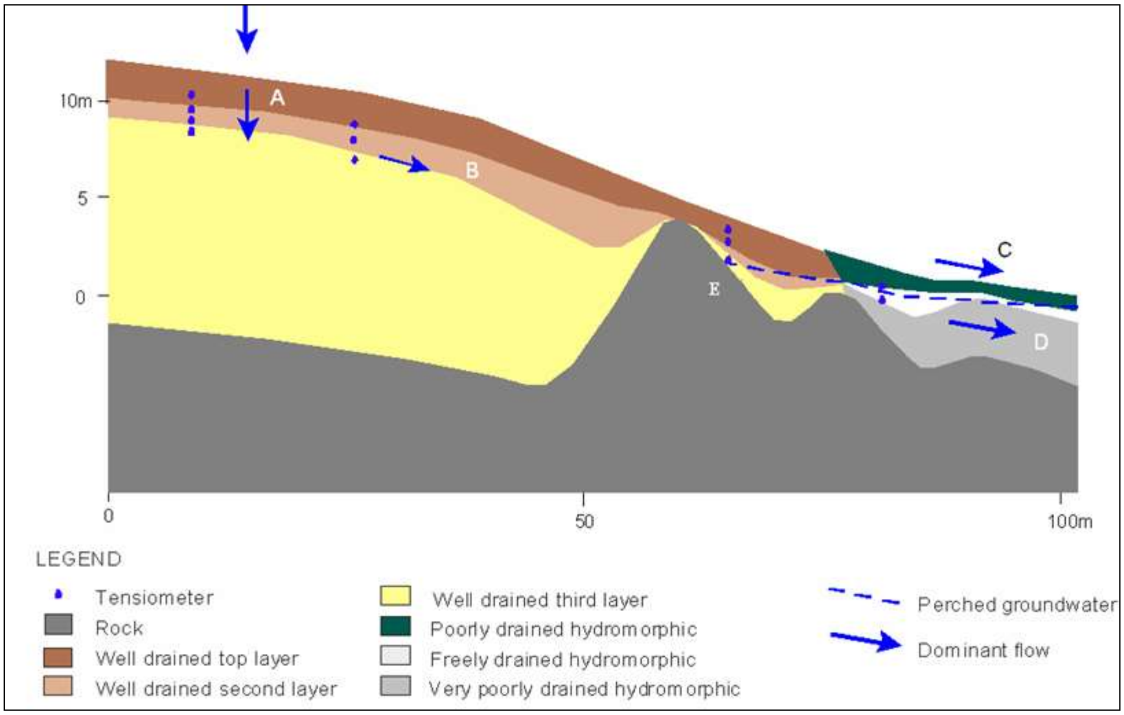


Figure 2.4 W17 Zululand hillslope hydrological process conceptual description (After van Zyl, 2003).

These two examples from different parts of South Africa show the ability for similar typical hillslope responses to occur on similar geological formations, at disparate locations. Uninterrupted sedimentary forms allow for the development of deep well drained soils dominated by vertical infiltration, while the interruption of hillslope connectivity by intrusive geological forms or terracing results in the formation of perched water tables in the soil profile, albeit by two completely different processes.

A third example is taken from the Two Streams research catchment, located in KwaZulu-Natal, South Africa. The consistent sub surface topography allows for the development of continually deep soils along the hillslope transect, resulting in the dominance of vertical infiltration, with delayed ground water contributions from the riparian zone dominating streamflow. These conditions allow for an increased baseflow component due to the extensive storage capacity of the soils as well as the extensive hydrological connectivity along the length of the slope transect, Figure 2.5.

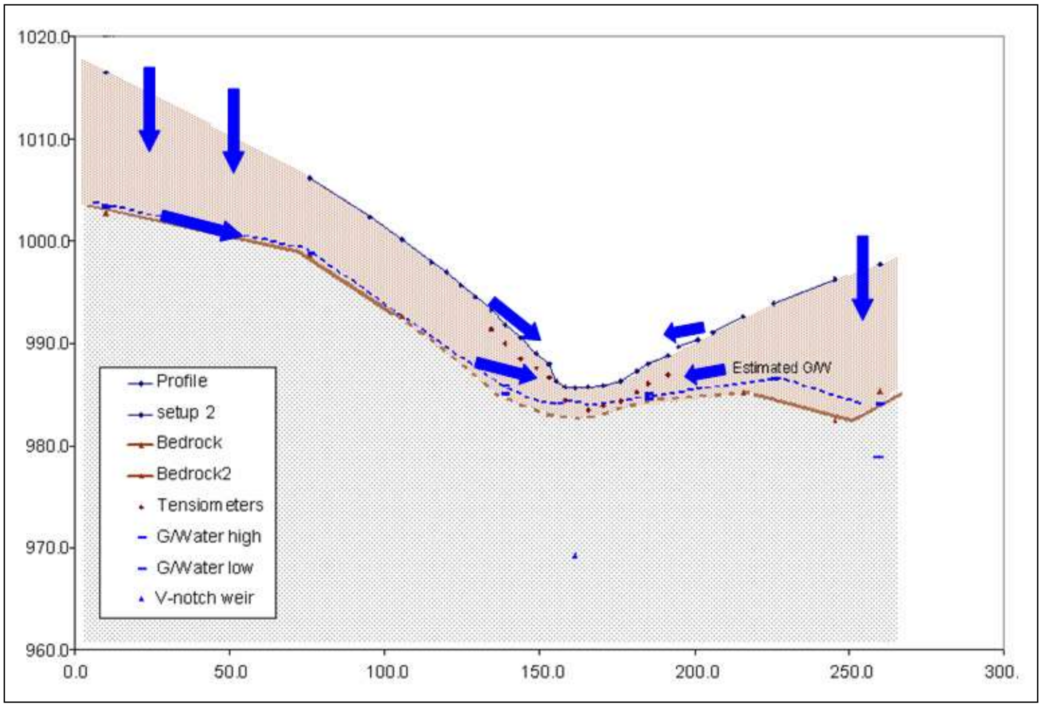


Figure 2.5 Two Streams hillslope hydrological process conceptual description.

These three examples have shown that abrupt changes in subsurface connectivity are typically as a result of abrupt transitions in dominant soil formation characteristics dictated by geological interfaces, as described by Ashman and Puri (2005). In an attempt to better understand the dominant processes active along various hillslope sequences, a hydrological soil classification was carried out by the University of the Free State, department of Crop, Soil and Climate Sciences in a number of South African research sites. The study considered dominant hydrological soil markers in classifying four distinct hydrological soil process zones, termed Hydropedological soil types.

2.6 Hydropedological soil types

Hydropedology encompasses fundamentals of both pedology and hydrology, by considering dominant pedoligical markers formed because of typical hydrological responses occurring in different soil types across spatial and temporal scales, addressing knowledge gaps between hydrology, pedology and soil physics (Lin, 2003, Lin et al, 2005). The basis of hydropedology is underpinned by four general characteristics. Firstly, the nature and structure of soil horizonation forms the basis of soil hydrological flow characteristics. Secondly, Soil distribution patterns (catenas) are a first order control of runoff generation. Thirdly, soil morphology and pedogenesis act as hydrological indicators of different hydrological soil types. Fourthly, the functional classification of soil properties can be considered indicators of soil hydrological response (Lin, 2009). The accumulation of these four points constitutes the basic theory of hydropedology, outlining the vast scope of the interdisciplinary approach to solve problems related to subsurface process characterization.

Uhlenbrook and Didszun (2004) identify the importance of catchment discretization when applying models in gauged and ungauged catchments. The main obstacle is the ability to conserve real world hydrological heterogeneity in a model, through capturing only the dominant processes. For this to occur, the crucial environmental factor governing runoff generation must be identified. There are a range of processes which occur at varying scales that have bearing on the hydrological cycle yet soil distribution patterns stand out as a dominant control across a range of climates (McGuire and McDonnell, 2005). Below the soil is the bedrock/parent material, which has played a major role in the soil formation. Above the soil, vegetation is, limited in distribution due to the availability of soil water. Slope gradient also manipulates the formation of soil, allowing for accumulation and erosion (Ashman and Puri, 2005). These factors all suggest that at the hillslope scale, slope and soil morphology are closely linked, and should thus form the basis of a hillslope hydropedological characterization and classification.

Assessing the hydrological nature of typical soil types found at distinct slope positions revealed distinct trends in hillslope scale observations. Uhlenbrook *et al* (2002) carried out a catchment discretization and modeling study that identified similar hydrological areas based on the hydrological nature of the soil. Six HRU's were identified in the Dreisam research catchment, south-west Germany, based on the soils typical hydrological behaviour, these six HRU's can be further simplified into three soil types; Surface runoff soils or responsive soils were identified first; these areas include wetlands, urban areas, rock outcrops and water bodies. Secondly, soils that were deemed to contribute to baseflow were identified. These soils typically occur on the flat areas situated at the upper part of the hillslope and are termed recharge soils. Recharge soils have a large storage capacity and do not contribute large proportions of water during an event, but rather discharge water slowly to sustain streamflow during low flow periods. Thirdly, soils that occur on steep slopes were delineated. The formation of the soil on steeper slopes will generally make it coarser in texture, thus initiating quick lateral flows in the shallow soil horizons, as well as preferential flows (macroporosity). These soils are termed interflow soils due to their tendency to generate shallow level lateral, soil water flows. Similar findings were published in by Uhlenbrook and Didszun, 2004; Weiler 2005; Helmschrot 2006, suggesting the occurrence of typical hydropedological behaviour at distinct hillslope positions occurs at a number of disparate positions. The transferability of the theory behind the hydropedological classification of soils identifies it as a major tool in linking hydrological responses across different spatial scales. However, such a theory is still a topic of debate (McGlynn *et al*., 2003; McGuire *et al*., 2005; Mueller *et al*., 2012; Soulsby and Teztlaff, 2008)

In order to monitor and analyse these different hillslope zones a diverse and intensive hydrometric and tracer based study is applied. The analysis of the stable isotopes of water is an effective way of characterizing hydrological flow paths and linkages, which can be effective at any scale. (Helmschrot, 2006; Uhlenbrook and Didszun, 2004; Weiler, 2005). A combination of tracer observations and hydropedological data allows for greater insight into hillslope hydrological connectivity.

2.7 Isotope Tracer Descriptions of Hillslope Hydrological Processes

Environmental tracers such as the stable isotopes of water, oxygen and deuterium, are a vital tool in the characterization and quantification of hillslope hydrological processes. The applications of environmental tracers is carried out in three main ways

- Water resource estimations,
- Conceptualization of hydrological connectivity between different hydrological zones in ungauged basins and
- Observation of hydrological flow processes, otherwise impossible to monitor (Leibunbgut and Maloszewski, 2009).

The application of environmental isotopes occurs through precipitation that usually has a specific isotopic pattern. Incident precipitation defines the input time and signal, which can be observed arriving (or not) at any particular point, revealing detailed information about the flow distribution characteristics. This makes environmental tracers ideal for the observation and analysis of subsurface hydrological processes (McGuire *et al*., 2002; Mueller *et al*., 2012).

The accurate analysis of hydrological systems requires the reconciliation of hydrometric and tracer data. Tracer data compliments hydrometric data as both provide a point specific value at any given time. This makes the use of environmental tracers such as oxygen and deuterium ideal for small scale intensive studies (Leibunbgut and Maloszewski, 2009).

2.7.1 Introduction to the use of isotopes

The description of hillslope processes is commonly undertaken with a range of different observation techniques including hydrometrics, remote sensing, soil survey's and tracer studies. Tracer based studies allow for time and cost efficient conclusions, with a high level of certainty. Tracer studies can be carried out using a variety of techniques based on naturally occurring environmental or artificially injected tracers (Kendall, 2003; Singh and Kumar, 2005; Leibunbgut and Maloszewski, 2009).

Environmental tracers are intrinsic components of the hydrological cycle. These are comprised of naturally occurring stable isotopes of water, oxygen and hydrogen occurring in 9 different combinations. The possible stable isotope composition of water includes the following isotopes:

$H_2{}^{16}O$, $HD^{16}O$, $D_2{}^{16}O$
$H_2{}^{17}O$, $HD^{17}O$, $D_2{}^{17}O$
$H_2{}^{18}O$, $HD^{18}O$, $D_2{}^{18}O$

For the scope of tracer hydrology only $H_2{}^{16}O$, $H_2{}^{18}O$, $HD^{16}O$ and $H_2{}^{17}O$ are considered. These isotopes of water occur in differing ratios of abundance that gives insight into the processes water has undergone to reach a particular point in the hydrological cycle. The ratio of a depleted isotope, N_i, to an abundant isotope, N, is expressed as:

$$R = N_i / N \quad \text{(Equation 2.1)}$$

Oxygen and Deuterium isotopes are commonly expressed in terms of Standard Mean Ocean Water (SMOW) or VSMOW as defined by the International Atomic Energy Agency in Vienna. The VSMOW abundance ratios are expressed in the following manner:

$$R_{^{18}O/^{16}O} = \left(\frac{^{18}O}{^{16}O}\right)_{VSMOW} = 0.002 \quad \text{(Equation 2.2)}$$

$$R_{D/H} = \left(\frac{^{2}H}{^{1}H}\right)_{VSMOW} = 0.00016 \quad \text{(Equation 2.3)}$$

The isotopic abundance ratio of a sample R_{sample} is calculated with respect of the VSMOW standard, with an abundance ratio $R_{standard}$ and is expressed as a δ value.

$$\delta = \frac{R_{sample} - R_{standard}}{R_{standard}} \quad \text{(Equation 2.4)}$$

Oxygen and deuterium isotope δ values are commonly multiplied by a factor of 1000, as a ‰ difference from the VSMOW standard. Positive values are indicative of enrichment of oxygen 18 and deuterium, while negative values indicate depletion of heavy isotopes (Kendall 2003; Singh and Kumar 2005; Leibunbgut and Maloszewski, 2009).

The practical application of isotopes is based on the occurrence of two processes which influence the abundance ratios of stable isotopes of water. These two processes are functions of evaporation and mixing, which allow for the clear distinction between different bodies of water.

2.7.2 Fractionation

Enrichment and depletion of heavy isotopes occurs because of fractionation. Fractionation of natural waters occurs as result of a range of climatic conditions such as evaporation, condensation, sublimation, freezing and melting. The exchange of isotopes during phase changes results in alterations in the relative abundance of oxygen and deuterium isotopes (Leibunbgut and Maloszewski, 2009). Fractionation processes are due to both physical and chemical reactions (Singh and Kumar 2005). Studies typically consider the degree of fractionation as an indicator of the amount of evaporation a body of water has been subjected to (Leibunbgut and Maloszewski, 2009).

2.7.3 Attenuation

The term attenuation refers to the dampening in variation of a trend or signal from the excitation source. Within the saturated and unsaturated parts of the soil profile, a dampening or attenuation of seasonal rainfall isotope signals occurs with increasing soil depth. This relationship is a function of both soil depth and texture, and is as a direct result of the different velocities of a wetting front moving vertically through a soil profile. Fine textured soils result in attenuation of isotope time series values at shallower depths than coarse textures soils. This relationship is illustrated in Figure 2.6, where the isotope/soil depth relationship is described by an exponential function. Due to the exponential nature of the soil texture/depth relationship, soil water isotope values are expected to be extremely variable over time at shallower soil depths while isotope values of deeper soil water show a relatively low variability in time, Figure 2.6 (Kendall 2003; Singh and Kumar 2005; Weiler 2007; Leibunbgut and Maloszewski, 2009).

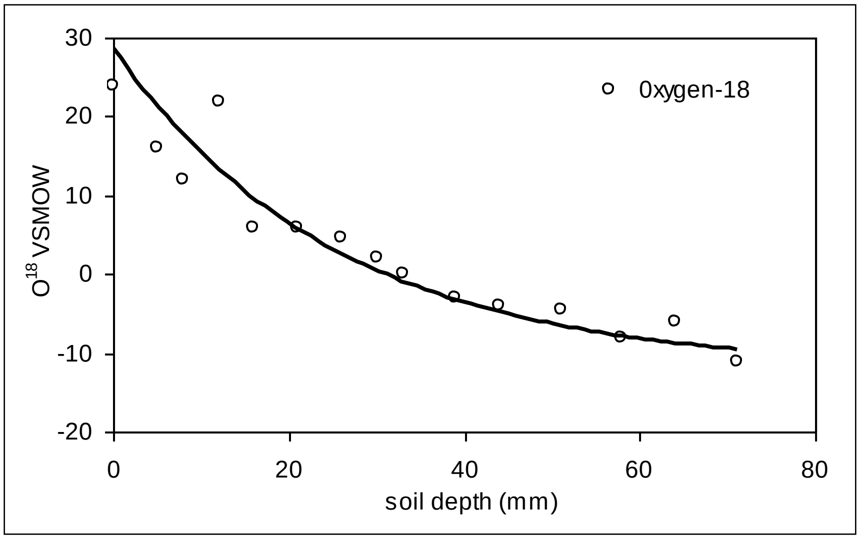


Figure 2.6 Stable Isotope profile of a saturated soil (after Kendall and McDonnell, 2003)

A practical example of this attenuation is given in Figure 2.7, where the variability in the soil water isotopic time series becomes increasingly attenuated with increasing soil depth (Leibunbgut and Maloszewski, 2009).

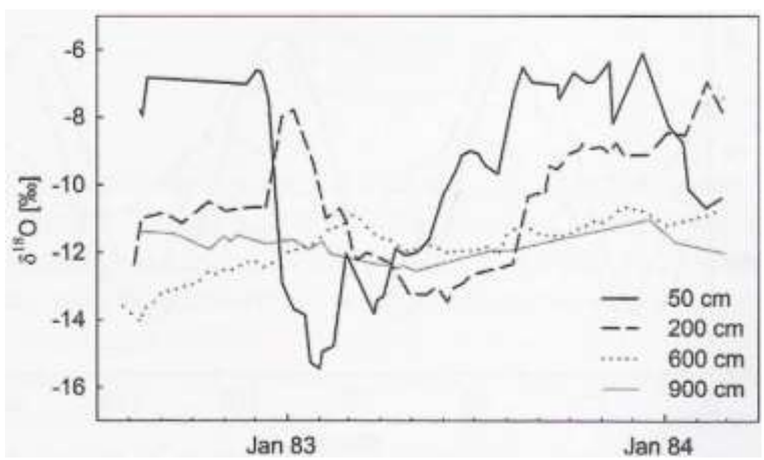


Figure 2.7 Soil water isotopic composition at varying soil depths, Munich Germany (Leibunbgut and Maloszewski, 2009).

2.7.4 Typical isotope trends

The initial reference point for all terrestrial water is defined by the source of precipitation known as the Global Meteoric Water Line (GMWL). The GMWL (Figure 2.8, a) characterizes the source of the ocean waters which feed precipitation through different climatic regimes. Rainfall isotopes with both negative

δO^{18} and $\delta^2 H$ values are representative of humid, lower altitude coastal areas, where the majority of rainfall is ocean derived (Figure 2.8, b). Positive δO^{18} and δH^2 values typically represent rainfall derived from polar fronts which carry moisture for long periods of time causing evaporation of lighter, δO^{16} isotopes, Figure 2.8, c) (Singh and Kumar 2005; Lorentz 2008). Both these sources of rainfall appear to be evident in the rainfall isotope values of the Weatherley catchment, given in (Figure 2.8). The abundance of negative δO^{18} and $\delta^2 H$ rainfall isotope values indicated by the linear slope of 7.0, Figure 2.8, signifies the dominance of locally derived oceanic precipitation sources. This is indicative of the climate where summer rainfall constitutes up to 80 percent of annual rainfall with intense orographic and advection thunderstorms playing a dominant role in delivering precipitation.

The isotopic composition of runoff is comprised of various combinations of the current and previous events water based on catchment runoff characteristics. Runoff that is comprised mainly of the current events precipitation will show a linear trend similar to that of the current precipitation (Figure 2.8, b or c). Runoff originating from previous events precipitation may exhibit evidence of fractionation shown by (d) in Figure 2.8. The fractionation processes occurs during either atmospheric or terrestrial residence of water. Precipitation from previous events (pre event water) can mix with the current events precipitation (event water), its signature may become evident in two ways. Firstly, in the observation of a lagged rainfall isotope signal evident in the runoff a number of hours or days after an event. Secondly, rainfall from previous events collects isotopic markers of enrichment through fractionation and/or mixing with even older soil water (saturated and unsaturated), before mixing with event water allowing runoff to reflect an element of both depending on catchment runoff characteristics. These markers, along with a detailed set of rainfall isotope data, allow for the detailed description of catchment and hillslope scale hydrological processes given in the section.

Catchment scale δO^{18} and δH^2 values give a general overview of the role of pre event water, any decrease in the linear gradient of streamflow isotopes in respect of the rainfall isotopes is evidence for the enrichment experienced by transient catchment waters. This indicates the presence of pre event water during the current precipitation event. Thus, the soil is an evident contributor to the runoff hydrograph.

The identification of the different processes influencing isotope trends in time is conceptualized in Figure 2.8.

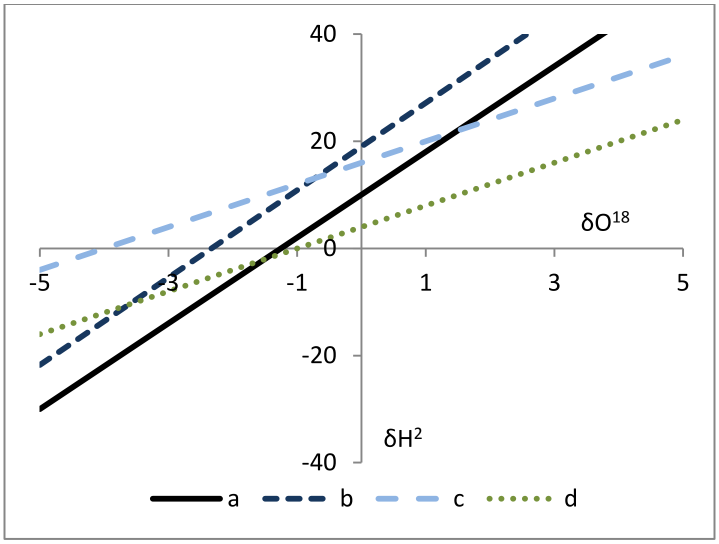


Figure 2.8 Conceptual isotope compositions of rainfall and runoff.

A combination of the qualitative and quantitative tracer methods of describing hillslope and catchment processes described in this chapter are typically used in the derivation of models to quantify the magnitude of hillslope and catchment responses. These methods include tracer based residence time models (McGuire and DeWalle, 2002), soil hydraulic models based on non-linear partial differential functions (Simunek 2008), topographically defined similarity index models (Beven 1997; Ciarapica and Todini 2002) and physically based catchment and hillslope scale models (Lorentz 2008).

2.7.5 Isotope based quantifications

The most common application of isotopes in tracer-based studies is the simulation of mean residence time. Mean residence time simulations are estimated by a applying a precipitation input signal to transfer functions which describe subsurface flow characteristics, where the temporal fluctuation of the tracer input is used to replicate the output characteristics. There are a number of models available depending on the application. These include the Piston flow model, Exponential model, combined exponential piston flow model and the dispersion model (Asano and Uchida, 2002; Rodgers and Soulsby, 2005; DeWalle *et al*., 1997; Leibunbgut and Maloszewski, 2009; Maloszewski and Zuber 1982; McGuire *et al*., 2002; McGuire *et al*., 2006). The piston flow and the exponential model transit time distributions are applied in single porosity simulations. Dual porosity applications with porous bedrock or macropores, require the use of the combined exponential piston flow model or the dispersion model so a distinction can be made between mobile soil water in the macropores and immobile soil water in the micropores (Leibunbgut and Maloszewski, 2009). The majority of work carried out with these models has focussed on deeper ground water applications with minor temporal variations in comparison to shallower sub surface responses. Thus a large body of literature exsists to guide consequent ground water isotope studies. However, there is an lack of literature outlining the application of environmental tracers within different soil profiles across a catchment. This is due to the complixity incurred through the addition of a large amount of parameterization and sampling required (McGuire *et al*., 2006).

To accurateley quantify hillslope responses a combination of hydrometric and tracer data is required to accurately represent a system. Dynamic variables such as rainfall and ground water levels are used to estimate static descriptors of recharge, drainage and storage, that transform rainfall to streamflow. the following section describes the theory behind the quantification of hillslope responses.

2.8 Quantification of Hillslope Responses

The quantification of hillslope responses typically involves the application of mathematical descriptions of hydrological processes. These mathematical descriptions range from simple mass balance equations, which represent the components that make up water storage in a catchment, to complex non-linear partial differential equations that describe three dimensional flow and transport in a porous media. Incorporation of the relatively simpler equations into models using computer-programming codes is easily achieved. This is because the equations can be solved analytically as they use specified catchment boundary conditions. However non-linear partial differential equations cannot be solved analytically and require a further stage of approximation (Beven 2001). There are a number of numerical ways of solving these equations as described in detail by (Bronstert 1999; Altinors and Oender 2008). These methods manifest themselves in the form of hydrological models, which incorporate systems of dynamic equations to describe the hydrological process.

Darcy's law forms the basis of all descriptions of subsurface flow applied in distributed models. The law is based on an assumed linear relationship between the flow velocity and hydraulic gradient for saturated media. The application of this law should be limited to homogenous soil, as it is unable to account for characteristic variations of the potential gradient, except at extremely small scales. The presence of macropores hinders the application of Darcy's law as flow in the macropores is governed by a different local gradient to flow in the matrix of the porous media, and thus the application of Darcy's equation is limited to a particular range of scales (Beven 2001).

It is widely accepted that there are lower and upper limits outside which Darcy's law is not applicable. Any estimation of flow outside these limits is considered to be non-linear (Altinors and Oender, 2008). The quantification of non-linear flow is based on modifications to Darcy's law describing variably saturated flow and solute transport with the Richards and Advection Dispersion Equations (Van Genuchten, 1999; Altinors and Oender, 2008).

Hydrological models typically represent soil water interactions with kinematic wave algorithms, or non-linear analytical functions such as the Richards equation. A combination of these expressions is often used to describe different limits of flow within the same modelling scenario. The following section will review the Kinematic wave equation, Richards's equation and the Advection Dispersion Equation, followed by a short review of some models considering the respective functions.

2.8.1 Kinematic wave models

The kinematic wave equation is derived via a combination of a mass balance equation and a functional relationship between storage and flow. There is only one assumption underpinning the theory and is described for a hillslope as,

> "a functional relationship between storage and discharge that can be specified for the particular flow processes being studied", (Beven 2001)

The relationship between storage and flow is non-linear but retains a single value. This is because flow can be defined for any storage level at a particular point in a catchment. The kinematic wave equation can be defined as:

$$\frac{\partial h}{\partial t} = -\frac{\partial q}{\partial x} + r \qquad \text{(Equation 2.5)}$$

Where:
h = depth of flow
t = time
q = mean downslope discharge per unit width
x = flow variable
r = rate of addition or loss of water per unit length and width of slope

An advantage of the kinematic wave equation is that for steady state conditions analytical solutions exists for both surface and subsurface flow. The equation can also be easily extended to account for different catchment parameters such as slope or channel width, overland flow and channel flow and saturated subsurface downslope flow (Beven 2001). The kinematic wave equation can also be considered a reliable routing model for watersheds which have high land slopes, as it can account for increasing channel or slope roughness as the stream channel slope increases in steepness (Nourani and Singh, 2009). However the kinematic wave theory can only account for water movement downslope or down channel (Beven, 2001; Bogaart and Troch, 2004).

2.8.1.1 TOPKAPI

TOPKAPI is a distributed rainfall-runoff model. The name is an acronym for TOPographic Kinematic Approximation and Integration. TOPKAPI was developed with the aim of creating a physically based model in which the physical meaning of the output is preserved across a range of scales. It is derived on the presumption that a kinematic wave model can estimate the horizontal flow at a point both within and above a soil matrix. This assumption is then integrated into a grid cell description of a hillslope using a Digital Elevation Model (DEM). For each grid cell catchment parameters regarding evapotranspiration, snowmelt, soil water, surface water and channel water can be applied. This converts the differential equation (which defines the kinematic wave model) into a non-linear reservoir equation, which is a function of catchment parameters and is solved numerically. Hillslope responses are derived by cascading the non-linear reservoirs, which represent the soil matrix, soil surface, and drainage network based on the landscape elements of a hillslope.

The main advantage of the TOPKAPI model lies in its ability to be applied at various spatial scales. The model performed well during initial validation assessments at scales ranging from 20 to 400 meters. In terms of data requirements, Ciarapica and Todoni (2002), found that the accuracy of the model output was dependant on the level of available input data. Yet the blind calibration of the model from a well gauged catchment to a relatively poorly gauged catchment yielded acceptable results. This means that TOPKAPI could possibly be used to simulate ungauged catchments, which may addresses some of the scaling issues present in modern day hydrology (Ciarapica and Todini 2002).

However, TOPKAPI only considers a single soil layer that means percolation to deeper soil horizons is not represented. A second soil horizon was excluded from initial model development, as it was not deemed important in the catchments in which TOPKAPI was developed. In subsequent versions of the model the five modules describing each node are increased to ten, with the addition of interception, infiltration, interflow, vertical recharge of the ground water, and surface flow modules. Dynamic descriptions of the modules/processes considered in the updated version of TOPKAPI are illustrated in Figure 2.9. Up to five different soil layers can be considered in the updated version of TOPKAPI, however the availability of data at a scale sufficient to represent four soil layers if often a hindrance (Liu, 2005).

The emphasis of the development of the updated version of the model was based on the inclusion of the components described above (Section 2.8.1.1) as well as the ability to infer input data from public domains such as the internet. Results concurred favourably with measured stream discharge. Internal catchment processes were also well represented when compared to measured data from a nested gauging station (Liu, 2005).

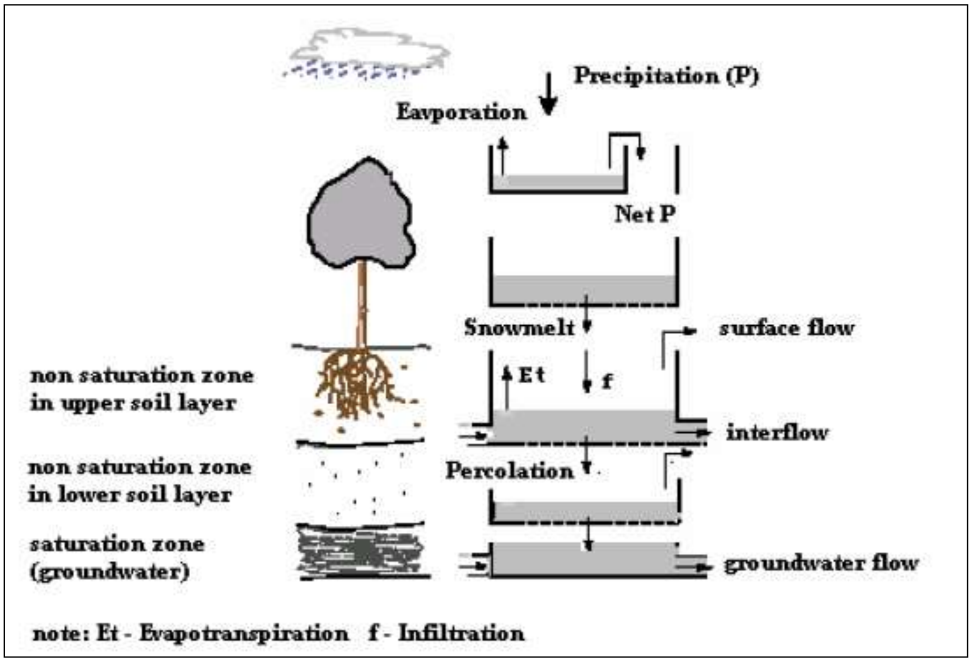


Figure 2.9 Water balance dynamics of the new version of TOPKAPI (Liu, 2005)

2.8.2 Richards' equation

Richards's equation is derived by combining the mass balance equation with Darcy's law.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} - K(h)\right] - S \qquad \text{(Equation 2.6)}$$

Where θ = volumetric water content

t = time

z = distance from soil surface downward

K = hydraulic conductivity as a function of (h) or θ

h = soil water pressure head (negative for unsaturated conditions)

S = sinks or sources for water

(van Genuchten and Sudicky, 1999)

The Richards equation can be defined as a partial differential equation which is non-linear. This is due to the non-linear relationship between hydraulic conductivity and soil moisture (Beven 2001). The ability of the Richards equation to account for the non-linearity of the hydrological cycle makes it both appropriate and inconvenient for modelling purposes. Appropriate in that it can account for the non-linear manner in which catchments respond, this is due to the different time frames that different responses have, and inconvenient because it requires numerical solution methods whenever it is applied (Finsterle and Doughty, 2008).

The Richards equation can be applied in various forms to estimate different responses. It is often used in simplified forms to reduce computational problems. Even though the Richards equation was derived to describe sub surface flows (Beven, 2001), it can be adapted to illustrate overland flow. Overland flow equations are integrated to extrapolate the Richards equation for use in saturated conditions (Kollet and Maxwell, 2006).

2.8.2.1 HYDRUS 2D

The HYDRUS 2D model provides for a two dimensional depiction of a hillslope. This is achieved by defining a finite element grid representing the hillslope or hillslope section to be simulated. The Richards equation governs unsaturated flow between nodes of the component grid. Unsaturated soil hydraulic properties are expressed with Brooks and Corey (1964) analytical functions (Simunek, 2008). Spatial variation of soils is accounted for by defining appropriate hydraulic properties over defined areas. Plant water uptake and evapotranspiration are defined through the selection of dominant root patterns and the identification of an atmospheric boundary at the soil surface (Lorentz, 2007). Delineation of boundaries is a key component in HYDRUS 2D, in particular, the model can account for flow restricted by irregular boundaries. These boundaries are delineated using a mesh generator which was designed for simulating variably saturated subsurface flow and solute transport in two or three dimensions (Simunek, 2008).

Figure 2.10 is an example from the Weatherly catchment (transect LC1 – LC4), showing the finite element mesh across which the Richards equation is solved for two-dimensional flow. The red squares indicate tensiometer position nodes, whose output can be used to calibrate hillslope simulations with measured data.

Typical outputs from the model include a two-dimensional colour display which illustrates the variation of parameters such as hydraulic conductivity and volumetric soil water content. An example of HYDRUS 2D output is shown in Figure 2.11. Unfortunately, the data intensive nature of HYDRUS makes scaling up impractical and thus it is restricted to small scale simulations.

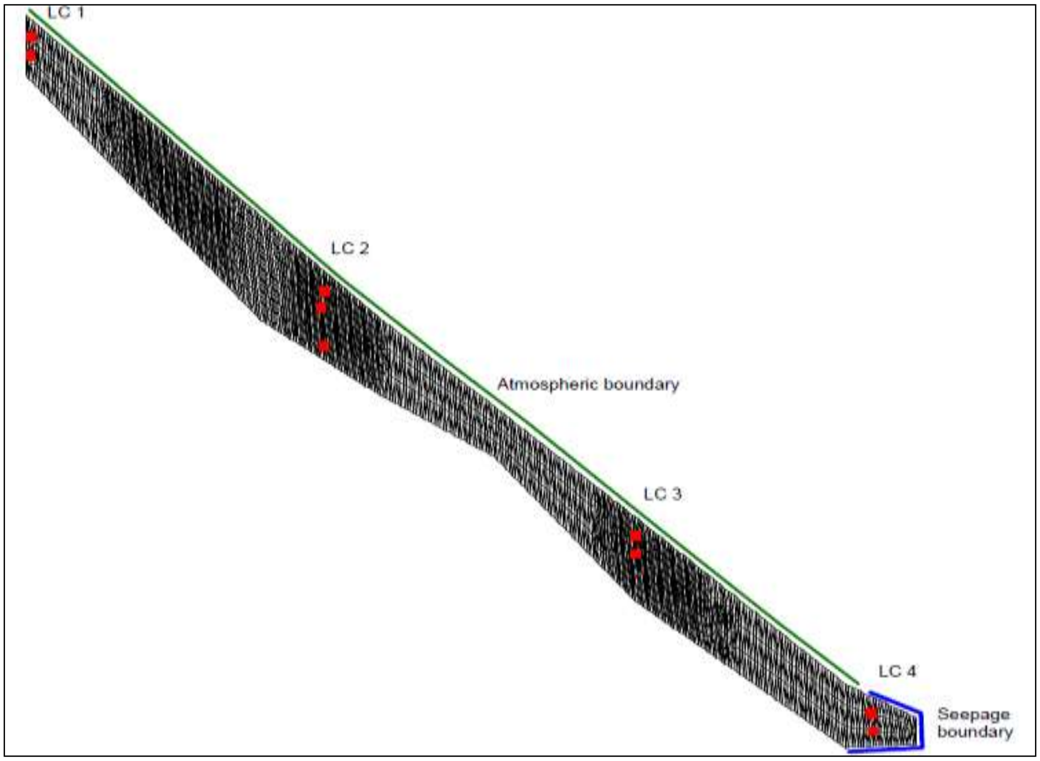


Figure 2.10 Finite element mesh of the HYDRUS 2D model, representing the hillslope cross section LC1 – LC 4 in the Weatherly Catchment, northern Eastern Cape, South Africa (Lorentz, 2007)

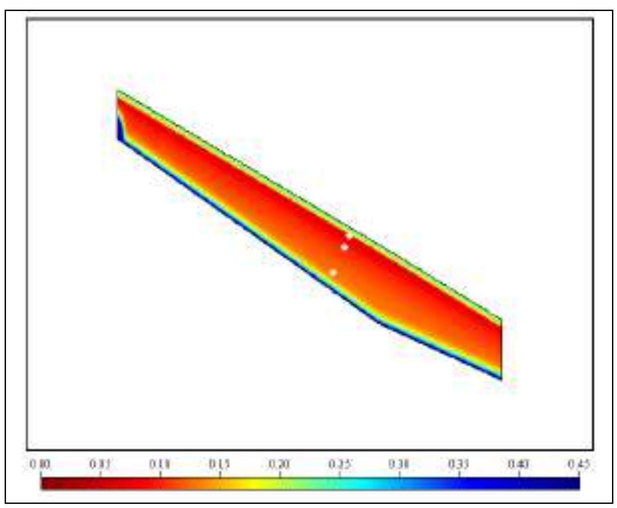


Figure 2.11 Soil water content in a hillslope section, as represented by the HYDRUS 2D model

2.8.2.2 TOPMODEL

TOPMODEL stands for TOPography based hydrological MODEL. As the name of the model implies, it is based on topographical aspects of a catchment (Beven, 1997). This is in the form of a topographic index of similarity, defined as

$$\ln(\alpha/\tan\beta) \quad \text{(Equation 2.7)}$$

Where: α is the drainage area per unit contour, and

β is the catchment slope (Yang *et al.,* 2002),

This index allows the model output to take the form of a set of simulated flow generation components. This is done according to the grouping of index values within a catchment in a digital terrain model. All points in a catchment with the same topographical index (Equation 2.7) will respond in a hydrologically similar way (Yang and Herath, 2002). This topographic index allows for the estimation of the ability of any point in a catchment to become saturated. Figure 2.9 illustrates the variation of the similarity index over the Slapton Wood catchment, Devon, UK. The distribution of the indices with respect to fractional area for the same catchment is a measure of hydrological response similarity of the catchment (Figure 2.12). The distribution of the topographic index allows for characterization of a catchment, for instance, higher index values typically lead to early saturation, signifying potential subsurface or surface contributing areas. Fluctuations in these saturated areas are indicated by the variation in the topographical index (Beven, 1997)

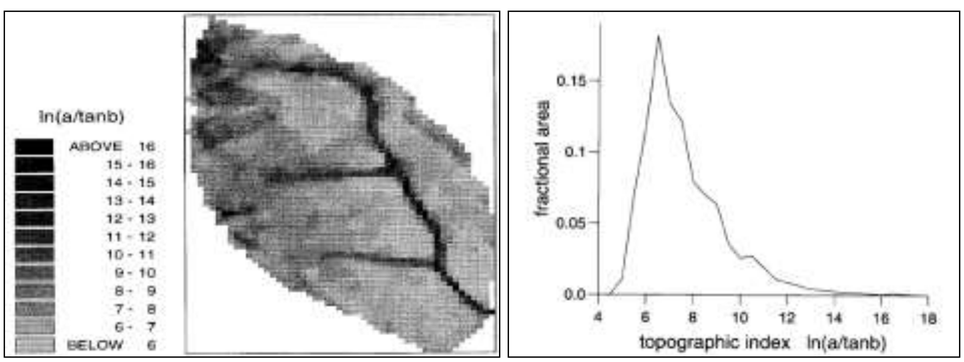


Figure 2.12 Distribution of similarity index (ln(α/tanβ) over Slapton Wood catchment, Devon, UK (Beven, 1997).

TOPMODEL is based on two basic assumptions. Firstly, soil water dynamics of the saturated zone are estimated with constant subsurface runoff generation, and secondly, the hydraulic gradient of the saturated zone is estimated as a function of slope gradient and transect length. This is represented by the function tanβ (Beven 2001).

However, as with all hydrological modelling, simplifications are inherent. The use of the topographical index causes a great degree of simplification of catchment dynamics. The two assumptions on which the model is based are considered restrictive. This is reflected by the omission of certain subsurface processes in aid of simplification. These include changes in soil hydraulic properties, subsurface flow channelling and variation in soil depth (Beven, 1997; Beven, 2001).

2.9 Advection Dispersion Equation (ADE)

The Advection Dispersion Equation (ADE) is based on the theory that if a large number of tracers are released from a point, they will disperse according to a limiting probability distribution. A limiting probability distribution is a concept which states that a sequence of unpredicitable and random events will begin to display constant behaviour after a certain period of time. This allows for the estimation of tracer concentration at any given time, thus describing the probability of a tracer concentration appearing at a particular point at a given time (Schumer *et al*. 2003). A typical response function can be expressed as a solution to the ADE as:

$$g(t) = \left(\frac{4\pi D_p t}{\tau}\right)^{-1/2} t^{-1} \exp\left[-\left(1-\frac{t}{\tau}\right)^2 \left(\frac{\tau}{4D_p t}\right)\right] \qquad \text{(Equation 2.8)}$$

Where:

$g(t)$	=	response function
D_p	=	Dispersion coefficient
τ	=	mean response time.

The ADE is typically applied in the simulation of solute transport. Shortcomings include the under estimation of the following and leading extremities of the solute plume. Further field scale application of the ADE revealed that dispersivity in hillslope soils is highly scale dependant, which compounds the amount of required data to estimate the position of a tracer concentration in space and time (Schumer *et al*. 2003).

The ADE can be applied in its one, two and three-dimensional forms and can be solved numerically in models such as HYDRUS. Studies have attempted to represent flow sources and pathways using simplified iterations of the ADE as opposed to topological indices as in TOPMODEL or TOPKAPI (McDonnell, 1996; McGlynn, 2001; Uhlenbrook, 2002).

A study by Weiler *et al*., (2003) applied the ADE in the development of a unit response function for different sources of flow generation. The unit response functions are representative of travel time distributions from each of the flow generation sources, given by a typical solution to the ADE by the exponential function:

Lorentz *et al* (2003) applied this solution of the ADE to the physically based ACRU model, adapting the historically catchment scale model for hillslope scale responses, allowing for lateral subsurface linkages to downslope positions.

2.9.1 ACRU Intermediate Zone routines

The addition of the Intermediate soil layer to the ACRU model came about through the identification and disaggregation of dominant flow mechanisms in various research catchments across South Africa. This work led to the inclusion of an intermediate soil layer simulated in-between the B-horizon and the bedrock or ground water store simulating the presence of a C-horizon or weathered rock. Properties of the Intermediate layer include a threshold response which triggers lateral hillslope ground water flow. This allows for a continuous function that mimics successive baseflow responses from the intermediate zone. This has been done in the form of a "threshold" unit response function. Essentially water is simulated to accumulate at the Intermediate zone/bedrock interface until saturation is reached; once saturation has been achieved, any additional water supplied will result in positive pore pressure thereby initiating lateral flow (Lorentz, 2007a). Root access is also given to the Intermediate zone, allowing for the simulation of deep-rooted vegetation. The intermediate layer also includes a rapid response mechanism, which simulates the generation of near surface ground water discharges due to macropore flow, partitioned from the traditional ACRU SCS derived event volume (Lorentz, 2007a), where flows to downstream sub catchment are only initiated when all water demands of the upstream sub catchment are satisfied.

The intermediate layer and ground water store of individual landsegments can be linked to downslope landsegments, simulating dominant soil and geologic hillslope discharge controls as demonstrated in Figure 2.13. Discharge from upslope landsegments to downslope landsegments are controlled by an Advection Dispersion Equation (ADE). An ADE can be defined as non-linear, partial differential equation (Van Genuchten, 1999). This is in contrast to the linear transfer functions used in ACRU 2000, which relate the storage state of ground water and stormflow storages to fluctuations in discharge from source components (Lorentz, 2007b).

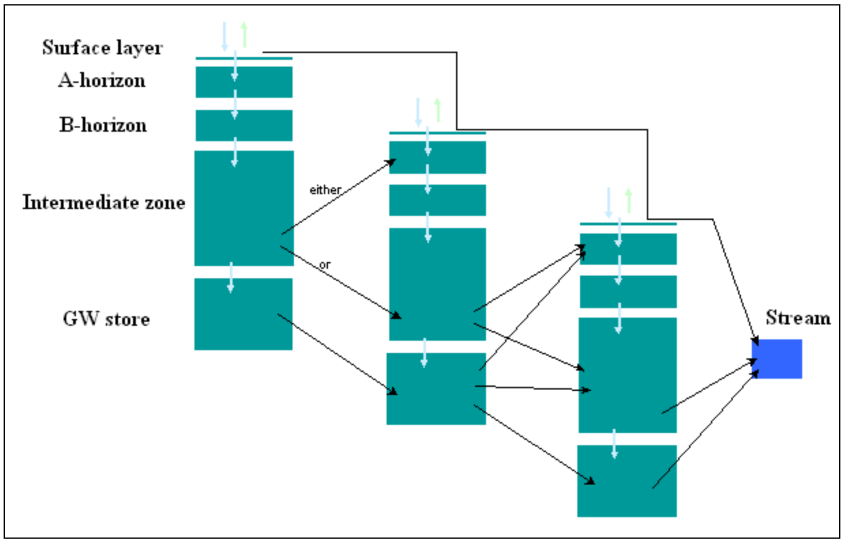


Figure 2.9 Possible subsurface flow routing options, ACRU Intermediate zone (Lorentz, 2007b)

Initial comparisons of ACRU 2000 and ACRU Intermediate zone in the Weatherley research catchment showed that ACRU 2000 did not simulate successive low flow responses adequately. This is due to the single coefficient describing baseflow responses in ACRU 2000 (COFRU). A second coefficient has been included in the ACRU 2000 algorithms to better represent the slope of the low flow recession curve (Lorentz, 2007b).

The inclusion of the new routines allows for the three dimensional representation of subsurface flow paths. At this stage the conceptualizations made from ‘collective field intelligence’, can be integrated into the model. The initial conceptualizations of dominant water movements and storages in the soil can now be represented and expressed by linking slope elements without the inclusion of highly detailed and intensive data.

2.10 Integration of Hillslope Responses in a Catchment Model

Troch *et al.*, (2003) suggests estimation of hillslope hydrological responses to rainfall poses one of the largest problems in modern day hydrology. This is with particular reference to the inclusion of hillslope responses into catchment scale models. In an attempt to integrate hillslope responses into catchment, models Duffy (1996) and Troch *et al.*, (2003) suggest that simplifications of the dynamic descriptions that form the hydrologic system are required to improve our understanding. However, this may prove risky, as there are hillslope processes such as macroporosity and the resulting preferential flows for which there are not accepted quantitative descriptors. Further compounding this is the fact that every catchment hillslope is unique, resulting in much knowledge being gained on the processes in the study catchment, but very little knowledge is added to the general understanding of typical hillslope responses (Freer *et al*., 2002).

2.10.1 Hydrological Scaling

The application of hillslope responses in a catchment scale model is an issue of hydrological scaling. In his 1997 critique of TOPMODEL, Keith Beven comments on the fact that field observations used in comparisons of simulation outputs are local with respect to representation. Often these point measurements are not representative at the hillslope or catchment scale, which propagates errors in the modelling process. It is suggested that the quantification of saturated contributing areas gives a better representation of hillslope responses. However this can only be done on a relatively coarse scale, which makes delineation of saturated areas difficult (Beven 1997). The misrepresentation of spatial variability in models can be put down to the fact that hydrological processes occur in a non-linear fashion (Schulze, 2008). When generalizations are made by lumped and distributed models, our ability to quantify spatial interactions amongst responses becomes diminished (Sivapalan, 2003). Beven (1997) argues that the modification of model processes to represent a range of scales is often carried out in a non-scientific manner. The non-scientific manner in which scaling practices often occur is deemed to be no more non-scientific than continuing to consider Darcy's law to describe flows in a porous media using physically based calibration techniques. These models or descriptions derived from flawed assumptions are deemed mediating models, and while they might offer some process description, they will not develop into full theories (Beven, 1997). Sivapalan (2003) expands on two methods of model development and resultant scaling of responses. Firstly the bottom up approach, which involves the inference of a model through field experiments. The locally gained field data is then applied in the development or improvement of models that represent hydrological responses at catchment scale. A problem with this method is that the field data are only representative of a few hillslopes within the catchment. The second method is termed the "top down" approach by Sivapalan (2003). This method involves analysing rainfall and runoff data from a catchment, this has formed the basis of a number of conceptual models. It is beneficial to the model if development is carried out using some description of internal processes as it makes misrepresentations easier to identify, suggesting that the bottom up approach is preferable.

Models such as TOPMODEL and TOPKAPI make use of a topographic index to estimate points in the catchment which will respond in a hydrologically similar manner. The index is derived, in part, with a DEM; this means that indices over a range of scales can be derived for the models. This is however dependant on the resolution of the DEM, once again identifying the data intensive nature of upscaling (Beven, 1997; Ciarapica and Todini, 2002).

If the issues hindering the scaling of hillslope processes to catchment scale are to be overcome, Sivapalan, 2003 proposes that better progress would be made if hydrologists were to link conceptualizations of processes across scales. For instance, water movement at hillslope scale is often described using models based on Darcian law, whereas models at a catchment scale can describe runoff response by means of a unit hydrograph or transfer function. The linking of the conceptualizations could occur through the identification of a common factor that can be easily scaled (Sivapalan, 2003). This is a very generic statement, yet it has formed the basis of several studies (McGuire and McDonnell, 2005; Rodgers and Soulsby, 2005).

2.11 Characterization of Hillslope Hydrological Responses

The representation of hillslope responses will inherently require a degree of generalization. This would normally occur through the identification of a dominant function of runoff response. However, for the characterization of such responses a common denominator is required. Sivapalan (2003) compares this common denominator to an underlying thread, identifying dominant mechanisms of aggregation to remove unnecessary detail in the modelling process. This is done such that only dominant processes are transferred from the hillslope to catchment scale. This approach has been used in several studies which have identified typical responses as a function of catchment morphology (Freer and McDonnell, 2002; D'Odorico and Rigon 2003; Berne and Uijlenhoet, 2005; Lyon and Troch, 2007). This link is often made via the application of a similarity index based on topography (TOPMODEL, Section 2.2). The advantage of this method is that hydrological responses can be simulated by means of quantifiable landscape descriptors. Freer *et al* (2002) included two topographic indices based on surface and subsurface characteristics respectively, in the aim of defining the impact of bedrock topography on subsurface responses. Other options such as the inclusion of width and area functions which determine the size of the hillslope have been used to derive hillslope discretization systems (Asano and Uchida, 2002). However, these classification schemes are have been criticized due to a lack of systematic relationships between flow processes and the landscape descriptions (Lyon and Troch, 2007).

2.11.1 Hillslope Péclet Number

In an attempt to overcome this lack in analytical relationships, Troch (2004) attempts to define hillslope responses with a dimensionless number which is a function of geometric catchment properties such as slope length, gradient, soil depth and hillslope convergence. This dimensionless number describes a hillslope Péclet number that defines advective and dispersive response dynamics along a complex hillslope. The number is derived through the application of the hillslope-storage Boussinesq (HSB) equation. This equation is formulated by expressing both the continuity equation and Darcy's law with soil water storage as the dependant variable. The equation is used to generate typical responses for soil water storage and fluxes for several different hillslope types and two different bedrock types. Hillslopes were differentiated on their plan shape, namely uniform, convergent and divergent. Characteristic responses of subsurface flows were calculated for the period just after partial initial saturation, as well as for the storm flow generated by saturation caused by an infinite, constant rainfall event (Troch and Paniconi, 2003; Berne and Uijlenhoet, 2005; Lyon and Troch, 2007). The application of the hillslope Péclet number is limited by the validity of the HSB equation. The HSB equation is only deemed to be representative on hillslopes with shallow soil profiles, streamlines that occur parallel to impervious rock, negligible hydrological influences of the unsaturated zone and the absence of overland flow (Berne and Uijlenhoet, 2005). This is not typical of semi-arid catenas where near surface process have been observed occurring under unsaturated conditions (Lorentz, 2007a).

2.12 Conclusions

It has been shown that there are a number different factors controlling hydrological responses at a wide range of scales. The spatial and temporal variation in these processes makes linking responses across scales difficult and often counterproductive. Part of the problem concerned with the application of hillslope measurements at a catchment scale is the understanding that similar processes differ across these scales. Therefore, in order to overcome this, hydrologists need to remove unnecessary detail when scaling data. This is done by identifying a common catchment characteristic that is representative of responses at a range of scales. Early studies carried out on the subject documented a link between catchment area and hydrological response. This theory has been disproven by recent studies in which catchment morphology has been identified as a possible common denominator between catchment response and scale. A review of modern day hydrological models revealed that much influence is assigned to morphological factors of a hillslope or catchment. Models such as TOPMODEL and TOPKAPI directly consider a topographic index or description of some sort, in the aim of identifying hydrologically similar areas within a catchment. While models such as HYDRUS-2D do not have a topographical index as such, but require the definition of a slope in the form of a finite element mesh or representative nodes at which variables such as gradient and hydraulic properties are defined. Therefore, it is risky to attempt a hillslope response description without the consideration of the functions of catchment morphology as this governs various soil parameters, thus controlling the movement of water within the soil matrix.

This study aims to apply qualitative and quantitative field observations in the description and eventual quantification of dominant hillslope processes. Hydropedological soil and hillslope delineations will provide the basis of catchment disaggregation for tracer, hydrometric and simulation analyses. The eventual aim is use process descriptions and quantification of dominant hillslope processes to simulate quaternary scale catchments using typical hillslope response distributions.

3 METHODOLOGY

The methodology of this study will follow a bottom up approach. Point data are used to describe hillslope hydrological continuity before quantifying numerical descriptors of subsurface flow. These descriptors are then applied in a traditional catchment scale model populated with highly generic input data. This was divided into three distinct objectives, comprising the proposed methodology.

1. Define the hydrological processes in two distinct hillslopes through hydrometric and tracer observations.

   Tracer and hydrometric observations from four different hillslope transects in the Weatherley catchment will initially be used to conceptualize the hydrological continuity between different parts of a hillslope. The hillslope scale descriptions are used in conjunction with an earlier hydropedological classification (van Tol, 2010) of study site hillslope soils.

2. Develop typical response functions for discharge from the hillslopes.

   The descriptions derived under the first objective are quantified by applying δO^{18} and δH^{2} isotope time series data in a numerical model. The numerical model transforms the rainfall time series signature to an output signature by lagging the input according to specific transfer functions. These transfer functions are simplified descriptors of the recharge and drainage characteristics of a soil profile.

3. Integrate the response functions into a catchment model to evaluate the improvement afforded by the hillslope hydrology responses.

   The transfer functions derived under the second objective are used as the only form of calibration in a catchment scale simulation, all other input data is constant across all simulations. If the transfer functions derived are to be applicable over a range of scales as the dominant control on hillslope hydrologic response, the simulations should improve through the addition of the transfer functions during model parameterization. This will assess whether the combination of model and method are suitable for further study.

4. Recommend future direction for catchment response simulations using classed hillslope responses.

   The culmination of the above three objects will form a proposed methodology for future research and practical application in prediction of ungauged basins.

3.1 Study Site

The Weatherly catchment is partially forested; $1.57km^2$ site situated in the northern part of the Eastern Cape, within in the $302km^2$, Mooi River Quaternary catchment (T35C). Hillslopes have been intensively instrumented since 1998, including afforestation with Eucalypt and Pine species in 2002. Weatherly is situated in the lower altitudes of the Mooi catchment (1300-1500 masl) in which the geology is dominated by Elliot sandstone and Molteno mudstone flatbed sedimentary formations comprised of horizontally bedded sandstone and mudstone layers. The sandstone and mudstone layers are periodically interrupted by intrusive dolerite dykes. The Elliot formations are situated at higher elevations than the Molteno formations, with the Dolerite dykes intruding only into the downslope, Molteno formations (Figure 3.1). The higher reaches of Mooi catchment are dominated by Clarens (1500-2000masl) and Basalt (2000+ masl) formations. The majority of the runoff generated in the Mooi catchment is expected from the upper reaches due to the higher rainfall and responsive nature of the steep slopes and bare rock.

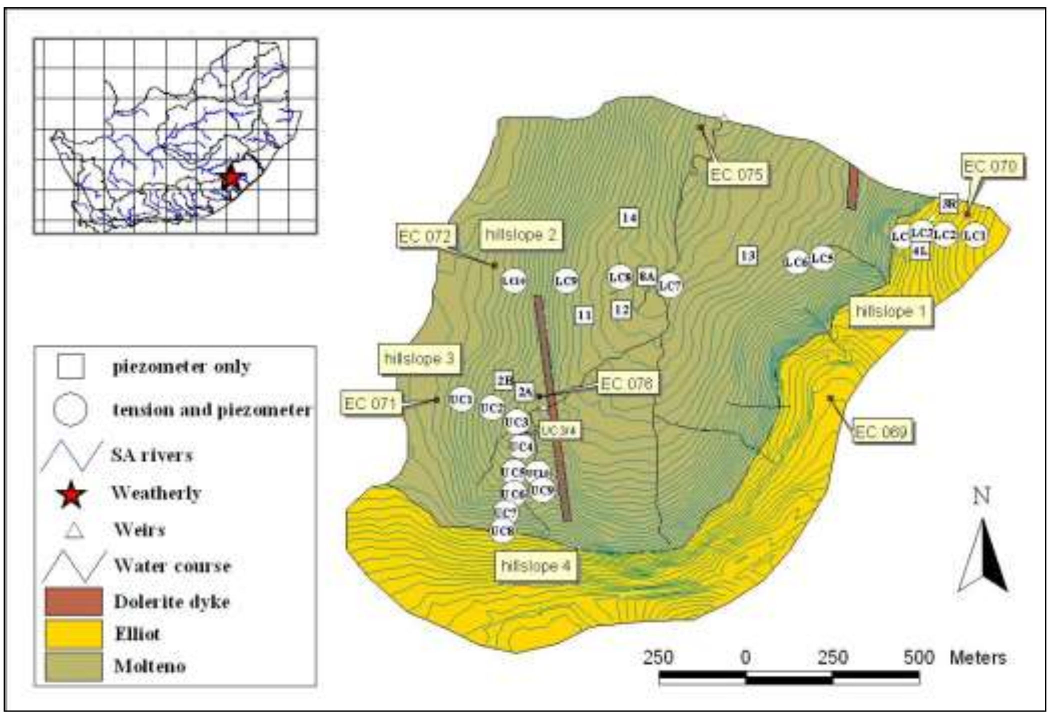


Figure 3.1 Weatherly situation, Geology and monitored hillslopes 1-4

For a detailed description of the Weatherly research catchment refer to, (Lorentz, 2008) and (Uhlenbrook, 2005).

3.2 Field monitoring

The three zones identified in Section 3.5.1 were concurrently monitored for the duration of the study period. Rainfall depth was measured at three different sites including a Davis AWS at the upper catchment weir, a tipping bucket (0.2mm per tip) at the lower catchment weir, and at nest LC 01 (0.2mm per tip) with another tipping bucket connected to a sampler containing 18 airtight, glass isotope sample bottles. Each bottles volume corresponds to a depth of 7.5mm rainfall. The glass sample bottles were secured in a sealed insulated container to prevent enrichment after sampling. Streamflow stage was measured using a Campbell CR 200 data logger, connected via an electronic switch to an ISCO 24 bottle flow sampler. The sampler was programmed to sample based on stream stage, and thus would be more active during both the climbing and receding limb of an event hydrograph. This allowed for the detailed analysis of the different sources and pathways of flow for very short time scales.

Four hillslope transects had existing watermark and tensiometer devices installed at up to three different soil depths. 32 piezometers, augered to the soil bedrock interface, are situated throughout the catchment representing a range of different hydrological soil zones. The piezometers allowed for observation of a saturated water table which was measured for water table height below ground and manually sampled for isotope analysis. Atmospheric data were measured by the Davis AWS situated at the upper catchment weir. Six deep boreholes are situated throughout the catchment; depths were recorded on a monthly basis and water was extracted for isotope analysis. Weekly neutron observations of soil water content (by volume) were made by the University of the Free State, department of Crop, Soil and Climate, at each of the instrument nests located along the hillslope transects. For a detailed illustration of the experimental set up refer to Figure 3.1.

3.3 Isotope sampling

The field sampling process extended from the end of January 2009 through March 2010. Field trips were conducted on a monthly basis with two month long intensive study periods in February 2009 and February/March 2010. However due to some initial sample collection errors and the failure of automated sampling equipment, the data used for this study extends from October 2009 through March 2010. Samples collected in early 2009 showed signs of an evaporated isotope trends in the form of positive δO^{18} and $\delta^{2}H$ values, while those collected in late 2009 and early 2010 showed no real evidence of any evaporation. It is suspected that the enrichment observed in the early 2009 sampling was because of incorrect sampling techniques, or the presence of trace amount of hydrocarbons in the sampled soil water. Incorrect sample collection allows enrichment to occur within the sample bottle after collection. However, the presence of enriched isotope values was not observed after the use of amber glass sample bottles. The application of

Los Gatos Research Liquid Water Isotope Analyser, Spectral Contamination Identifier software, did not reveal any presence of hydrocarbons for samples in the period October 2009 through March 2010. Therefore, isotope data from this period will be used in the description of catchment scale processes, with the intensive sampling period in March 2010 used to give event based hillslope descriptions from Section 4.3 onward.

The isotope sampling procedure involved an intensive manual component. Only rainfall and streamflow were sampled automatically, the balance of the soil water, seepage and deep ground water samples were collected manually. Manual sampling of seepage occurred as near to the seepage face as possible in an attempt to reduce exposure to evaporation. Piezometer and deep borehole samples were collected with a self-sealing collection tube. The tube was rinsed extensively with any excess waters from the sampled piezometer or borehole prior to the extraction of the final sample. Samples bottles were filled to the brim and pressure applied to the sides upon tightening the lid to remove as much air from the bottle as possible. Samples were then stored in insulated cooler boxes for transportation, packed into fridges, and held at 5 degrees Celsius until analysis.

3.4 Isotope analysis

The main component of this study is the use of isotopes to estimate hillslope responses. Samples were analysed through laser adsorption, using a Loss Gatos Research Liquid-Water Isotope Analyser. The isotope data are expressed relative to the VSMOW reference as parts per thousand. Analytical errors of ±0.2‰ for δO^{18} and ±0.1‰ for δH^{2} were not exceeded during the isotope analysis, denoting an analytical accuracy within the 95^{th} percentile.

The isotope analysis allows for the distinction of different contributing areas and flow paths. Firstly, examining the hydropedological hillslope characterization with the isotope data and secondly quantifying the contributions from the different soil types to the stream. Isotope data were used for both finger printing and characterization of catchment and hillslope processes. This was carried out at three different scales in an attempt to highlight similarities in hillslope response based on catena similarity because of underlying geological formations.

3.5 Hillslope Descriptions

The hydropedological classification of the Weatherly catchment formed the basis of the hillslope characterization, which is used extensively to delineate hillslope types in this study. Hillslope characterization allowed for the identification of different hydrological zones distinguishing different sub surface frames-works of hillslope connectivity.

3.5.1 Hydropedological classification

Description and identification of the dominant processes active on the various study hillslopes is initially based on the hydropedological classification of Weatherley soils, carried out by the University of the Free State, department of Crop, Soil and Climate. The Hydropedological survey identified the presence of three distinct hydrological soil types using three different types of data. These three types of data include soil survey observations, hillslope hydrological response units and land type data. These soil types include recharge, interflow and responsive, and are characterized in terms of the dominant hydrological patterns evident in the morphological properties of the soils (Figure 3.2). While there is variation between the different hydropedological soil groups found within the Weatherley catchment, it is the general distribution of the soil types across the study hillslopes which is of importance to this study. The distribution sequences of these soils across the different study hillslopes is believed to be directly linked to the underlying geology, which forms the basis of the hillslope model calibration in which parameters such as soil depth and extent are defined.

Recharge soils are characterized by deep, well-drained profiles showing evidence of oxidizing conditions (red soils). Interflow soils are shallower, typically situated on the steeper midslopes. These soils show signs of saturation on the soil bedrock interface and/or zones of abrupt change in permeability. As a water table develops on the permeability interface, the increased effect of gravity on the steeper slopes initiates' lateral subsurface movement. Responsive soils refer to both riparian soils and bare rock. These are zones of surface runoff production, especially riparian soils; typically occur directly adjacent to the stream channel. These soils are therefore vital in the delivery of water from the hillslopes to the stream channel.

This characterization of the Weatherley soils is used in conjunction with isotope and hydrometric data to define typical hydrological responses to each of the soil types. The isotope data and hydropedological classification are intrinsically linked as they serve to verify one another. This allowed for the detailed description of the connectivity between the different hydropedological soils types, forming the basis of the response quantification, which ultimately contributed the only level of exclusive data in the catchment scale runoff simulation. For a detailed description of the different hydropedological soil types and their identification refer to le Roux et al, 2011.

Sample sites are situated along four hillslope transects mainly situated on interflow and responsive soils, while only 2 'true' recharge sites (LC 10 and UC 1) are monitored, Figure 3.2. The distribution of the different hydrological soil types in the catchment makes it possible to assume that the responsive soils are recharged by the mid and upper hillslope areas, typical of interflow and recharge soils respectively. This is due to the fact that the responsive soils form a buffer between the stream and the mid and upper slope areas.

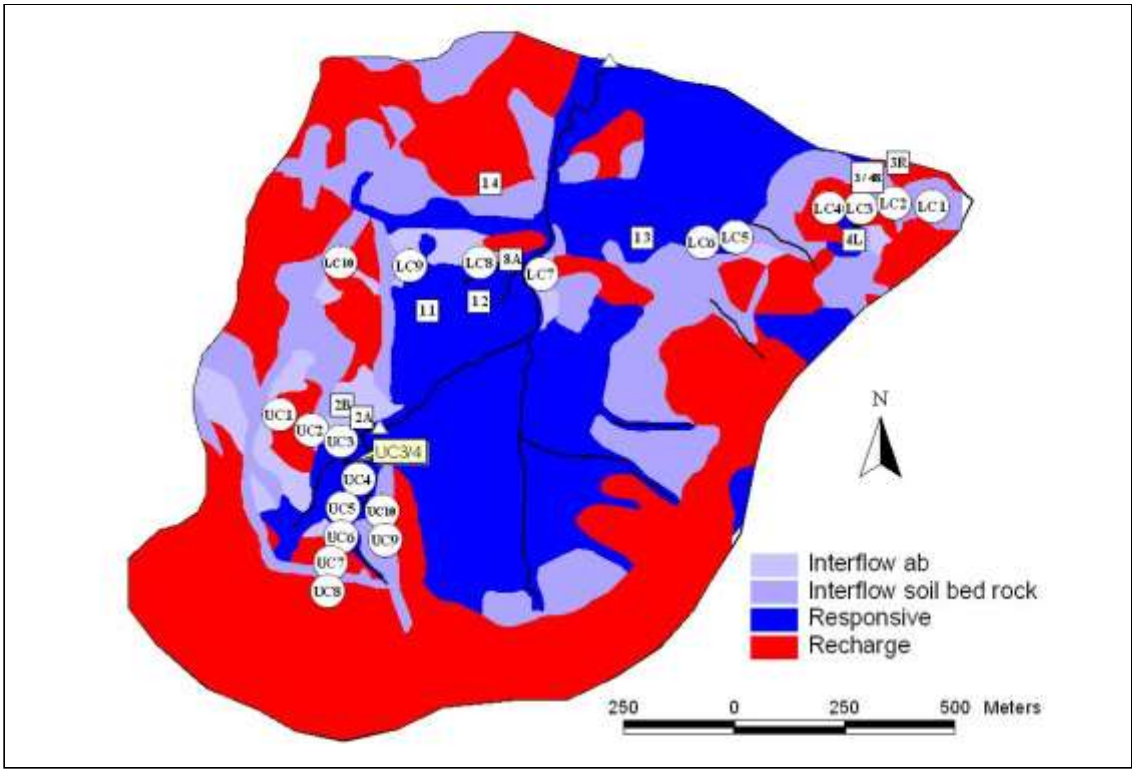


Figure 3.2 Weatherly Hydropedological soil classification

3.6 Two Component Hydrograph Separation

Hydrograph separations using δO^{18} isotopes are based on steady state mass balance equations that have several underlying assumptions:

- significant difference in δO^{18} value between event and pre event contributions,
- variations in pre event and event δO^{18} signal can be accounted for,
- vadose zone contributions are insignificant, or the δO^{18} value of soil water must be similar to that of ground water, as a two component separation cannot distinguish more than one subterranean water source, and
- surface storage contributions to streamflow are insignificant.

These assumptions are satisfied in the Weatherley catchment in Section 4.1. For the 2-component separation pre, event water is characterised by pre event streamflow or baseflow, with variable compositions of streamflow and rainfall as sampled representing the change in input and output δO^{18} over time.

The 2-component hydrograph equation is given by:

$$Qt = Qp + Qe \quad \text{(Equation 3.1)}$$

$$QtCt = QpCp + QeCe \quad \text{(Equation 3.2)}$$

Re-formed to solve for event and pre event contributions respectively:

$$Qe = (Ct - Cp)/(Ce - Cp) \quad \text{(Equation 3.3)}$$

$$Qp = (Ct - Ce)/(Cp - Ce) \quad \text{(Equation 3.4)}$$

Where Q = volumetric flow rate
C = δO^{18} value permil
t = total streamflow
p = pre event contribution
e = event derived contribution

The 2-component hydrograph separation characterizes the response of the entire catchment. Only the total streamflow time series flow data is required together with the δO^{18} or δH^{2} values for rainfall streamflow and the pre event based sources. The catchment response is a reflection of how the various hillslope types respond individually, producing the accumulated catchment response, which is transient through riparian soils .

3.7 Advection Dispersion Equation Simulations

Advection Dispersion Equations (ADE) applies a limiting probability distribution to a known set of input values or tracer concentrations. The ADF is used to represent the arrival time distribution of water from a profile or hillslope in response to a unit excitation such as excess rain. The ADE is applied in two separate instances. Firstly, to derive generalized descriptors of mean response time and the dispersion coefficient for each monitored hillslope transects using δO^{18}, secondly, to quantitatively simulate lateral soil water movement to downslope areas.

3.7.1 Convolution Integral

Hydrological systems exhibiting steady flow regimes of output δO^{18} values can be related to the input δO18 signal of the rainfall thought the application of the convolution integral (Maloszewski, 1982).

$$\delta(t) = \int_{-\infty}^{t} \delta_{in}(t')g(t - t')dt' \qquad \text{(Equation 3.5)}$$

Where:

δ(t)	=	output δO^{18} signal
t'	=	integration parameter describing entry time of the tracer into the system
t	=	calendar time
δin	=	input δO^{18} signal
g(t - t')	=	residence time distribution

The numerical model applied in this study represents the downslope drainage of hillslope water using the convolution integral with the dispersion model to solve for the response function g(t). There are a number of other models available to solve the response function g(t) including the Piston Flow model, the Exponential model and Exponential Piston flow model, for a detailed description refer to Section 2.7.5 or (Maloszewski and Zuber, 1982; Kirchner *et al.*, 2001; Schumer *et al.*, 2003; Weiler and McDonnell, 2004). The Dispersion model is chosen as it is the only model that is applicable in all situations of ground water flow as outlined by (Leibunbgut and Maloszewski, 2009).

$$g(t) = \left(\frac{4\pi D_p t}{\tau}\right)^{-1/2} t^{-1} \exp\left[-\left(1-\frac{t}{\tau}\right)^2 \left(\frac{\tau}{4D_p t}\right)\right] \qquad \text{(Equation 3.6)}$$

Where:

g(t)	=	response function
D_p	=	Dispersion coefficient
τ	=	mean response time.

The input δO^{18} (δin(t)) signal considered in the convolution integral is extremely important and must be representative of the bodies of water contributing to streamflow generation. It has already been established in previous studies that there are multiple bodies of water contributing to streamflow in the Weatherley catchment as identified by (Lorentz, 2008). Therefore, the input δO^{18} rainfall signal will be adjusted to represent the fraction of pre event hillslope water and ground water that it mixes with before entering the stream. The adjustment of the input δO^{18} rainfall signal is carried out using a method described by (Grabczak, 1984; McGuire and DeWalle, 2002). The input function is required to represent the pre event water that contributes to hillslope and catchment scale event based recharge. This input function is estimated from the pattern of the rainfall δO^{18} values with Equation 3.8, and transformed based on the recharge factor, α_i, for a series of rainfall events, P.

$$\delta_{in}(t) = \frac{N\alpha_i P_i}{\sum_{i=1}^{N} \alpha_i P_i}\left(\delta_i - \delta_{gw}\right) + \delta_{gw} \qquad \text{(Equation 3.7)}$$

Where:

N	=	number of time steps/samples
α_i	=	recharge factor
P_i	=	precipitation amount (mm)
δ_i	=	precipitation δO^{18} value (‰)
δ_{gw}	=	ground water δO^{18} value (‰)

The ultimate value gained from the implementation of the convolution integral is the descriptors of the modelled hillslope response in the form of the Dispersion coefficient D_p and mean response time τ (Equation 3.6). This will allow for the calibration of similar values in the ACRU Intermediate zone numerical model which simulates lateral downslope discharges using an identical form of the convolution integral solved with the dispersion model ($\delta_{in}(t)$). This will be used as input ($\delta(t)$) to the convolution integral (Equation 3.5) to model different values of D_p and τ.

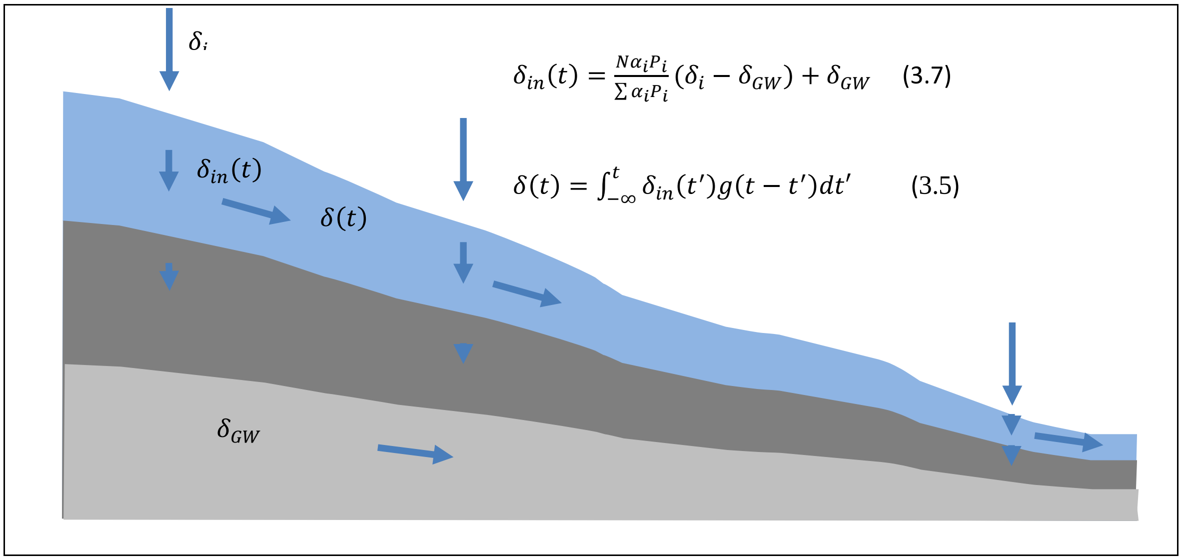


Figure 3.3 Conceptual diagram illustrating the application of equations 3.5 and 3.7.

3.7.2 ACRU modelling

The main objective of the ACRU Intermediate zone modelling is to assess the applicability of the estimated D_p and τ values to the observed responses in the Weatherley catchment. The D_p and τ values calculated for each hillslope transect will be used to parameterize individual hillslopes in a catchment scale model. Thus, a combination of hillslope responses will be used to simulate a catchment response. The only factor, other than area and calibrated subsurface drainage linkages that will be different between the hillslope input files will be the D_p and τ values. The results of the ACRU modelling will reveal the applicability of the study contents as a methodology for future application. This will be achieved by carrying out an identical simulation using the same rainfall and static input data with "classic" ACRU 2000 and ACRU Intermediate zone. Climate and rainfall input data for the ACRU 2000 simulation will be drawn from quaternary scale data from the Quaternary Catchments Data Base. Soil physical characteristics were parameterized using soil textural data, the ACRU model has predetermined values for drained upper limit, porosity and wilting point for each of the eleven soil textural classes considered by the model. All sub catchment input data for the ACRU 2000 and ACRU Intermediate zone simulations are identical (Figure 3.4).

The addition of the Intermediate zone routines means the model will be more data intensive and therefore more representative of the hillslope and catchment scale responses. However, the lack of detail in the static data in both ACRU 2000 and ACRU Intermediate zone simulations will mean that the ACRU Intermediate zone simulations will have a baseline against which the results can be compared. If a range of typical hillslope response descriptors can be derived, it would prove a more efficient means of calibrating models than conducting an intensive survey of a multitude of hydrological properties.

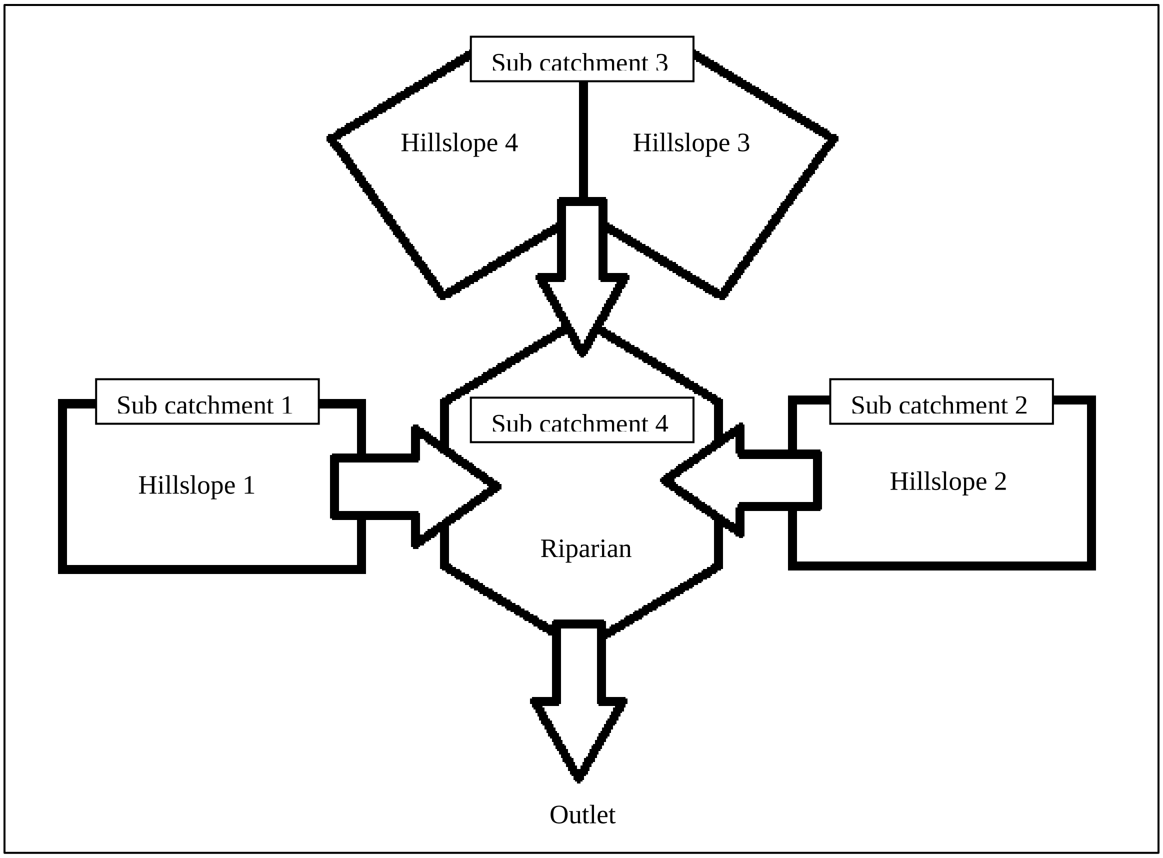


Figure 3.4 Weatherley ACRU 2000 and Intermediate zone hillslope surface water configuration.

Simulation results will be compared against observed soil volumetric water content and catchment streamflow. This is presented in the form of time series and regression analysis data.

3.8 Methodology "Road Map"

The road map outlines the basic steps undertaken in this study in order to parameterize the ACRU Intermediate zone model, demonstrating the manner in which qualitative catchment knowledge and quantitative observed data is used to derive generalized descriptors of catchment responses. The generalized descriptors allow for model parameterization without intensive scale specific data typically required to achieve the desired results.

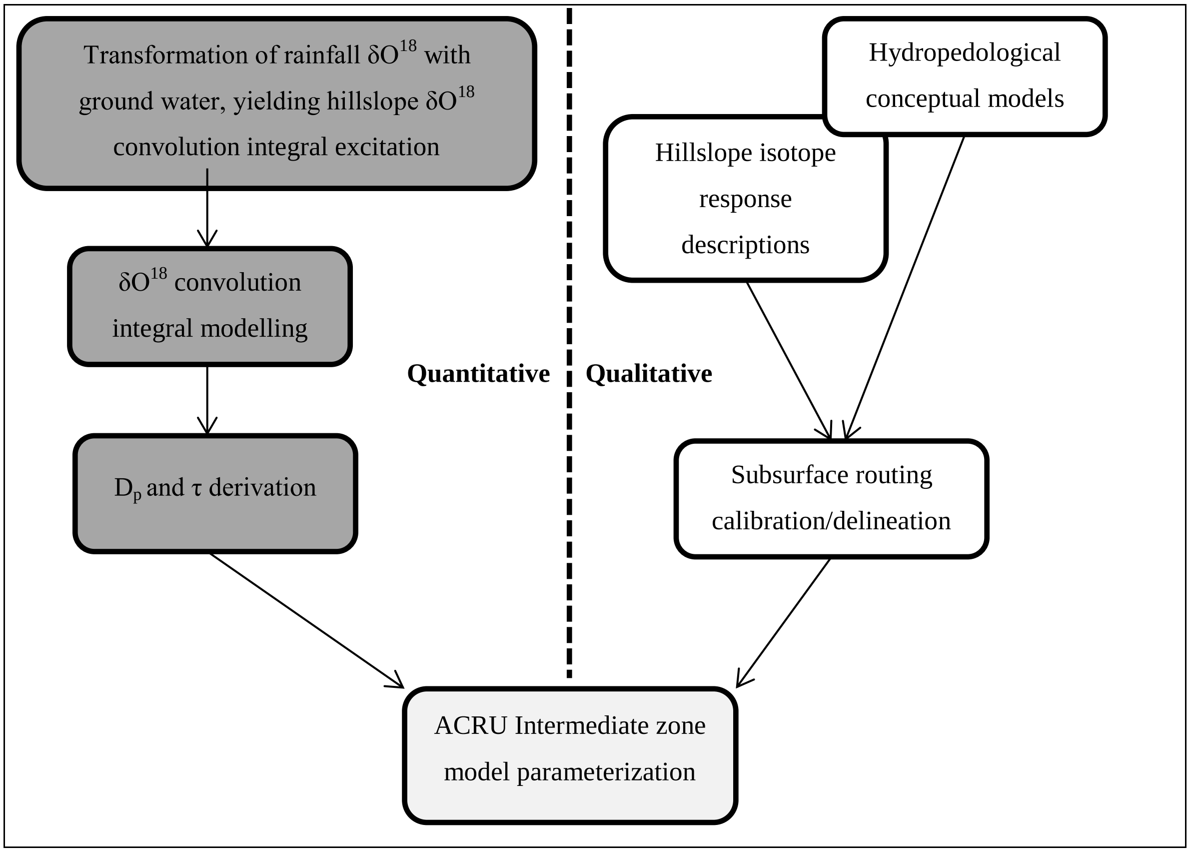


Figure 3.5 Methodology "road map"

4 RESULTS AND DISCUSSION

4.1 Weatherley Catchment Description

The NECF, Weatherley research catchment is a headwater catchment with distinct soil distributions observed at different topographical slope positions. The occurrence of distinctly different subsurface processes is observed at similar hillslope positions within catchment areas associated with specific soil morphological properties. This section serves as introduction to the tracer and hydrometric descriptions of the study hillslopes by giving a general overview of the Weatherley catchment end members, rainfall and streamflow.

A combination of hydrometric and tracer observations made from January 2009 to April 2010 are used to define typical hydrological responses that control hillslope connectivity based on dominant patterns evident in four different hillslope soil catena's. Oxygen 18 or δO^{18} isotope values sampled from rainfall, streamflow and hillslope piezometers are applied in the derivation of generalized descriptors of hillslope recharge and drainage using the Advection Dispersion Equation (ADE). These generalized hillslope descriptors are applied in the parameterization of a catchment scale model, simulating distributed hillslope segments. The process of sampling to catchment scale modeling is compiled in a concise methodology for the derivation of typical hillslope hydrological responses and their integration in hydrological models.

As the analysis and interpretation of δO^{18} and δH^{2} isotopes forms a large component of this study, an overview of the interactions between rainfall, runoff and deep ground water isotopes is given. The four study hillslopes will be conceptually described using a combination of tracer and hydropedological observations, resulting in a conceptual descriptions of event and pre event based hillslope processes. The descriptions are applied in the calibration of the subsurface routing of hillslope drainage in the catchment scale model. At this stage hillslope δO^{18} values are applied in the quantification of generalized hillslope descriptors. δO^{18} values are simulated to generate a "best fit" to observed data at different slope positions by simulating with different combinations of the dispersion coefficient (D_p) and mean response time (τ). The values of D_p and τ are used to calibrate the Advection Dispersion Equation used in the catchment scale model.

4.2 Catchment rainfall, runoff and streamflow

4.2.1 Surface runoff characteristics

The Weatherley catchment is instrumented with six USLE runoff plots monitored with tipping bucket style gauges. Unfortunately, due to continuous water damage to the electronic equipment in the riparian soils no automated data set could be constructed. Fortunately, mechanical counting meters were fitted to each tipping bucket mechanism resulting in a very coarse data set. Although the data set is at a very coarse time scale it was of enough significance to draw the relevant characteristics of surface flow at different hillslope positions. In the case of the hillslope runoff plots, the lack of data is evidence in its self. For the duration of the study period, no surface runoff was observed at hillslope nests LC 02, LC 10, UC 01 and UC 07 (Figure 4.1). From this, one can conclude the absence of surface runoff generation at these upslope positions is due to the large infiltration capacity. Increased surface roughness caused by the afforestation of these areas would also cause a shortening of slope length. This stops surface runoff generated gaining downslope momentum, and thus further perpetuates the likelihood of vertical infiltration.

In rather stark contrast, the riparian runoff plots at nests LC 08 and UC ¾ show relatively coarse but defined responses to rainfall in terms of the hillslope observations. The presence of surface runoff in the riparian soils indicates the existence of maintained soil moisture resulting in the generation of infiltration excess overland flow. The sustained free water levels in the riparian soils are possibly because of hillslope discharge and will be discussed further in Section 4.6.

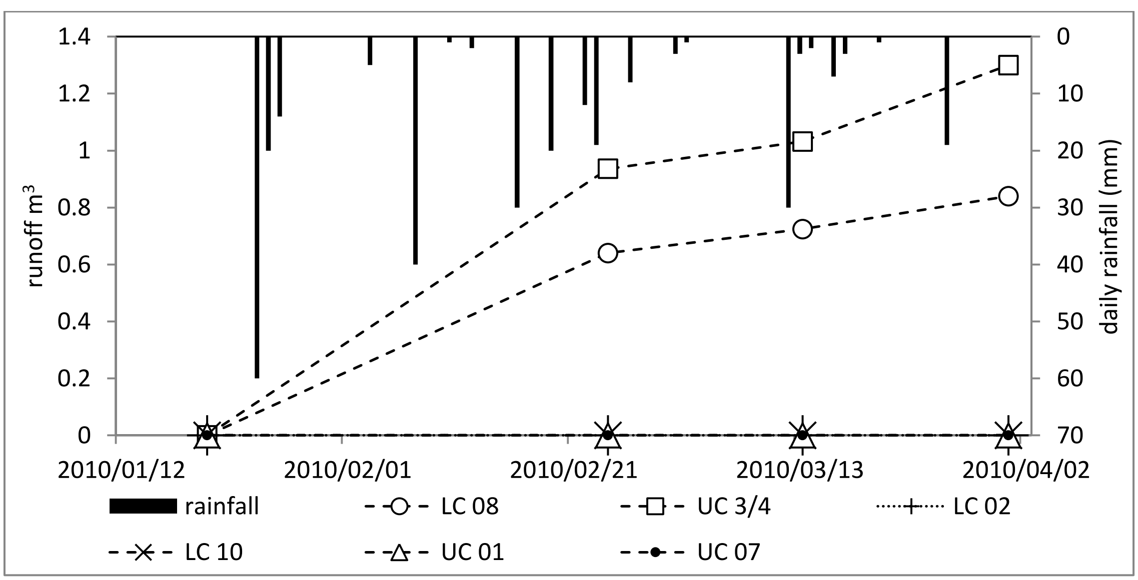


Figure 4.1 Weatherley runoff plot data, Riparian runoff plots LC 08 and UC3/4, and Hillslope runoff nests LC 02, LC 10, UC 01 and UC 07.

Automated flow samplers were not fitted to any of the runoff plot gauges. Therefore, no isotope sample could be taken as water remaining in the tipping bucket for a number of days before sampling would have a high possibility of enrichment through evaporation. For this reason, there are no tracer-based descriptions for the runoff plot data, and the data can only be used as supporting evidence for the isotope based hillslope descriptions to follow in Section 4.3.

4.2.2 Rainfall and streamflow isotopes

The application of tracer-based techniques in hydrology allows for the determination of sources and flow paths contributing to runoff generation. The conservative nature of δO^{18} and δ^2H isotopes allows for the quantification of sources and flow paths using a variety of mixing equations. It is imperative that all waters entering and exiting a catchment are sampled to make representative quantifications. The use of δO^{18} and δ^2H isotopes as tracers relies on the distinction between values of waters at different stages in the hydrological cycle. The three main groups defining different isotopic values are; atmospheric water, terrestrial water and oceanic water. For the purposes of catchment based hydrological studies, terrestrial water is of greatest interest, yet both atmospheric and oceanic water define rainfall δO^{18} and δ^2H patterns. Each group provides a standardized reference point, which is used to make assumptions on either of the opther two isotope groups, including transient water within the groups. For the purposes of this study, the relationship between atmospheric and terrestrial water is used. The two main processes identifying hydrological activity within the transformation of rainfall to runoff are fractionation and attenuation, described in Section 3.5.1. The identification of these two processes distinguishes dominant flow paths or drainage characteristics allowing for the definition of dominant hillslope hydrological processes.

Average monthly analysis of the rainfall and streamflow hydrometric and isotopic data shows a significant correlation between streamflow and rainfall oxygen isotopes. This is reflected in the manner in which the streamflow δO^{18} values display a similar but dampened rainfall δO^{18} pattern. δO^{18} rainfall values range from-8.85 to 6.42, while streamflow values range from -5.12 to 2.6, shown in Figure 4.2. This is evidence that event derived surface runoff is a dominant contributor to the total catchment response. This is typical of small head water catchments such as Weatherley (Singh and Kumar, 2005). The periodical deviance of the streamflow isotopes from the rainfall isotopes, October 2009 and January 2010, Figure 4.2, is indicative of the presence of more than one active ground/soil water source. If only a single soil water source was active in a small headwater catchment such as Weatherley, where the isotopic composition is highly dependent on precipitation, the streamflow isotope data would mimic a mixture the rainfall and soil water isotope data (Singh and Kumar, 2005). The deviance of October 2009 and February 2010 average monthly streamflow isotopes from those of rainfall, Figure 4.2, indicates the contribution of multiple subterranean sources to streamflow generation.

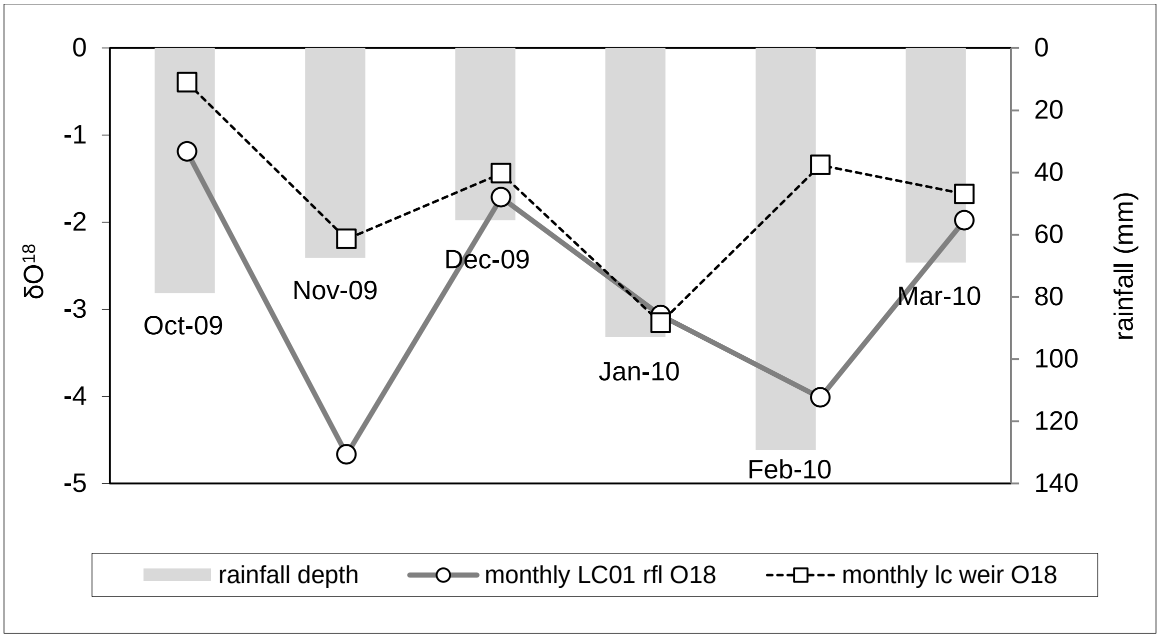


Figure 4.2 Weatherley monthly average rainfall and streamflow δO^{18} and δH^{2} isotopes.

The enrichment caused during the transformation of rainfall to streamflow is evident in the linear trends of the monthly weighted isotope data plotted in Figure 4.3. Rainfall (rfl, Figure 4.3) has a slope of 8.0 which is the same as the GMWL, while the linear slope of streamflow (strmfl, Figure 4.3) is 5.0. A linear slope of 8.0 denotes locally derived rainfall absent of signs of long atmospheric transit times that would promote enrichment. Streamflow isotopes show a linear slope of 5.0, indicating that different sources and pathways of streamflow generation have longer transit times, whereby transient flows are potentially exposed to greater levels of evaporation and mixing. The decreased linear slope of streamflow compared to rainfall is evidence for presence of pre event hillslope water, with longer transit times, contributing to streamflow leaving the catchment.

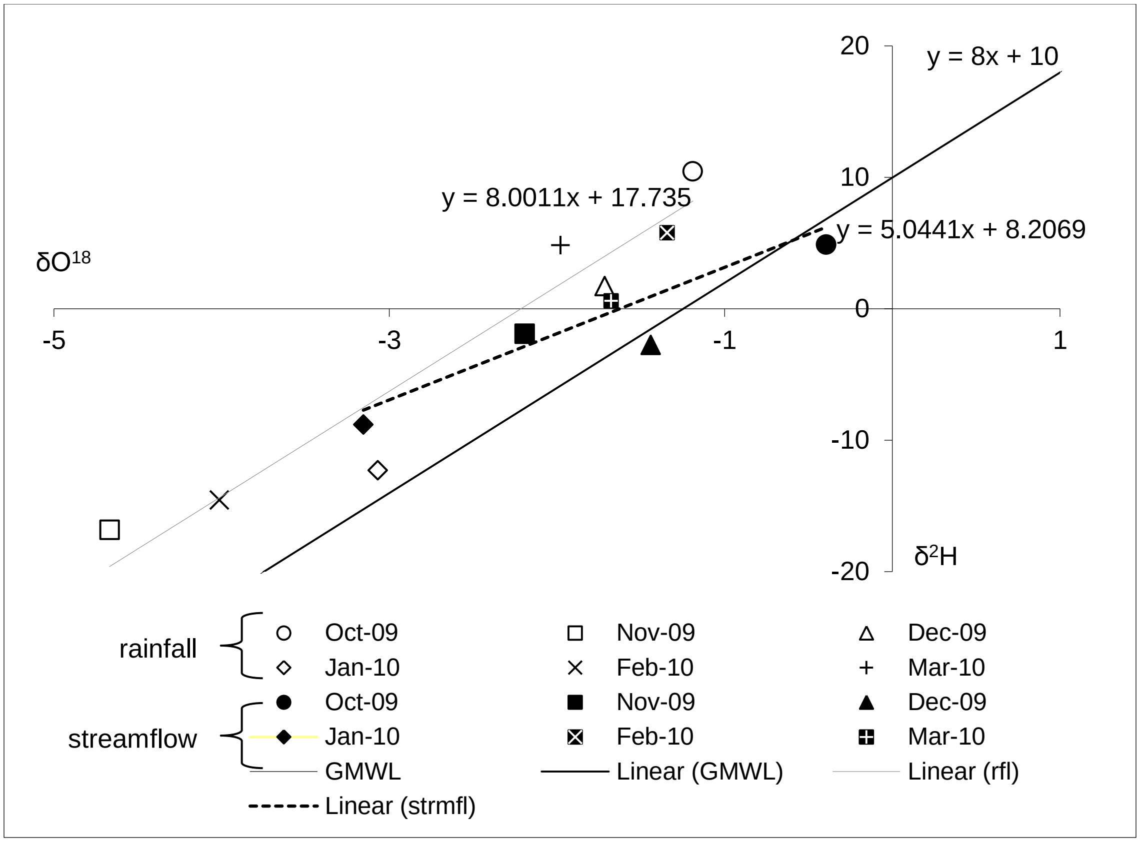


Figure 4.3 Weatherley monthly average rainfall and streamflow δO^{18}, δH^2 isotopes.

This previous section describes the general runoff patterns of involved in the transformation of rainfall to streamflow. It is an initial starting point as we proceed to the more specific descriptions and quantifications of mechanisms of streamflow generation. This is achieved by examining dominant hydrological processes at the hillslope scale.

4.2.3 Soil/Hillslope water isotopes

The soils of the Weatherley catchment are characterized based on hydrological properties. Soils are characterized by determining the dominant direction of drainage based on soil observations at different topographical slope positions (Section 3.5.1). This allows for the construction of a conceptual model of the hydrological connectivity from the crest to stream, providing a starting point for the tracer based descriptions.

Recharge and Interflow soils, comprising 60% of the catchment area (Figure 3.2), are typically found on the crest and midslope topographical units respectively. Recharge soils are characterized by deep red soils in which vertical drainage dominates, with no extended observation of a perched water table on the soil/bedrock interface or through transmissivity feedback. Therefore, oxidizing conditions prevail, perpetuating the red colour of the soils. Interflow soils are characterized by steep slopes and shallow soils where the coarse texture of the soil and the increased slope gradient cause any accumulation of water above zones of decreased hydraulic conductivity to drain horizontally down slope.

Basic hillslope connectivity theory dictates hillslope water must pass through the riparian area to reach the stream. However as the riparian area possibly represents an accumulation of surface, shallow and deep sub surface processes, a dampening of these various isotopic signatures will be observed as a result of a mixture of sources and flow paths (Tromp-van *et al*., 2006; McGuire, 2010). Responsive soils, which comprise the remaining 40% of the catchment area (Figure 3.2), are found predominantly adjacent to the stream in the riparian zone. These soils show signs of long term saturation and are expected to generate a high percentage of overland flow due to infiltration excess. For a detailed description of the theory behind Hydropedological soils types refer to Section 2.3. For the purposes of this study, the Hydropedological classification of the Weatherley hillslope soils acts as tool in the conceptualization of hillslope hydrological connectivity.

Soil water samples were taken at different topographical slope positions, extracted from free water in piezometers and assigned to a particular soil type as defined by the Hydropedological classification i.e. Recharge, Responsive or Interflow hillslope segments.

The difference in riparian and hillslope isotopic data is shown by the linear relationships plotted in Figure 4.4. In Responsive soils where perched water predominates, the isotope relationship is described by a linear gradient of 5.3, while both Recharge and Interflow soil types are described by a linear gradient of 3.9. This indicates that hillslope (Recharge and Interflow soil types) water has far greater transit time than riparian (Responsive soils) water as it is potentially exposed to greater levels of evaporation and mixing.

The shallow gradient and greater depth of Responsive soils allows for high event water interception and storage in respect of the hillslope soil types; this is dependent on antecedent soil moisture conditions as demonstrated in Section 4.9. The linear gradient of the Responsive soils piezometer isotope data, 5.3, falls in between those of event water, 8.0, and hillslope piezometer isotopes, 3.9. As described in Section 2.4 this indicates a contribution from both “older” hillslope water (Recharge and Interflow soils) and “new” event water.

The linear gradients of the isotope data show that hillslope water is detected at the catchment outlet. This is visible in Figure 4.4 and in Table 4.1, where the linear gradient of streamflow isotopes (A), 4.8, sits below Responsive soils (C), 5.3, but above hillslope soils (D and E), 3.9 (Recharge and Interflow).

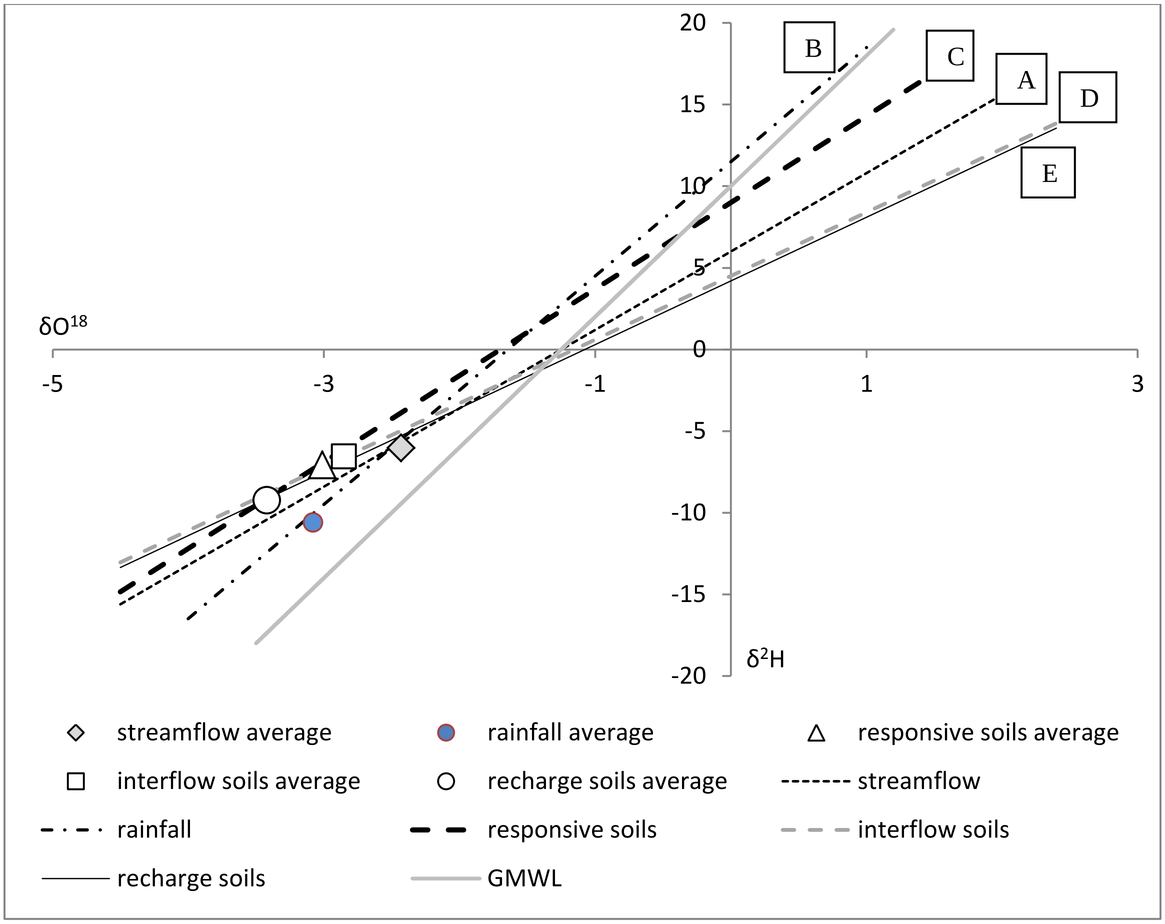


Figure 4.4 Weatherly weighted average linear isotope relationships of Hydropedological soil types.

	Label (Figure 4.4)	δ^2H average	δO^{18} average	Linear slope	N	R^2
Streamflow	A	-6.04	-2.43	4.80	136	0.82
Rainfall	B	-10.59	-3.08	7.00	208	0.82
Responsive soils	C	-7.08	-3.01	5.30	118	0.72
Interflow soils	D	-6.57	-2.85	3.90	55	0.74
Recharge soils	E	-9.25	-3.42	3.90	31	0.59

Table 4.1 Weatherley Hydropedological soil types, Rainfall and Streamflow linear slopes and average isotope value over the study period.

4.2.4 Deep ground water isotopes

Deep boreholes were periodically sampled for isotopes during the study period. Results showed highly stable time series behaviour. The effect of vertical infiltration and soil texture described in Section 2.7.3 is reflected by the stable/attenuated isotope signature in all six boreholes as shown in Table 4.2 and illustrated in Figure 4.5. As described in Section 2.7.3, the depletion of the heavier isotopes (negative values) the older and deeper the soil water. This allows for the assumption that no event based, rapid recharge of the deep ground water occurs in any of the six boreholes situated throughout the Weatherley catchment shown in Figure 3.1.

Borehole	Average depth to W/T (m)	δO^{18} average	N	R^2
EC075	4.00	-3.73	17	0.32
EC076	5.00	-3.90	16	0.75
EC071	13.00	-4.22	12	0.96
EC069	14.00	-4.37	16	0.96
EC072	17.00	-4.13	16	0.12
EC070	44.00	-4.44	16	0.93

Table 4.2 Weatherly average deep borehole depths and oxygen 18 values

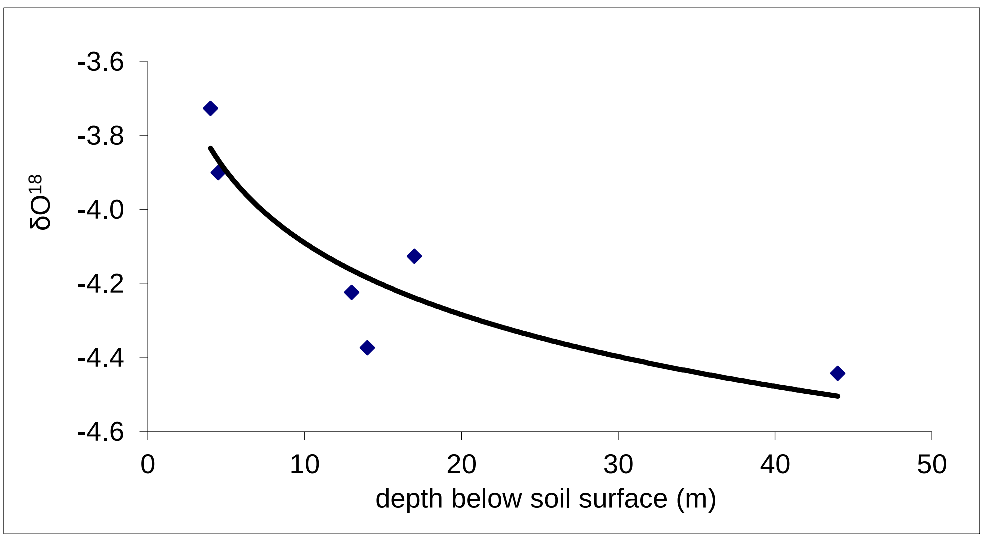


Figure 4.5 Weatherley boreholes, soil depth and δO^{18} relationship

A marked decrease in the gradient of the isotope linear gradients is observed with an increase in the approximate age of catchment water. Rainfall isotope data has a linear gradient of 8.0, decreasing to 5.3 in the riparian responsive soils, then dropping to 3.9 in the hillslope soils (Interflow and Recharge). This is also evident in the borehole isotope data. Boreholes directly adjacent to the stream, EC 075 and EC 076 (0-5m) have a linear gradient of 3, those in the midslope area, EC 069, EC 071 and EC 072, (5-20m) have a linear gradient of 2.3, and the upslope borehole, EC 070, has a linear gradient of 2.2, plotted in Figure 4.6. Therefore, borehole or deep ground water isotope data reveals a similar trend to piezometer data, where a flattening of the linear trend is observed with increased soil depth, Figure 4.6. There were no marked seasonal variations observed in the deep borehole isotope values (Figure 4.6), this can be attributed to the long transit times taken for precipitation to reach the saturated regional water table.

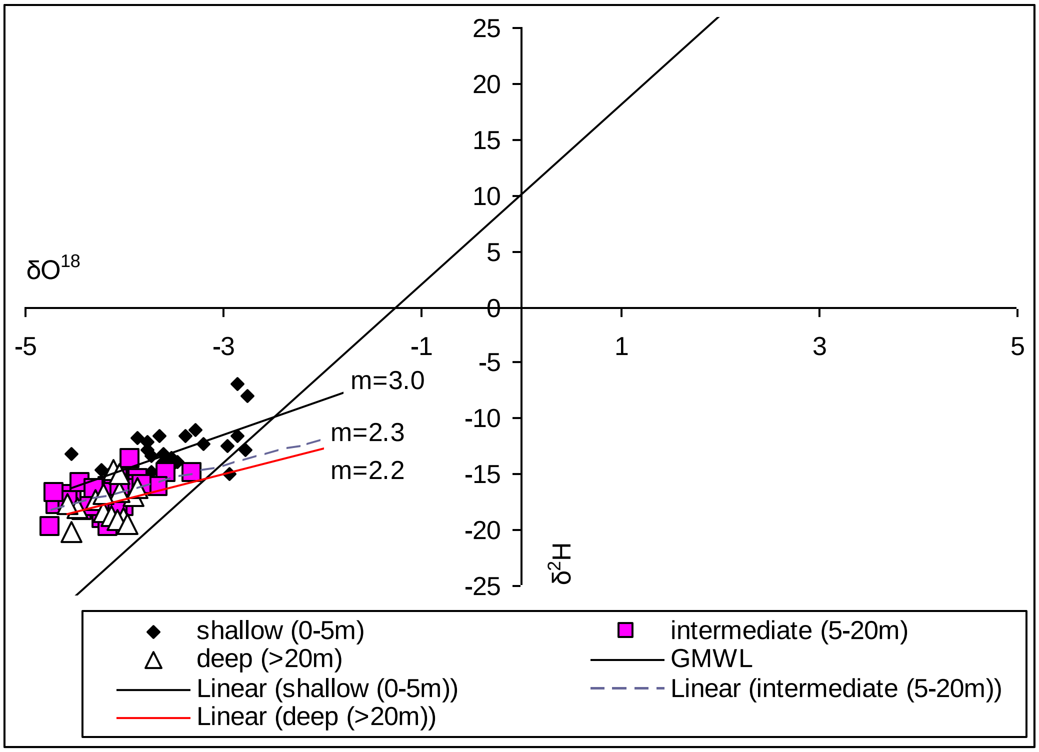


Figure 4.6 Weatherley, Deep borehole isotope δO^{18} and $\delta^2 H$ data with linear gradients showing the effect on isotope values with increased soil depth

Riparian Responsive soils and Streamflow isotopic trend analysis identifies the effect of hillslope water (Recharge and Interflow) in the riparian soils adjacent to the stream, and in the streamflow leaving the catchment. As shown in the borehole data, water that has resided in the catchment soils for longer periods will have a shallower linear gradient. Therefore, the dampening of any input isotope signal (rainfall) will occur because of mixing with older transient catchment water, already in motion or storage under the active hillslope processes.

4.3 Hillslope Descriptions

The previous section describes the isotopic relationships of the entire Weatherley catchment giving a lumped description of the accumulation of the different hillslopes responses resulting from different combinations of hydropedological soil types. The lumped description of the Weatherley catchment has shown the presence of hillslope soil water at the catchment outlet. In order to understand how each of these hillslopes contributes to the final catchment response a detailed isotope based description will be carried out for each of the different hillslope types identified in the Hydropedological classification of the Weatherley catchment. These hillslope descriptions allow for the development of an illustrative framework of how a hillslope stores and releases water to the riparian soils. For the purposes of the hillslope descriptions the detailed sampling period from 03/03/2010 to 13/03/2010, including a 30mm event late on 12/03/2010, will be used to distinguish different dominant pre and post event processes across 4 different intensively monitored hillslopes as illustrated in Figure 3.1.

4.4 Hillslope 1 (LC 01 – LC 07)

Hillslope 1 extends from nests LC 01 to LC 07 and is dominated by sedimentary geological forms. A series of Elliot sandstone terraces dominates the upslope recharge areas (LC 01-LC 04), while a Molteno mudstone formation comprises the bedrock in the Interflow and Responsive soils found on the mid and lower slopes respectively (LC 05- LC 07). Hillslope 1 is dominated by impermeable sedimentary geologies, which are expected to allow for the development of perched water tables in the soil profile which feed the riparian Responsive soils and stream.

4.4.1 Hydropedology and hydrometery

The development of a significant perched water table is evident on the interface of the Elliot and Molteno formations, where the Elliot terrace intersects the soil surface, creating a responsive rocky outcrop (Figure 4.7, immediately below LC 04). The perched water (Figure 4.7) at LC 04, responds over the outcrop in the form of surface seepage. This surface seepage was observed responding, and sampled for the duration of the wet season observations. Water tables were observed at Responsive soil sites throughout the wet and dry season, Figure 4.8 piezometer 13. Interflow soils show rapid drainage of saturated water; with saturated water observed and sampled for brief periods in the piezometers situated in these soils. This trend is illustrated in Figure 4.8 where the soil water level at riparian piezometer 13 is shown to be more stable during drainage periods than the hillslope piezometer at LC 04.

The link between the hillslope and riparian soils is crucial in understanding the final hillslope response. By analysing pre and post event linkages between these two zones the storage and delivery mechanisms of the hillslope can be determined.

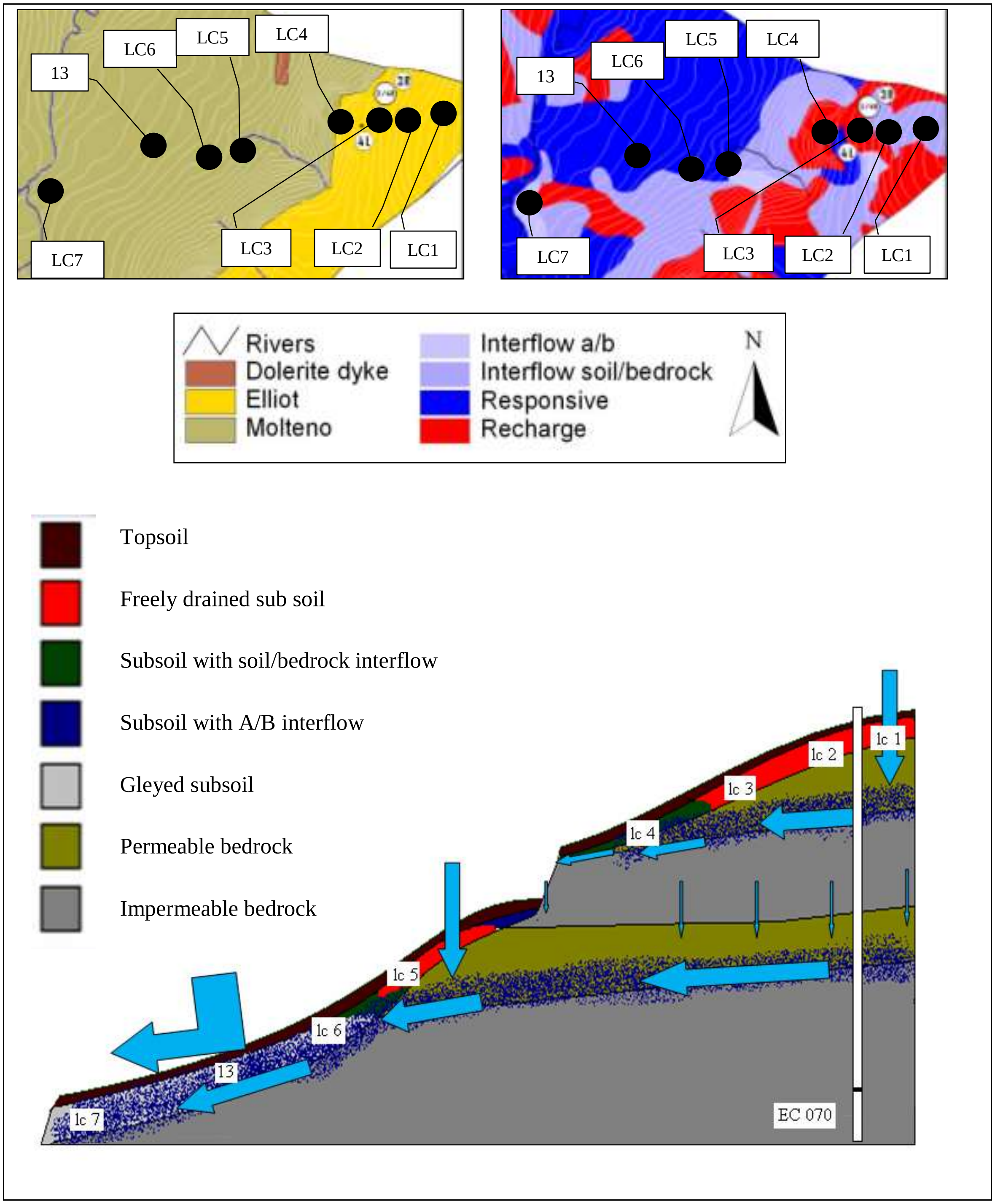


Figure 4.7 Weatherley, Hillslope 1, Illustrative description and conceptual flow paths

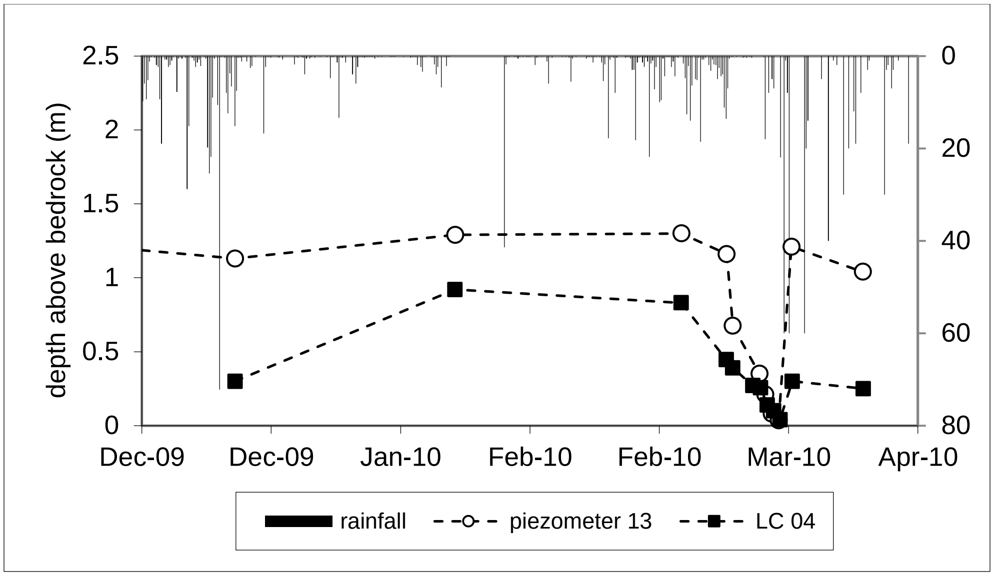


Figure 4.8 Weatherley, Hillslope 1 water table depth above bedrock for Responsive soils at piezometer 13 and hillslope soils at LC 04.

4.4.2 Pre-event

With increasing time from previous event, the most marked drainage occurs in the responsive soils directly adjacent to the stream at piezometers 13 and LC 07. However, the level of perched water at sites further from the stream at the hillslope soils/riparian soils interface, piezometer LC06, remains almost constant in respect of nests LC 07 and 13 which are situated in the riparian soils adjacent to the stream, Figure 4.9. This is an indication that upslope soil water contributions sustain the levels of perched water at site LC 06.

Isotope responses along the hillslope transect remain stable for the period leading up to the 12/03/2010 event. The attenuation in the hillslope isotope profile is further evidence of vertical infiltration and drainage of successively deeper zones of the soil profile as discussed in Section 2.7.3. This is reflected in the similarity between pre event isotope values along the hillslope transect (Figure 4.10), and the manner in which they tend towards the deep ground water isotope values as the drainage period extends, becoming more negative as the drainage period proceeds, Figure 4.11. The values for Figure 4.9, are given in Table 4.3.

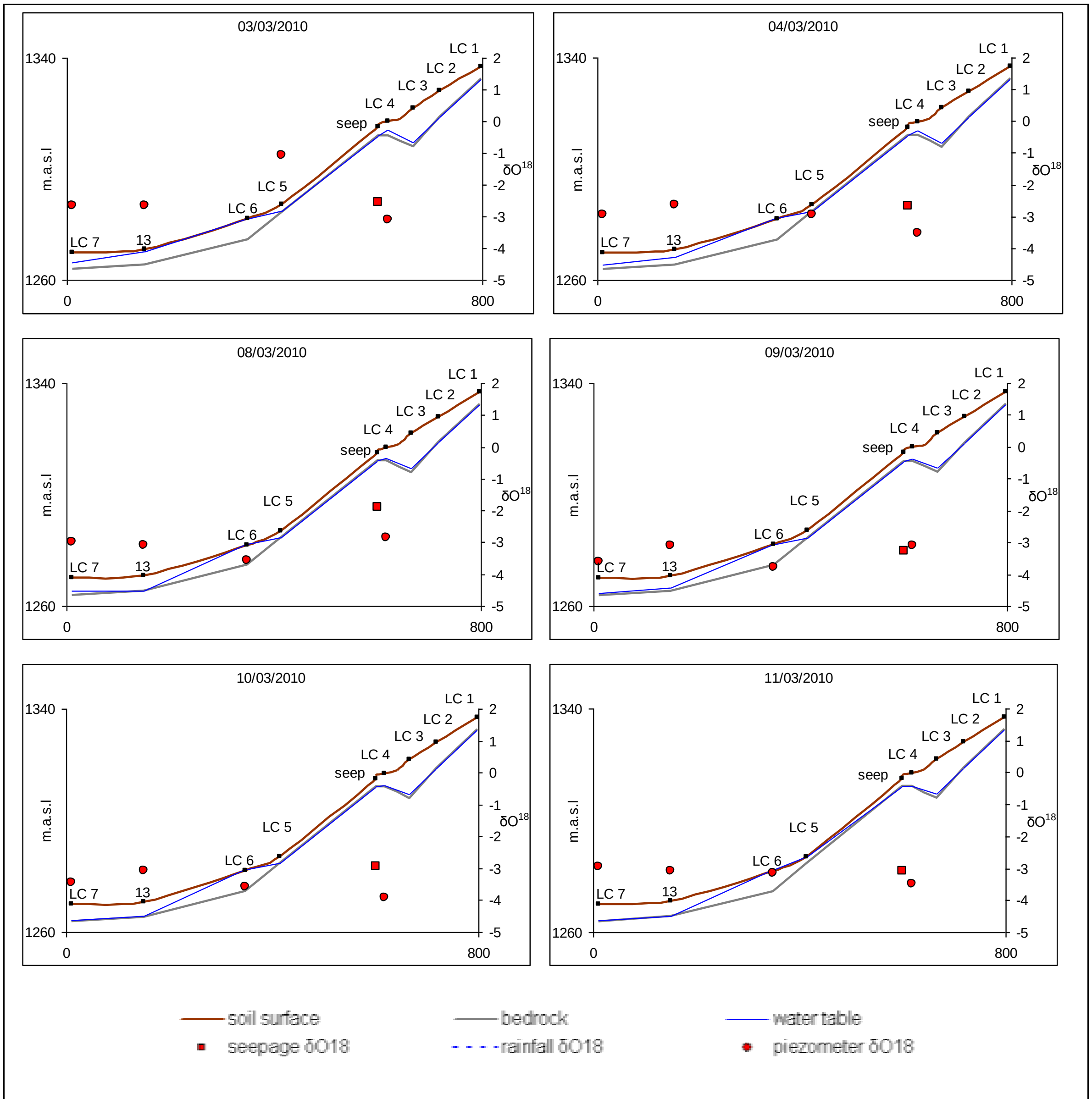


Figure 4.9 Weatherley, Hillslope 1, pre-event water table drainage and δO^{18}.

	Hillslope 1 (LC 01 - LC 07)						
location	03-Mar	04-Mar	08-Mar	09-Mar	10-Mar	11-Mar	13-Mar
lc07	-2.64	-2.95	-3.00	-3.59	-3.43	-2.94	-2.32
Piezo 13	-2.65	-2.62	-3.09	-3.09	-3.07	-3.07	-2.19
lc06			-3.58	-3.77	-3.60	-3.16	-2.502
lc05	-1.06	-2.94					-2.014
rock o/c	-2.56	-2.68	-1.89	-3.26	-2.93	-3.07	-2.431
lc04	-3.12	-3.53	-2.83	-3.10	-3.92	-3.47	-3.27
lc03							
lc02							
lc01							
std dev	0.78	0.36	0.55	0.23	0.44	0.23	0.44

Table 4.3 Weatherley, Hillslope 1, δO^{18} isotope data 3-13 March 2010.

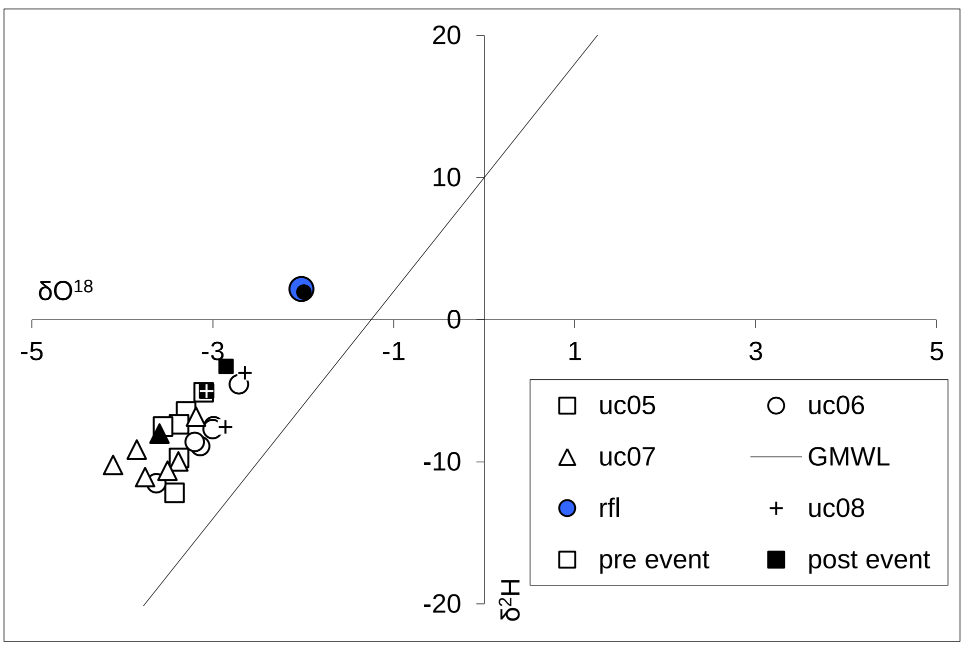


Figure 4.10 Weatherley, Hillslope 1, March 2010 δO^{18} and δ^2H isotopes.

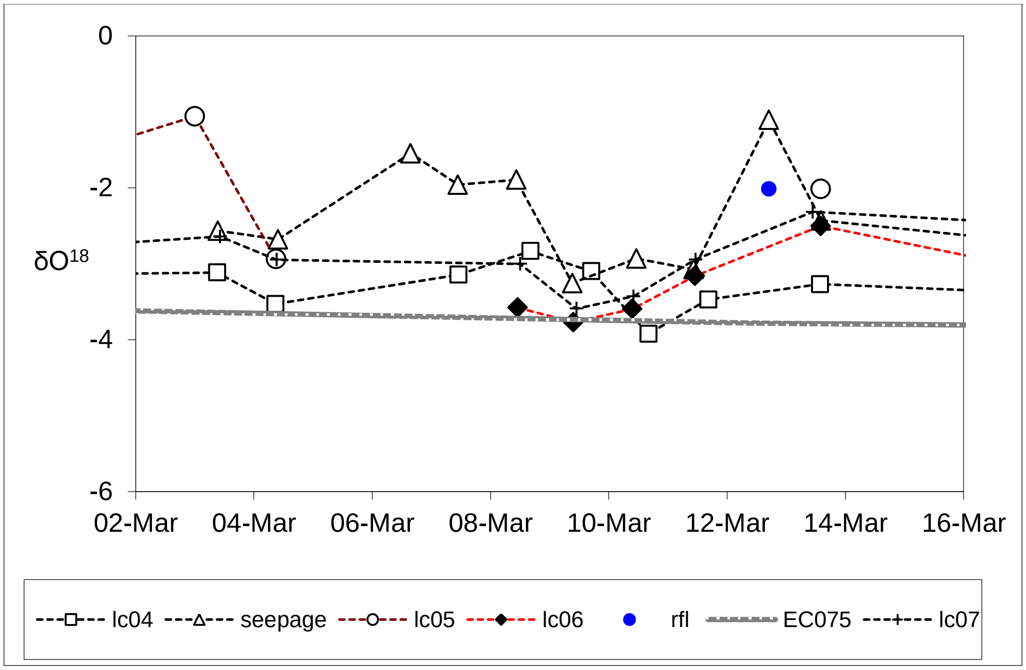


Figure 4.11 Weatherley, Hillslope 1, March 2010 δO^{18} isotopes.

Pre-event processes along the Hillslope 1 transect appear to be dominated by deep interflow occurring on the soil bedrock interface, Figure 4.9. The relative impermeability of the underlying geology allows for the development of saturated soil water, which drains slowly downslope through a combination of vertical and horizontal vectors.

Unfortunately, there are no other comprehensive piezometer and isotope observations for well-defined pre-event periods. However, an analysis of the long-term depth of the perched water tables at sites LC 06 and LC 07 indicates that LC 07 is able to drain more freely than LC 06. The stable level of the water table at LC 06 shows the presence of upslope contributions sustaining the levels of saturated soil water at LC 06, as shown in Figure 4.12, indicating that these two areas are hydrologically connected.

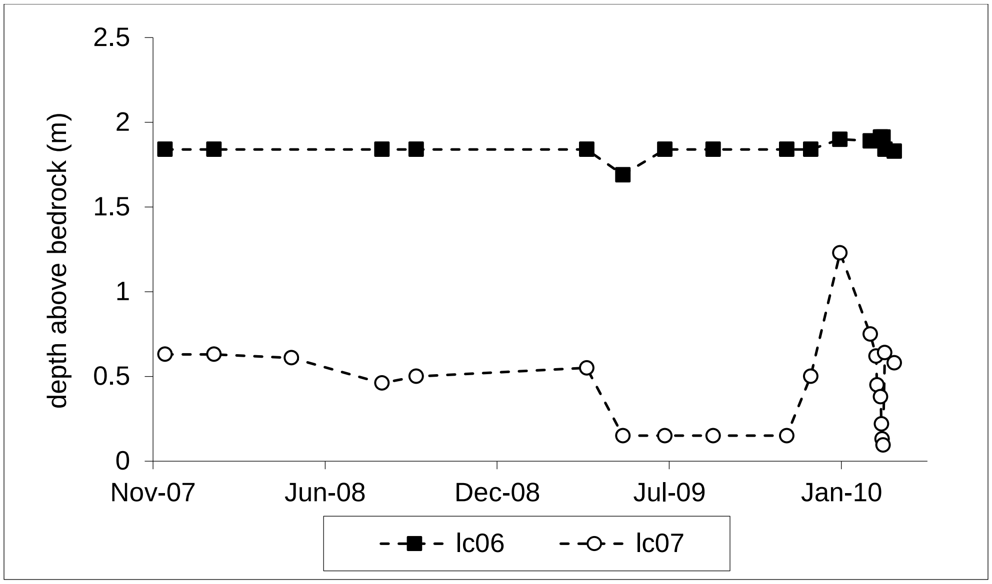


Figure 4.12 Weatherley, Hillslope 1, LC 06 and LC 07 long term piezometer depth observations

4.4.3 Post-event

Post event water table responses indicate the rapid recharge of the riparian Responsive soils adjacent to the stream, piezometers LC 07 and 13 in Figure 4.13. The δO^{18} isotope values in piezometers LC 07 and 13, rise from -2.94 and -3.07 to -2.32 and -2.19 respectively, immediately after an event with an average δO^{18} value of -2.02. Time series δO^{18} values indicate that the recharge of the Responsive soils is event based. This is evident in the manner in which all δO^{18} values increase to match the average δO^{18} value of the 12/03/2010 rainfall event (-2.02), with the exception of nest LC04, shown in Figure 4.11 and Figure 4.13. The highly stable or attenuated δO^{18} time series values observed at nest LC04 indicates that recharge of the water table in the soils, immediately upslope of the rock out crop is as a result of soil/bedrock interflow. This is because, firstly, the post event δO^{18} isotope value does not show the influences of the rainfall δO^{18} isotope signature, and secondly, the δO^{18} value continues to show a depleted value, indicating mixing with older hillslope water.

Pre and post event analysis of hillslope 1 indicates two distinct zones of hydrological processes. Upslope responses appear to be dominated by slower vertical infiltration followed by lateral drainage on either bedrock or a zone of reduced permeability. Downslope or riparian responses indicate the presence of older hillslope water at piezometer LC 06, but are dominated by more rapid (compared to upslope) vertical recharge of the soil profile. LC 06 post event δO^{18} isotope value of -2.50 sits in between those of LC 04 post event (-3.27) and the rainfall average (-2.02). This means that the post event soil water at piezometer LC 06 is made up of a combination of event and pre event water.

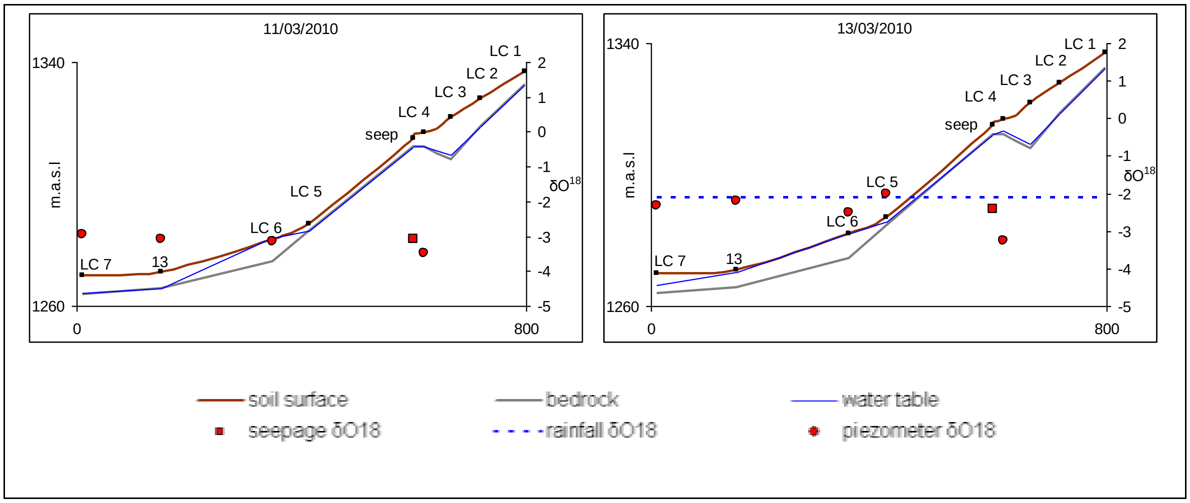


Figure 4.13 Weatherley, Hillslope 1, pre event (left) and post event (right) water table drainage and δO^{18} isotopes.

4.5 Hillslope 2 (LC 08 - LC10)

Hillslope 2 is situated on the slope directly opposite Hillslope 1. Extending from observation nests LC 08 through LC 10 (Figure 4.14). Hillslope 2 is formed on a Molteno flatbed sedimentary formation that is expected to facilitate the development of perched soil water due to the low permeability of the mudstone. The Molteno sediment is interrupted by an intrusive dolerite dyke intersecting the hillslope transect in a North/South orientation, affecting the midslope drainage patterns by creating a large midslope recharge zone in the vicinity of LC 10, as shown in Figure 4.14. Even though the dyke itself is impermeable, the presence of the dyke effects the morphology of the surrounding sedimentary soils, facilitating the development of deep, oxidised recharge soils in the upslope region due west of LC 10.

4.5.1 Hydropedology and hydrometery

The increased drainage, as a result of the dyke, is observed in the lack of perched water in three piezometers located in the midslope Recharge soils in between LC 09 and LC 10. Downslope of the dyke perched water tables are commonly observed for the duration of the wet season, indicating the tendency for the development of perched water tables on the Molteno sedimentary formation.

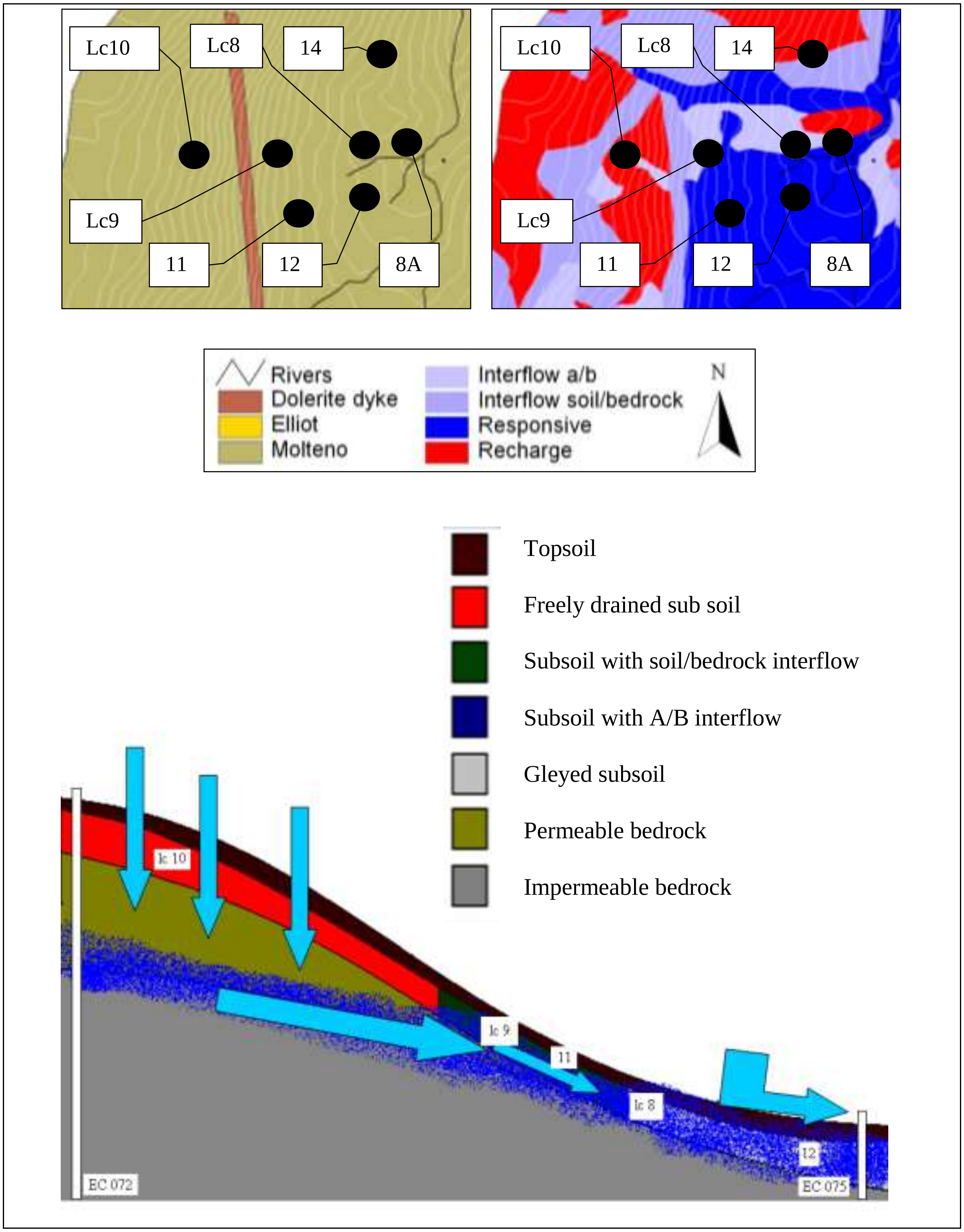


Figure 4.14 Weatherley, Hillslope 2, Illustrative description and conceptual flow paths

4.5.2 Pre-event

The presence of the Dolerite dyke is expected to dominate the hydrological response of Hillslope 2. Pre event water table observations indicate the most substantial drainage from the hillslope soil profile occurs from nest LC 09 toward the stream (Figure 4.17). The shallower gradient of the soil surface and the bedrock allows for an accumulation of soil water in the Responsive soil zone (LC 08 – 8A) (Figure 4.17). The stability of the isotope values across the hillslope transect, as well as over time, indicates vertical infiltration is dominant during pre-event periods through the attenuation/soil depth relationship detailed in Section 2.7.3. This is evident in the tight grouping of the δO^{18} and $\delta^2 H$ isotope values in Figure 4.15, and the uniform drop in δO^{18} isotope values in piezometers LC 08, LC 09, 8A and 12 during the drainage period (Figure 4.16). The increased depletion of the deep ground water isotopes (represented by borehole EC 072, Figure 3.1) in comparison to those of the piezometers indicates very long vertical travel times. This allows for greater levels of mixing with old hillslope water, resulting in the depleted values in relation to those closer to the surface.

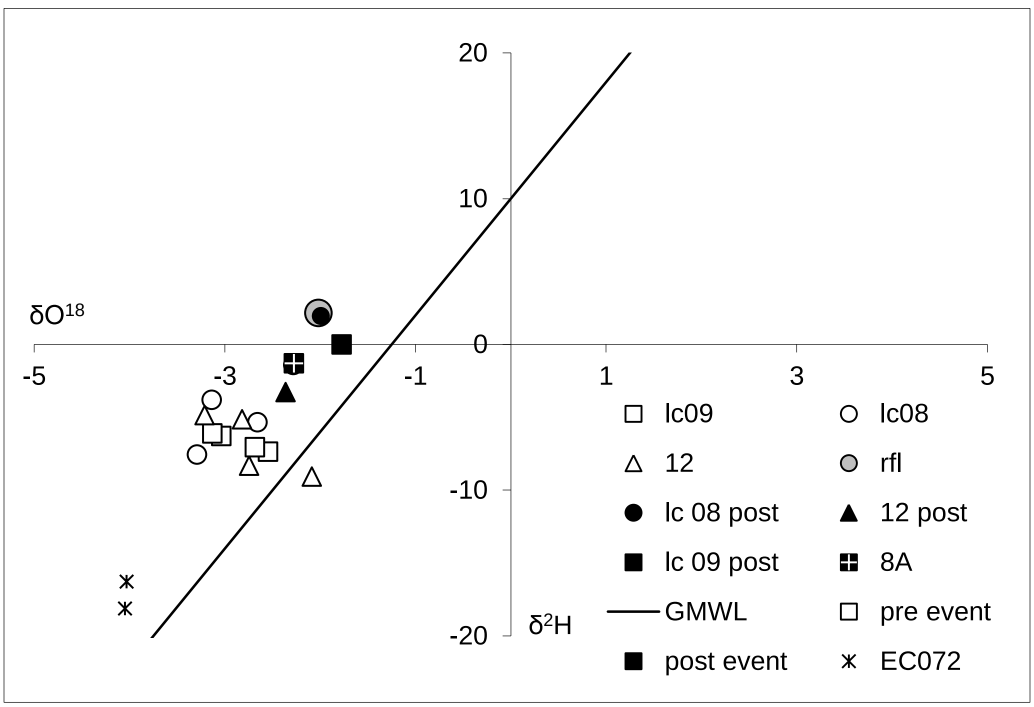


Figure 4.15 Weatherley, Hillslope 2, March 2010 δO^{18} and $\delta^2 H$ isotopes.

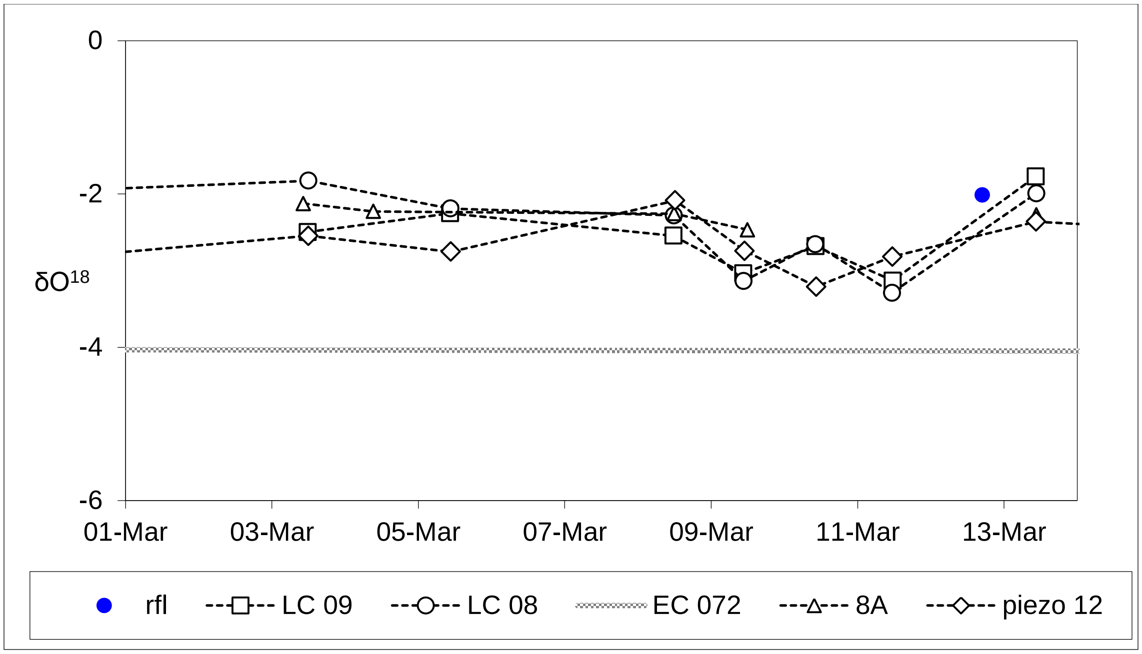
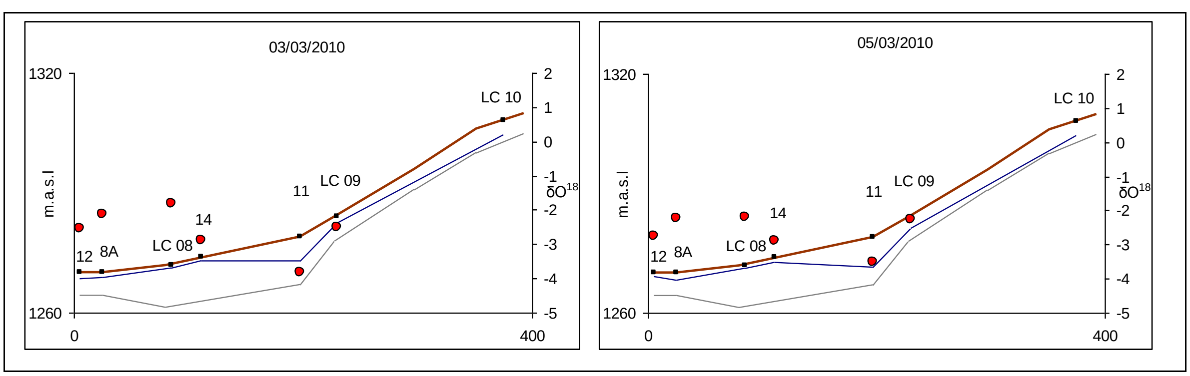


Figure 4.16 Weatherley, Hillslope 2, March 2010 δO^{18} piezometer isotope values.

The attenuated isotope time series data (Figure 4.16) indicates the dominance of vertical infiltration along the hillslope transect as all piezometer δO^{18} isotope values follow the same trend, becoming slightly enriched into the drainage period. Furthermore, the uniform drop in δO^{18} isotope values at all piezometers across the hillslope transect shows that a uniform body of soil water extends from piezometer LC 08 through piezometer data (Figure 4.16) Thus, the hillslope and riparian soils are shown to be hydrologically connected by interflow above a layer of reduced permeability or the soil bedrock interface.



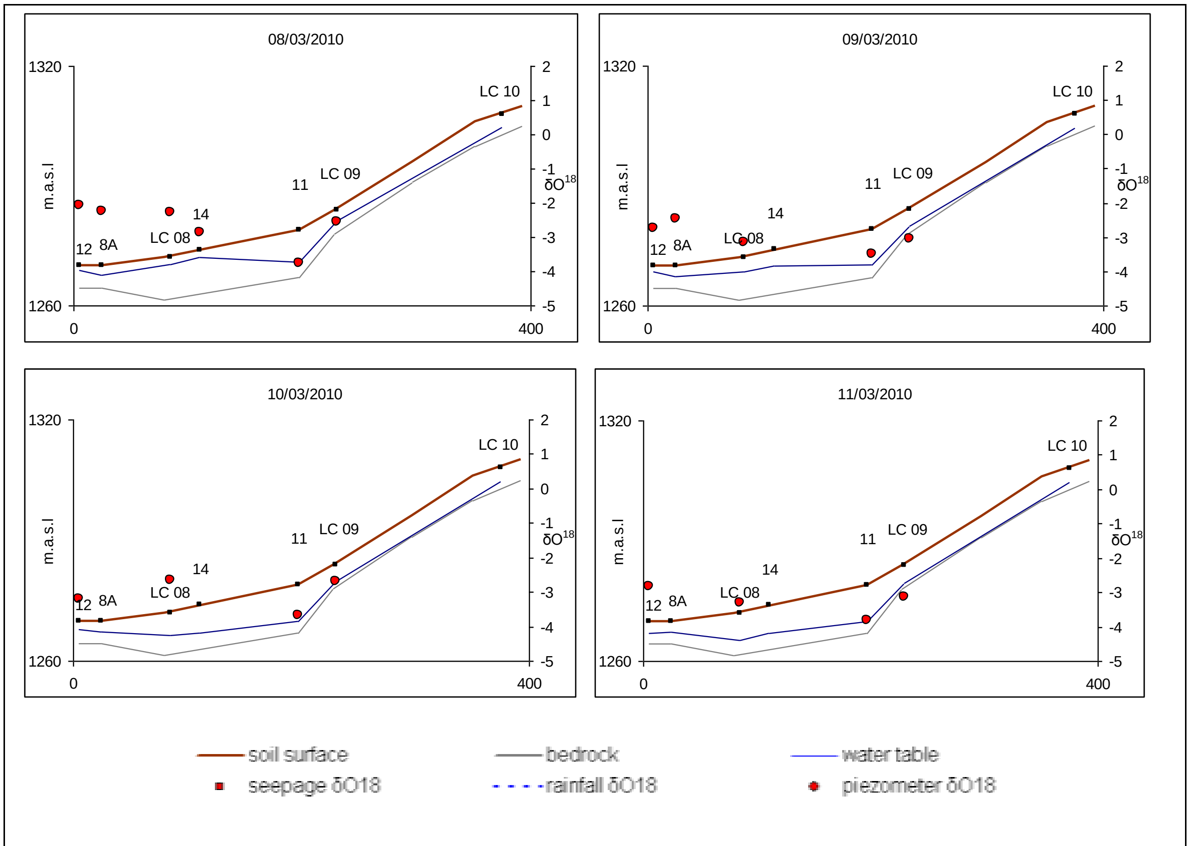


Figure 4.17 Weatherley, Hillslope 2, pre-event water table drainage and δO^{18}

	Hillslope 2 (LC 11 - Piezometer 8A)						
location	03-Mar	05-Mar	08-Mar	09-Mar	10-Mar	11-Mar	13-Mar
Piezo 12	-2.546	-2.754	-2.085	-2.743	-3.21	-2.818	-2.361
Piezo 8A	-2.126	-2.229	-2.256	-2.469			-2.274
lc08	-1.828	-2.191	-2.281	-3.135	-2.656	-3.29	-1.992
Piezo 14	-2.895	-2.874	-2.853				-3.086
Piezo 11	-3.807	-3.509	-3.748	-3.489	-3.672	-3.797	-1.992
lc09	-2.497	-2.254	-2.544	-3.035	-2.683	-3.131	-1.773
lc10							
std dev	0.69	0.52	0.61	0.39	0.48	0.41	0.46

Table 4.4 Weatherley, Hillslope 2, δO^{18} isotope data 3-13 March 2010.

4.5.3 Post-event

Post event responses indicate a significant event derived soil water recharge. Figure 4.15 and Figure 4.16 both show that post event δO^{18} isotope values for piezometers 12, 8A, LC 08 and LC 09 along Hillslope transect 2 show high levels of correlation (R^2 = 0.993) with the average rainfall δO^{18} value of -2.02. Piezometers LC 09, LC 08 and 8A all show high event water correlations the day after the 12/03/2010 event with δO^{18} values of -1.77, -1.99 and -2.27 respectively. The rise in post event δO^{18} values along the transect is illustrated in Figure 4.18. The fact that no significant perched water was observed at LC 10 post event further highlights the increased hydraulic conductivity of soil in the upslope area. However, the rapid manner in which the water table rises from piezometers LC 09 through 12, less than 12 hours after the event, indicates that the upper layers of the soil profile are highly permeable. The rapid infiltration allows for the development of a perched water table in the soil profile, which drains with both vertical and horizontal vectors accumulating on the soil bedrock interface, feeding the riparian soils through deep interflow.

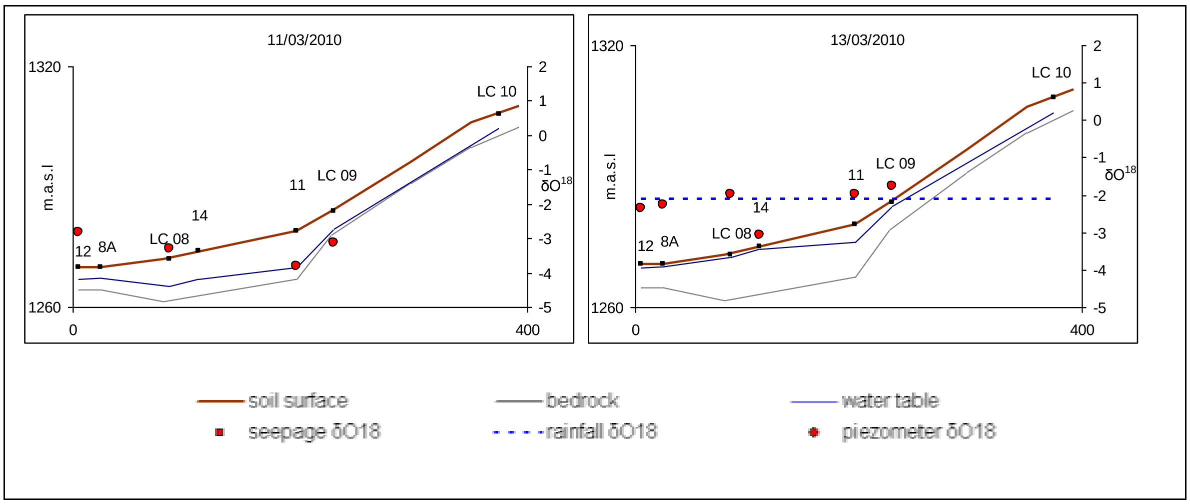


Figure 4.18 Weatherley, Hillslope 2, post-event (left) and post event (right) water table drainage and δO^{18}

4.6 Hillslope 3 (UC 01 – UC 03)

Hillslope 3 is situated in the north-eastern corner of the Weatherley catchment. The monitored transect extends from site UC 01, near the slope crest, through site 2A, adjacent to the stream, Figure 4.20. The hillslope is underlain exclusively by Molteno flatbed sediments, which have been shown to have decreased permeability compared to the overlying soil profile, allowing for the possible development of sustained water tables on the soil/bedrock interface. A dolerite dyke at the toe, on which the upper catchment weir is situated, interrupts the bedrock, is expected to influence the drainage characteristics of the lower parts of the hillslope transect.

4.6.1 Hydropedology and hydrometery

Hillslope 3 has a similar hydropedological soil sequence to that of Hillslope 2. The Recharge soils located in the mid slope region near UC 01 (Figure 4.20) are found in a similar slope position to those on Hillslope 2 near UC 10. The dolerite dyke found on Hillslope 2 intersects Hillslope 3 at the stream and is expected to dominate the hydrology of the two upper catchment Hillslopes, 3 and 4. Hillslope 3 allowed the unique opportunity to observe hydrological responses of a genuine recharge soil situated at an upslope position near the crest at piezometer UC 01 (Figure 4.20). Piezometer UC 01 is the only genuine recharge site with a sustained water table on the soil/bedrock interface, which allowed for detained hydrometric observations of old hillslope water.

The delayed response of the water table at piezometer UC 01 to rainfall is shown in Figure 4.19 by the consecutive peaks in soil water levels during January 2009 and 2010. This indicates seasonal scale recharge of the hillslope soil water, and therefore the presence of large-scale vertical infiltration. The soil depth at UC 01 is almost three meters deep, facilitating large potential water storage in the soil. Furthermore, isotope values from piezometer UC 01 showed high levels of attenuation in relation to other piezometers along the hillslope 3 transect, further indicating the presence of vertical infiltration. Hillslope and vertically infiltrating event water mix through advection, thereby dampening characteristic signals of the two sources. The water stored in the upslope soil profiles is expected to respond to the Responsive, riparian zone via deep level soil/bedrock interflow.

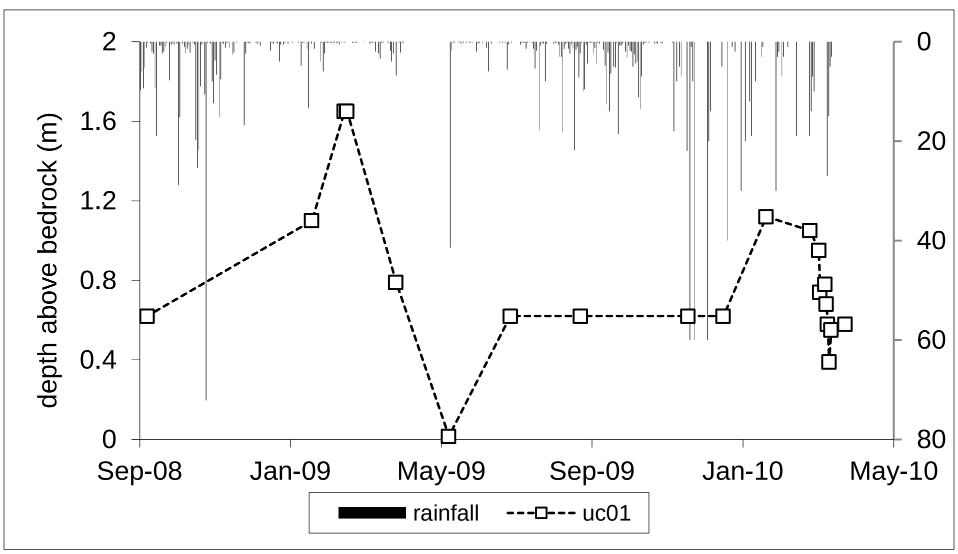


Figure 4.19 Weatherley, Hillslope 3, Piezometer UC 01 depth of soil water above the bedrock.

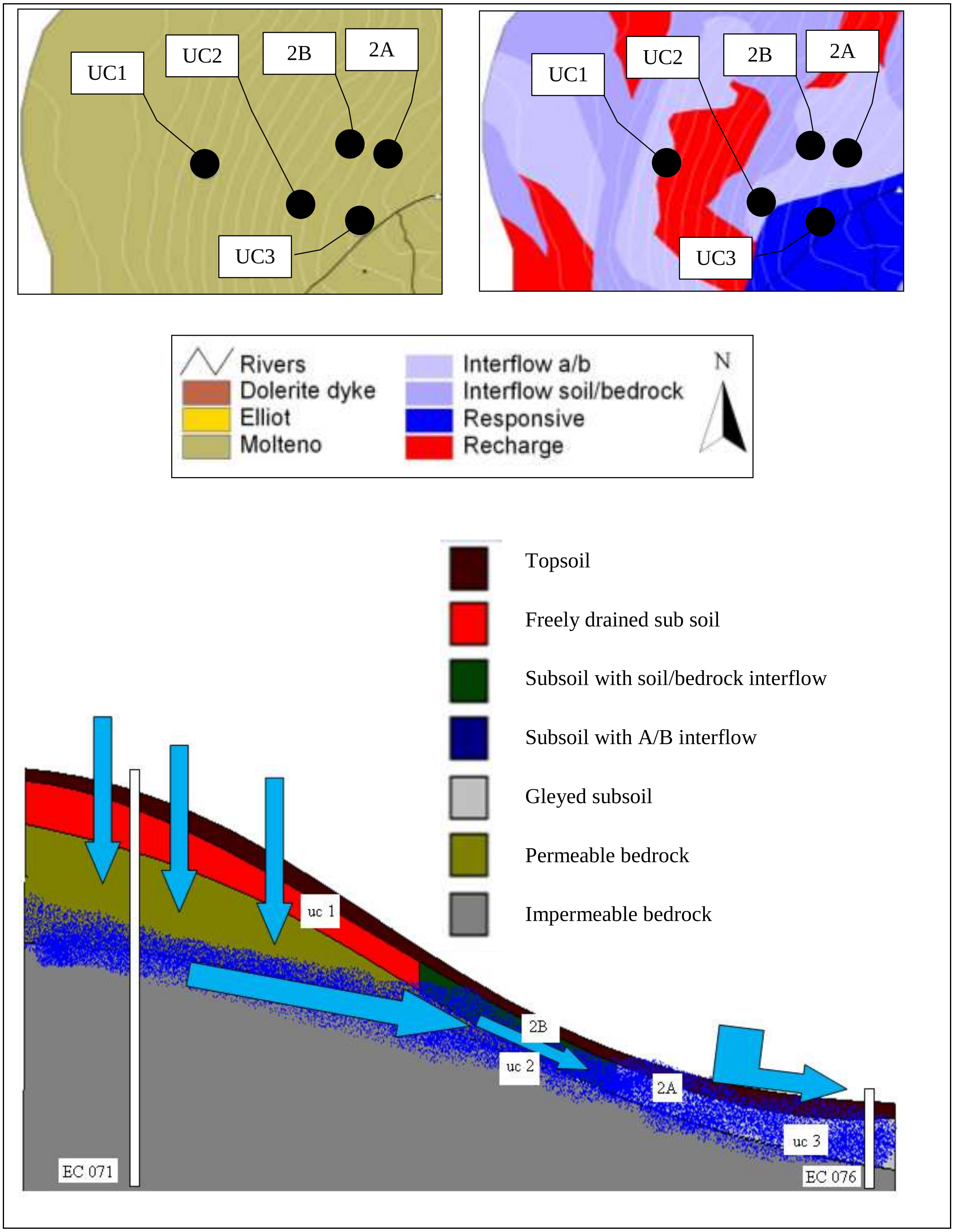


Figure 4.20 Weatherley, Hillslope 3, Illustrative description and conceptual flow paths

4.6.2 Pre event

Pre event water table and isotope values are stable over the entire pre event period (Figure 4.21). The stable isotope signature indicates the vertically infiltrated water upslope is responding to the riparian Responsive soils, maintaining the stable isotope signature in the absence of event water. The fact that piezometer 2B shows no observable perched water from the 08/03/2010 to 13/03/2010, Figure 4.21, indicates that a lateral response occurs within or below the bedrock. The sustained level of saturated water in Responsive soils (UC ¾), during the pre-event period is evidence for this.

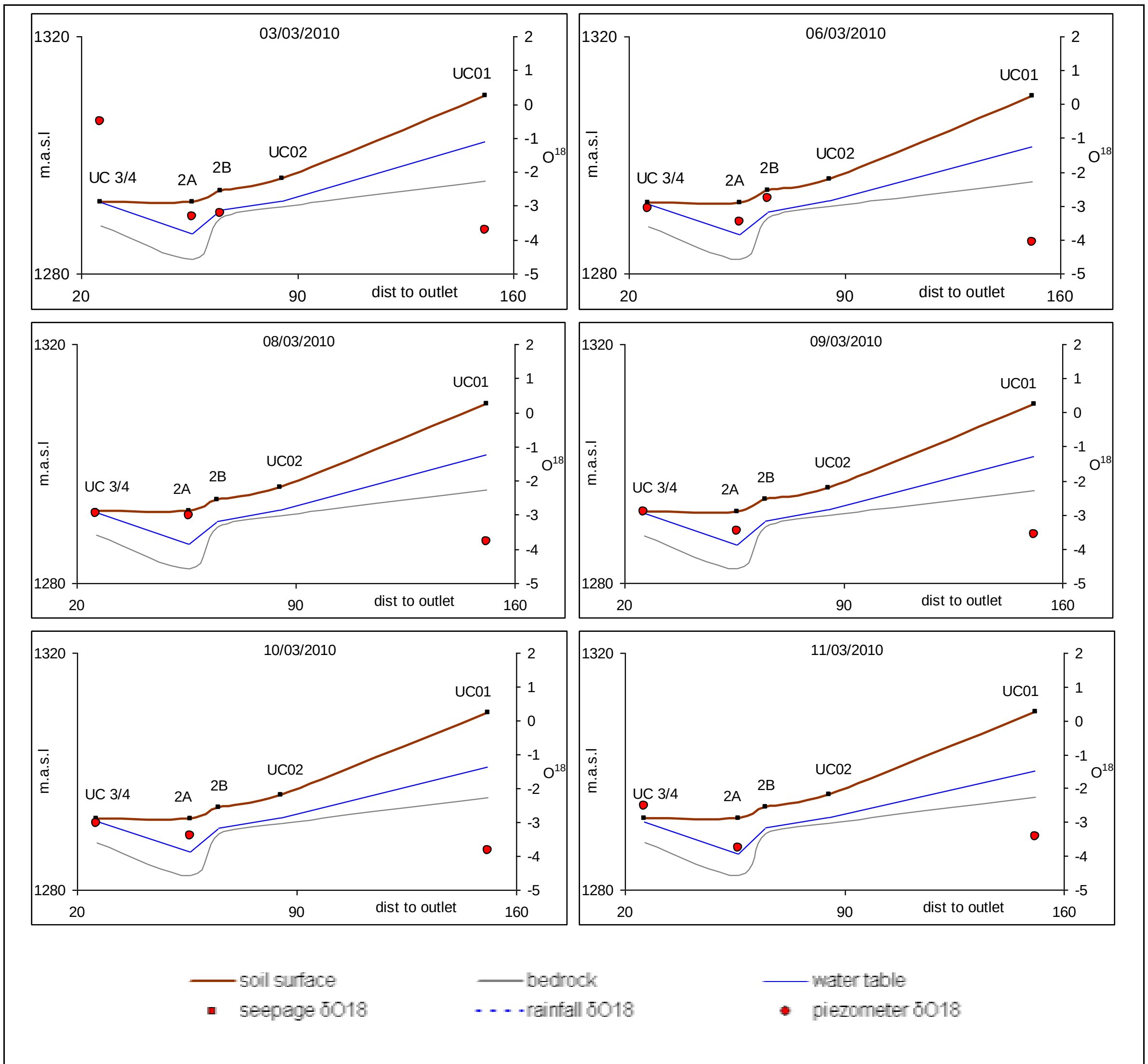


Figure 4.21 Weatherley, Hillslope 3, pre-event water table drainage and δO^{18}.

	Hillslope 3 (UC 01 - Zero tension lysimeter UC 3/4)						
location	03-Mar	06-Mar	08-Mar	09-Mar	10-Mar	11-Mar	13-Mar
uc3/4	-0.50	-3.09	-2.97	-2.90	-3.04	-2.52	-2.72
Piezo 2A	-3.31	-3.48	-3.03	-3.48	-3.40	-3.78	-3.51
Piezo 2B	-3.21	-2.79					-3.20
uc02							
uc01	-3.70	-4.06	-3.78	-3.56	-3.84	-3.42	-3.43
std dev	1.47	0.55	0.45	0.36	0.40	0.65	0.36

Table 4.5 Weatherley, Hillslope 3, δO^{18} isotope data 3-13 March 2010.

Further evidence of the dominance of vertical infiltration on this hillslope is the manner in which the δO^{18} values of piezometers 2A and UC 01 consistently intercept the δO^{18} values of the deep ground water sampled from borehole EC 076 (Figure 4.22). Long-term averages for piezometer UC 01 and borehole EC 076 are -3.52 and -3.77 respectively, suggesting that the hillslope soil water feeds deeper regional scale ground water similar to those observed in borehole EC 076.

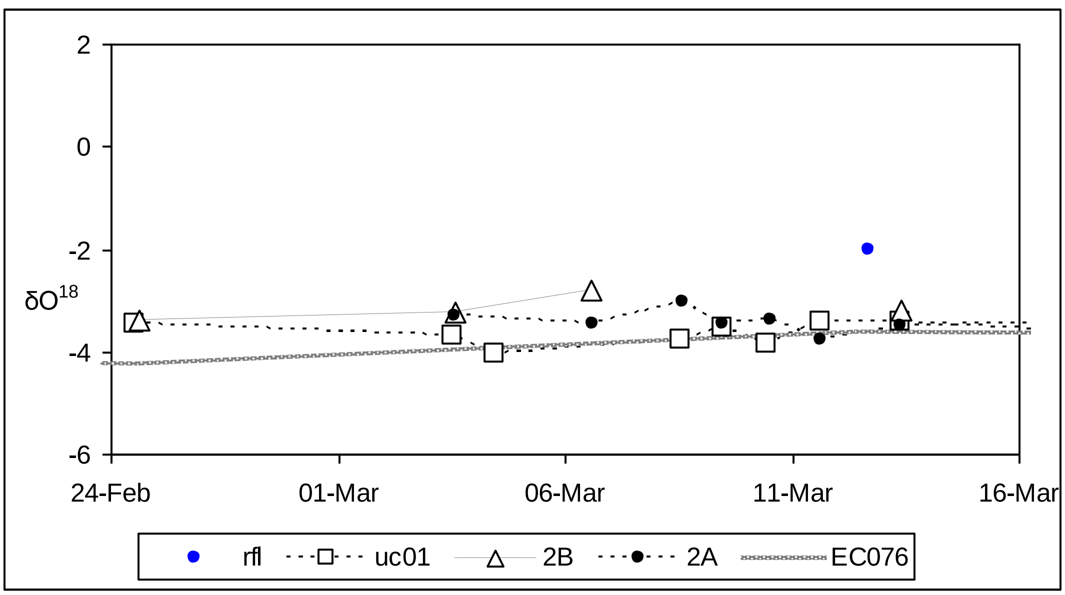


Figure 4.22 Weatherley, Hillslope 3, March 2010 δO^{18} piezometer values

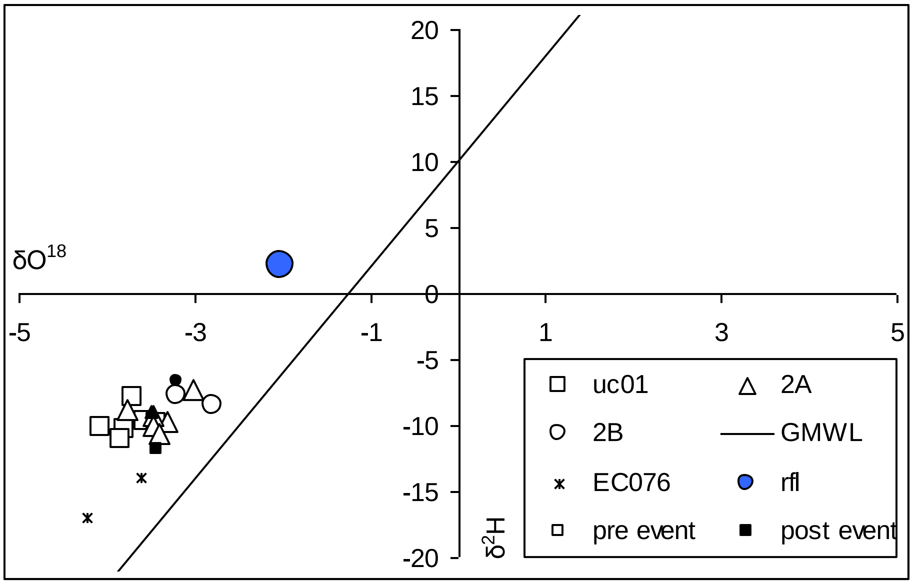


Figure 4.23 Weatherley, Hillslope 3, March 2010 δO^{18} and δ^2H isotope values.

4.6.3 Post event

Unlike Hillslope 1 and 2, post event observations show almost no change from pre event, with the exception of the observation of perched soil water in piezometer 2B. Post event δO^{18} values at all three piezometers (2A=-3.51, 2B=-3.20, UC01=-3.43) remain well below the volume weighted average of the 12/03/2010 rainfall event of -2.02 (Figure 4.24, Table 4.5). Therefore, the event-derived water has a negligible impact on the hillslope response. The possibility of overland flow generation due to infiltration excess can be discounted through a lack of observed surface runoff in the hillslope USLE runoff plots across the Weatherley catchment (Figure 4.1). Therefore, the effective rainfall reaching the soil is stored in the surface soil horizons, slowly permeating to deeper soil horizons and eventually accumulating on the soil/bedrock interface forming the perched soil water found at UC 01.

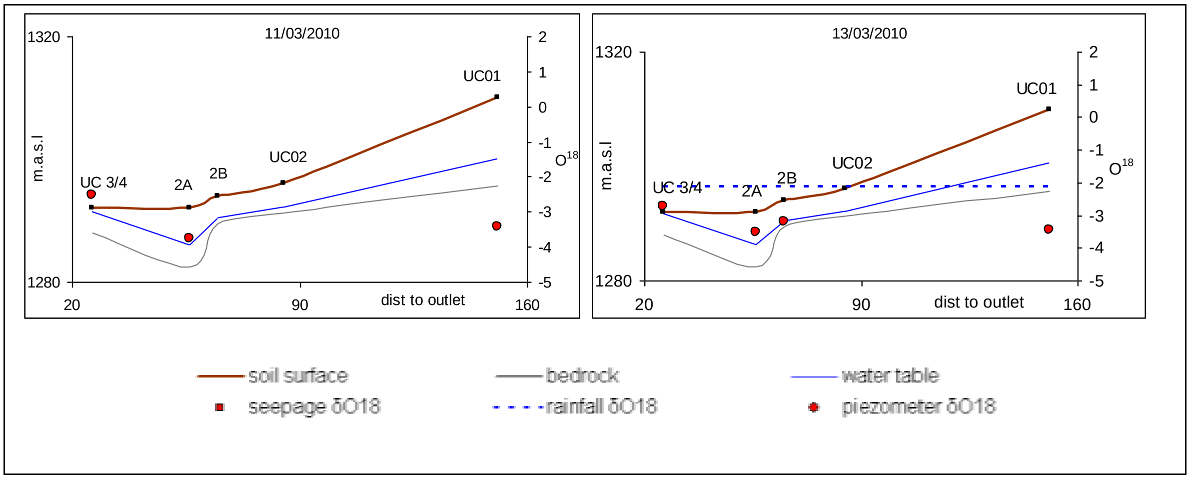


Figure 4.24 Weatherley, Hillslope 3, pre event (left) and post event (right) water table drainage and. δO^{18} values.

Hillslope 3 appears to have a considerably lower event derived contribution compared to Hillslope 2, during and shortly after rainfall. The magnitude of the deep interflow response from hillslope to wetland is sufficient to dampen the contribution of the 12/03/2010 event to the wetland, but not necessarily to the stream. Hillslopes 2 and 3 share similar conceptual sub surface descriptions in terms of hydropedological soil type distribution, Figure 4.14 and Figure 4.20. Vertical infiltration is evident in both the soil characterization and the isotope data.

Hillslope 2 riparian Responsive piezometers show a high event based δO^{18} values, while Hillslope 3 transect δO^{18} isotope values remain stable at values identical to those of the deep borehole, EC 076. These differences can be seen by comparing Figure 4.16 and Figure 4.22.

4.7 Hillslope 4 (UC3/4 – UC 08)

Hillslope 4 lies in the southern extremities of the Weatherley upper catchment area, extending from nest UC ¾ in the riparian Responsive soils, to UC 08 on the up slope Recharge soil areas, (Figure 4.25). Hillslope 4 is situated on a similar sequence of Elliot (upslope) and Molteno (downslope) sedimentary formations as Hillslope 1. Both Hillslopes 1 and 4 are conceptually described in the same way, depicted in Figure 4.25 and Figure 4.7. The major difference between Hillslope 1 and 4 is the permeability of the up slope Elliot terrace.

4.7.1 Hydropedology and hydrometery

The absence of a perched water table for much of the study period at site UC 08 indicates that the bedrock is more permeable here than at a similar slope position on Hillslope 1 (LC 04). Perched water tables are only observed in piezometer UC 08 during and shortly after rainfall, indicating rapid drainage from the Recharge soils. The absence of observable surface seepage at the Elliot/Molteno interface indicates that there is little or no change in the hydraulic conductivity at the soil/bedrock interface at upslope positions (UC 08) of hillslope 4.

In further contrast to Hillslope 1, Hillslope 4 has deep mid slope soils (piezometer UC 07, Figure 4.26) which allows for greater soil water storage. The effect of the depth of the soil is dominant enough for the hillslope section at piezometer UC 07, with a slope of 20%, to be classified as a recharge soil. The presence of this hillslope water is expected to cause a depletion in the isotope values along the transect, which is evident in both pre and post event isotope values observed in all the hillslope transect piezometers (Figure 4.26, Figure 4.27).

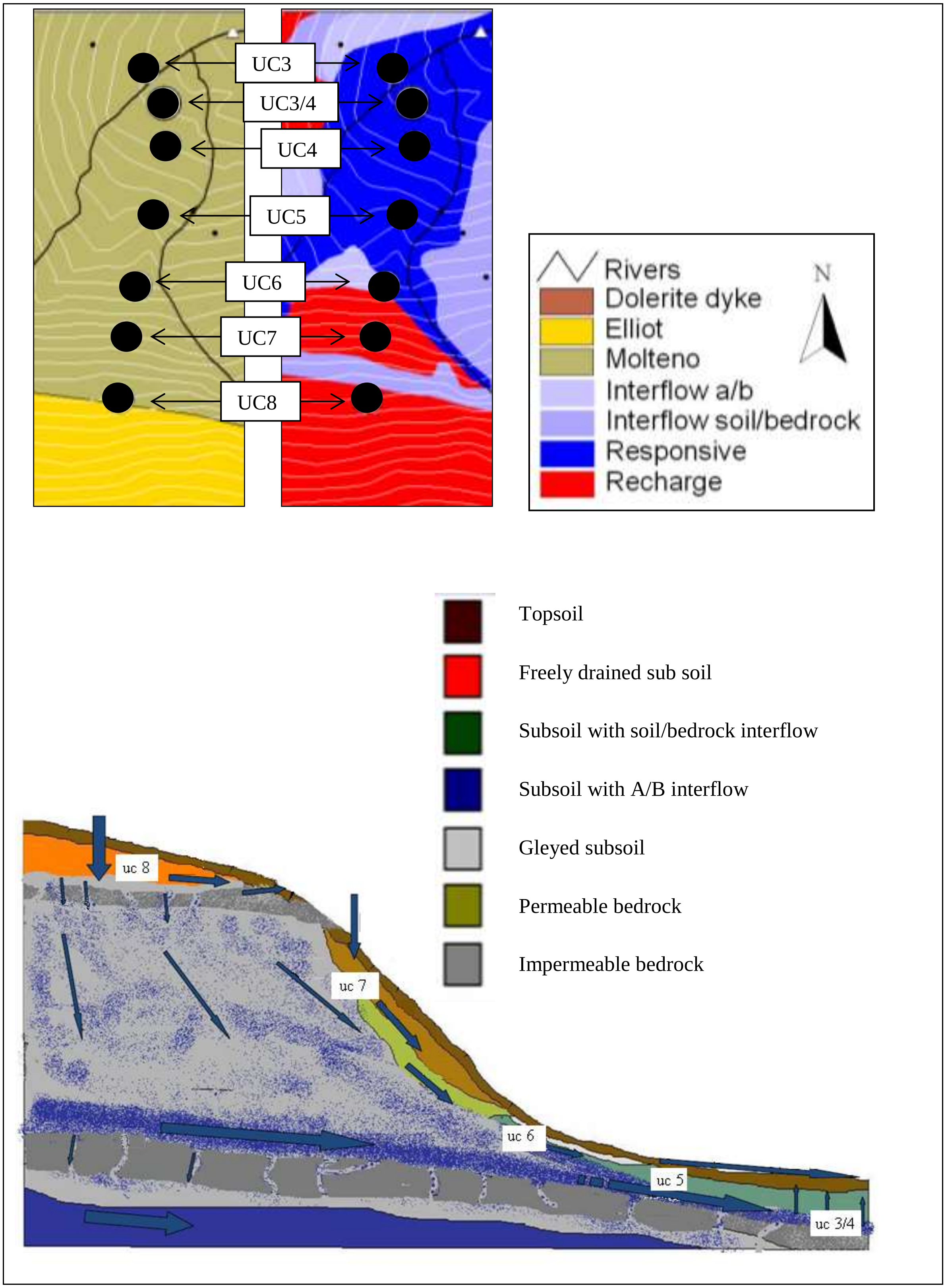
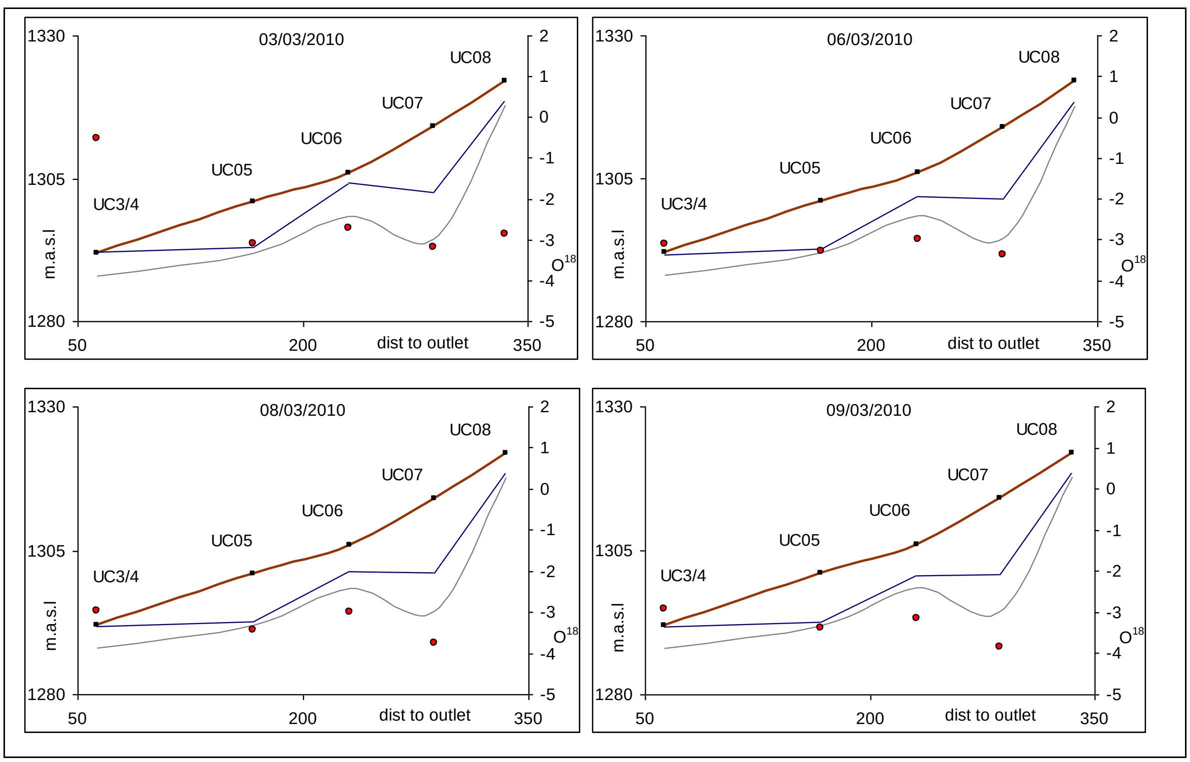


Figure 4.25 Weatherley, Hillslope 4, Illustrative description and conceptual flow paths

4.7.2 Pre event

Pre event water table responses remain constant throughout the pre event period, with only piezometer UC 06 showing marked drainage from the 2010/03/03 to 2010/03/06 (Figure 4.26). The fact that soil water levels in piezometer UC ¾ remain relatively constant during the drainage period while that of UC 06 shows a steady decline (Figure 4.26) implies the recharge of the riparian soils near UC ¾ by the hillslope (recharge) soils near UC 06.

δO^{18} isotope values are depleted across the hillslope transect with pre event δO^{18} isotope values similar to those found throughout the catchment (Figure 4.26 and Table 4.6). These show depletion of δO^{18} isotope values at individual piezometer sites over time and across the hillslope transect on individual days. This is illustrated in the stable daily values in the hillslope piezometers (UC 06, and UC 07) in Figure 4.26. This indicates that mixing of event water with older hillslope water as well as the subterranean hydrological continuity of the hillslope soil water from UC 07 through UC 3/4.



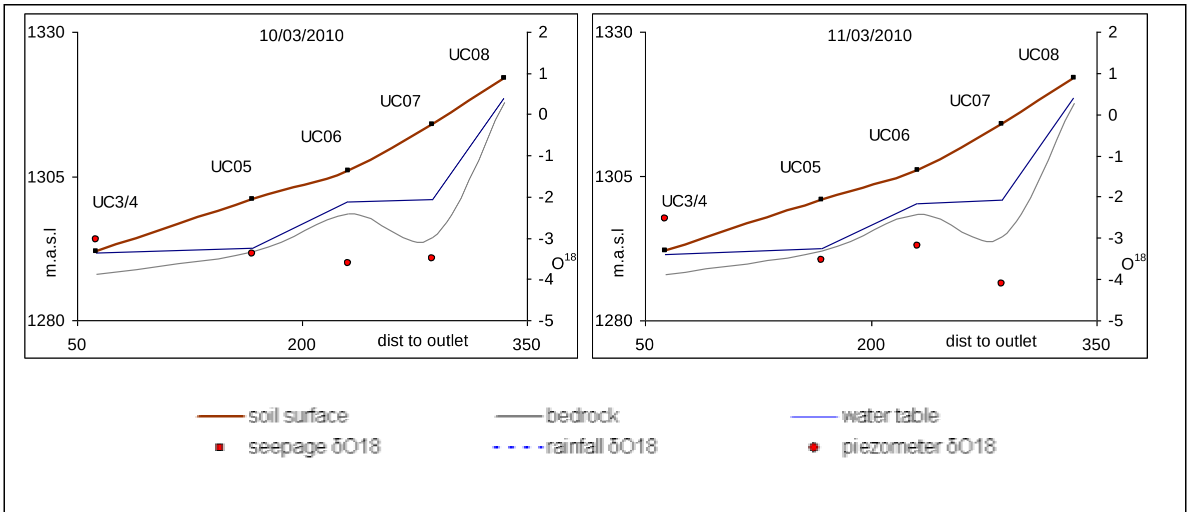


Figure 4.26 Weatherley, Hillslope 4, pre-event water table drainage and δO^{18} isotope values

	Hillslope 4 (UC 08 - Piezometer UC 3/4)						
location	03-Mar	06-Mar	08-Mar	09-Mar	10-Mar	11-Mar	13-Mar
uc3/4	-0.50	-3.09	-2.97	-2.90	-3.04	-2.52	-2.72
uc05	-3.10	-3.29	-3.42	-3.37	-3.37	-3.55	-2.85
uc06	-2.71	-2.99	-3.00	-3.14	-3.62	-3.20	-1.81
uc07	-3.18	-3.38	-3.75	-3.84	-3.50	-4.10	-3.59
uc08	-2.86						-3.07
std dev	1.12	0.18	0.37	0.40	0.25	0.66	0.65

Table 4.6 Weatherley, Hillslope 4, δO^{18} isotope data 3-13 March 2010.

4.7.3 Post event

Post event responses remain stable in comparison to pre event responses, with no noticeable event based isotope values observed in the piezometer samples, with the exception of UC06. At nest UC 06 a considerable rapid recharge of the perched soil water is observed within 12 hours of the 12/03/2010 event along with a shift in the δO^{18} isotope value toward that of rainfall, Figure 4.27 and Figure 4.28. This indicates an accumulation of surface and/or sub surface runoff where there is a decrease in the slope surface gradient. The soil water recharge observed in piezometer UC 06 is fed by up slope by rapid event based interflow in the upper horizons of the soil profile. Post event responses show UC 06 is recharged by waters with a similar δO^{18} isotope value to rainfall (-1.82 and -2.01 respectively), however other event δO^{18} isotope values along the hillslope transect show barely any influence of the rainfall, showing that UC 06 is not recharged by water perched on the soil/bedrock interface, but rather by event derived water. The fact that no surface runoff was observed in the USLE runoff plot adjacent to nest UC 07 (Figure 4.1), immediately upslope of UC 06 (Figure 4.25), confines the only possible source to the upper reaches of the soil profile near nest UC 07 and UC 08. This infers the existence of shallow rapid interflow as the dominant mechanism of recharge of hillslope water to the riparian soils during and shortly after an event.

The relatively small response of riparian piezometer UC 05 and UC ¾, δO^{18} isotope values in comparison to the rainfall event δO^{18} isotope value shows little or no event based recharge indicating the prevalence of hillslope water in the Hillslope 4 riparian soils. The observation of event based surface runoff between nests UC ¾ and UC 05, combined with the lack of response in the piezometers, confirms this as the dominant mechanism of downslope transport at these lower slope positions.

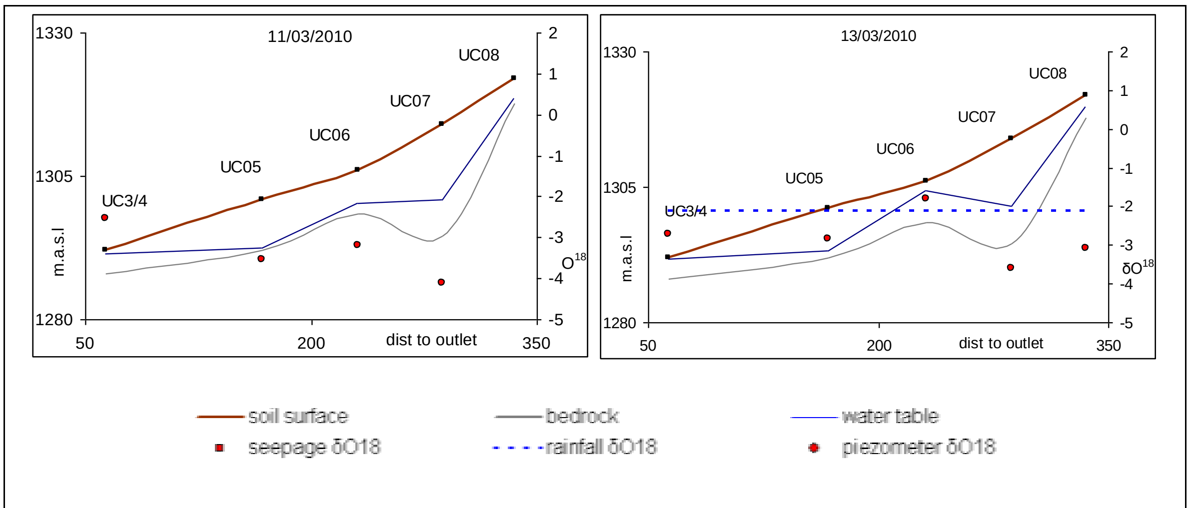


Figure 4.27 Weatherley, Hillslope 4, post-event water table drainage and δO^{18} isotope values.

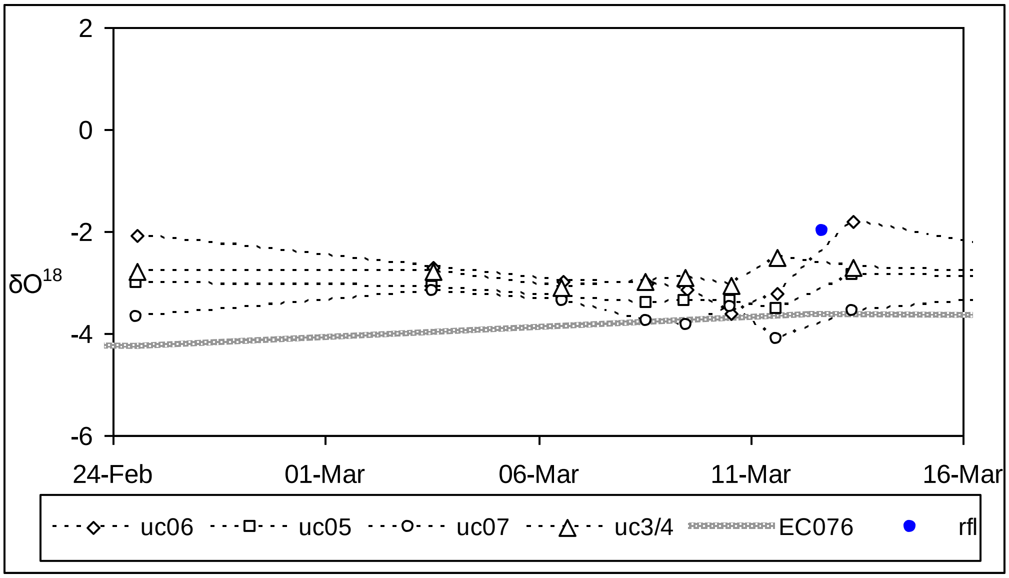


Figure 4.28 Weatherley, Hillslope 4, March 2010 δO^{18} isotope values.

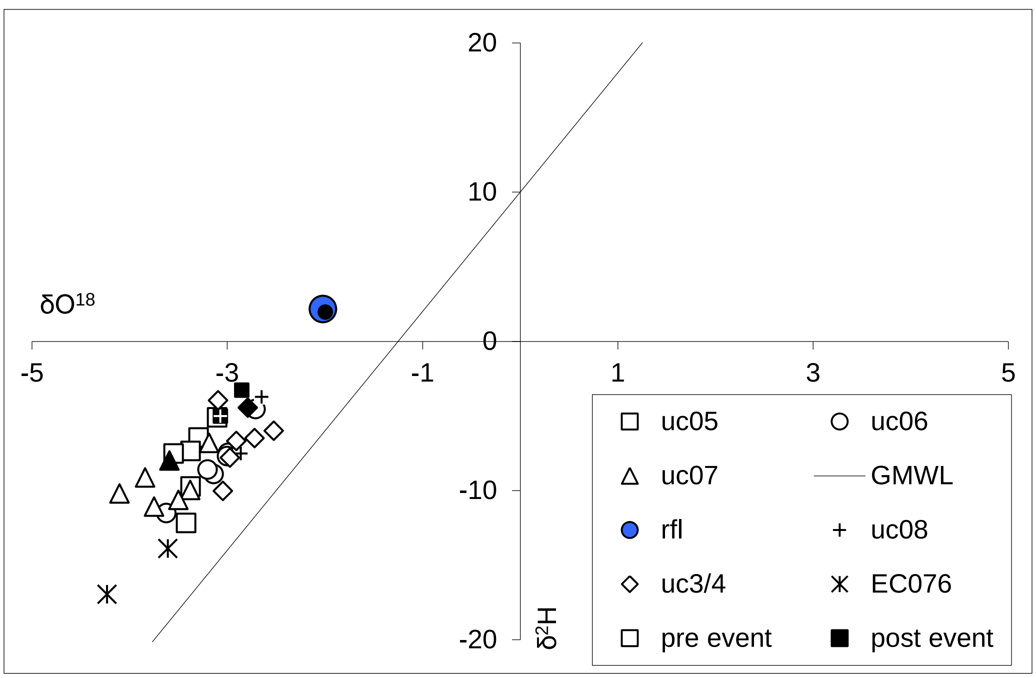


Figure 4.29 Weatherley, Hillslope 4, March 2010 δO^{18} and $\delta^2 H$ isotope values.

4.8 Conclusion

The generation of streamflow in the Weatherley catchment is the result of the combination of the range of hillslope processes identified on the different study slopes. Pre event hillslope water is identified as a dominant contributor to the perched water tables in the riparian Responsive soils adjacent to the stream.

Hillslopes 2, 3 and 4 all show the presence of a perched water table on the soil/bedrock interface. The perched water table appears to be hydrologically continuous along the reach of the hillslope and riparian soils, indicating that the hillslope soils are connected to the riparian responsive soils by soil/bedrock interflow. Hillslope 1 is different from the other hillslopes in that a defined geological break (nest LC 04) causes a decrease in vertical and horizontal movement of water facilitating the build-up of a perched water table on the upslope side of the rocky out crop, which then drains either over or under the outcrop as surface seepage or deep interflow respectively. A geological sequence similar to Hillslope 1 underlies Hillslope 4, however the permeability of the rocky outcrop on these two hillslopes sets them apart. The permeability of the rocky outcrop on Hillslope 4 has a higher permeability than that of Hillslope 1, this is deducted from the relatively short duration of perched soil/bedrock interface soil water observed in piezometer UC 08 compared to piezometer LC 04.

The majority of the riparian soils adjacent to the stream remain saturated throughout the wet season and well into the dry season in many instances. The close proximity of the piezometer δO^{18} isotope values to streamflow in comparison to rainfall indicates the significance of riparian soil water at the catchment outlet (Figure 4.30). These soils drain laterally to the stream above soil layers of decreased permeability and/or the soil/bedrock interface through transmissivity feedback. However, the slight depletion observed in piezometer δO^{18} isotope values compared to streamflow (Figure 4.30) indicates the presence of an enriched δO^{18} source such as rainfall at the catchment outlet. The rainfall that reaches the stream accumulates on the soil surface of the responsive riparian soils adjacent to the stream, creating conditions for infiltration excess overland flow, contributing directly to the stream during event periods.

The hydropedological and hydrometric descriptions of the Weatherley hillslopes allow for the development of an illustrative framework of mechanisms of hillslope water recharge, storage and drainage. This forms the first step in the modelling of these hillslopes and the eventual catchment scale simulation of Weatherley. The descriptions of the hillslopes allow for the subsurface calibration of different sources and pathways of the hillslope response to the responsive riparian soils, forming the basis of the subsurface routines in the ACRU Intermediate zone model.

The calibration of the subsurface routing of the different hillslopes describes the sources and pathways of hillslope drainage without any quantification of the specific contributions from pre event and event waters. The quantification of pre event and event contributions to flow are required to calibrate the drainage characteristics of specific hillslopes. The quantification of the different contributions serves as further evidence for many of the relationships defined in Section 4.3.

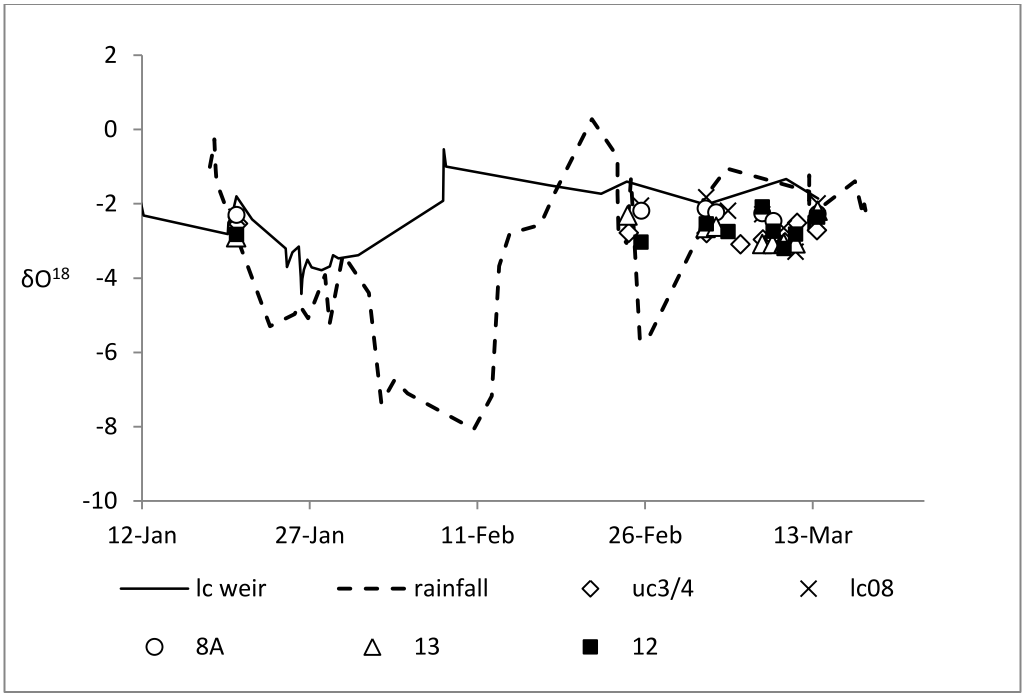


Figure 4.30 Weatherley δO^{18} isotopes of rainfall streamflow and riparian piezometers.

4.9 Hillslope and Catchment scale δO^{18} Hydrograph Separation

δO^{18} hydrograph separations were carried out at two distintly different scales. Firstly, at the hillslope scale, to assess the differences in event and pre event contributions along the individual hillslope sections. Secondly, at the catchment scale in to assess the the dominant hillslope types contributing to streamflow at the catchment outlet.

4.9.1 Hillslope scale hydrograph separations

Hillslope scale separations revealed the dominance of two distinctly different hillslope types as described in Sections 4.5 to 4.7. As these hydrograph separations are based on the same data used in the hillslope descriptions, the hydrograph separations form a numerical characterization of the descriptions given in Sections 4.5 to 4.7.

Hydrograph separations were performed at each of the piezometer sites along the different hillslope transects. The free water sampled for δO^{18} in the piezometer was considered the end member of the two component mixing analysis (C_t) discussed in Section 3.6. Sampling and therefore separation time steps were daily, with the previous days piezometer δO^{18} value used as the pre event value (C_p). Any rainfall measured was used as the input or event δO^{18} value (C_e) for Equation 3.3 and Equation 3.4.

Piezometers situated on the hillslope sections above the riparian zones show the dominance of pre event water throughout the hydrograph separation period. This included the period immediately after the rainfall event late on the 12 March 2010, shown in Figure 4.31, Figure 4.32 and Figure 4.33. Event derived contributions do not exceed 30% at any of the hillslope piezometers sites for pre and post event periods. This indicates that no rapid recharge of the soil/bedrock interface water table occurs during or immediately after the event. This along with the fact that no surface runoff is observed at the upslope positions (Figure 4.1) means that event water must infiltrate the upper layers of the soil profile above the perched water table, and either remain in longer term storage/vertical recharge or move laterally down slope.

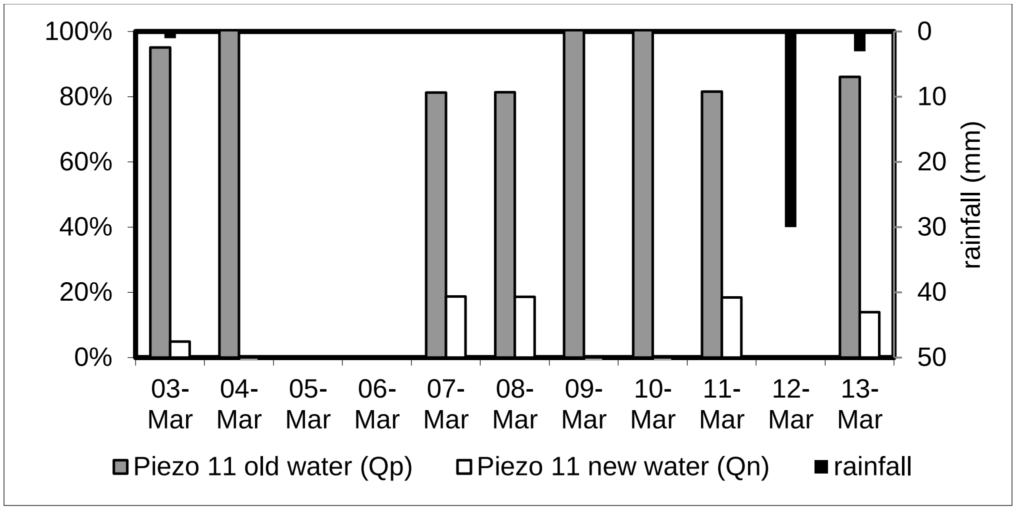


Figure 4.31 Hillslope 1, hillslope nest LC04 event and pre event contributions.

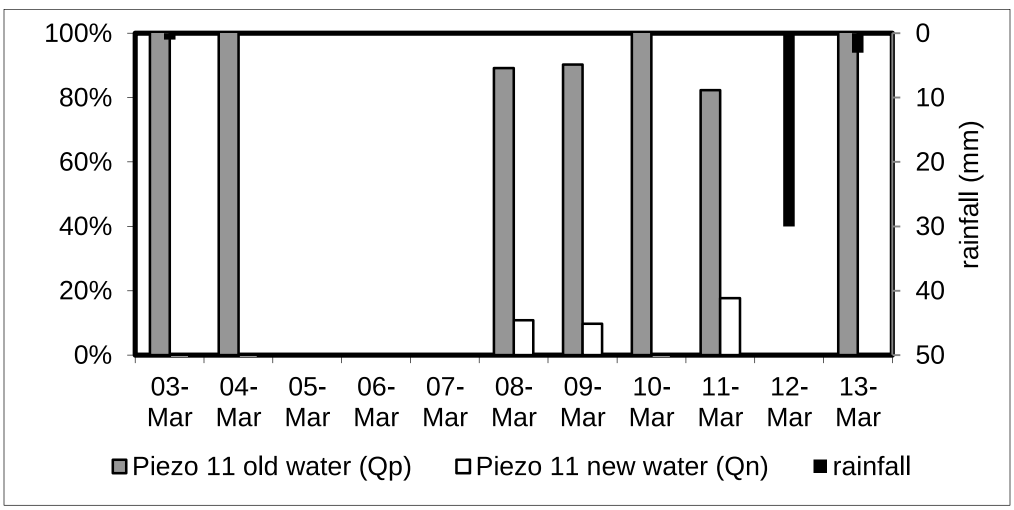


Figure 4.32 Hillslope 3, hillslope nest UC01 event and pre event contributions.

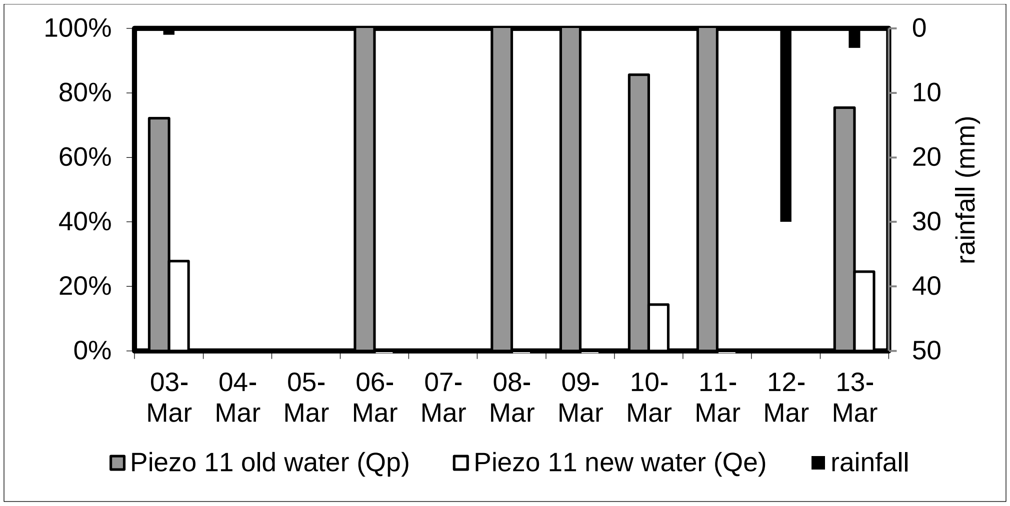


Figure 4.33 Hillslope 4, hillslope nest UC07 event and pre event contributions.

In stark contrast, the lower catchment Hillslopes 1 and 2, riparian hydrograph separations show high percentages of event-derived water (83.7% and 100 % respectively) shortly after the event on 12 March 2010 (Figure 4.34 and Figure 4.35). This implies that rapid vertical recharge of the riparian soil adjacent to the stream occurs and is the dominant source of event-based streamflow.

Riparian soils from the upper catchment Hillslopes 3 and 4 show the dominance of older hillslope water during both pre and post event periods with pre event contributions of 84.59% and 100% respectively. The lack of an event based response in the piezometers on Hillslopes 3 and 4, and the extent of the response observed in the USLE runoff plot located near UC ¾ (Figure 4.1) indicate that event waters are transported by infiltration excess overland flow from the riparian soils to the stream.

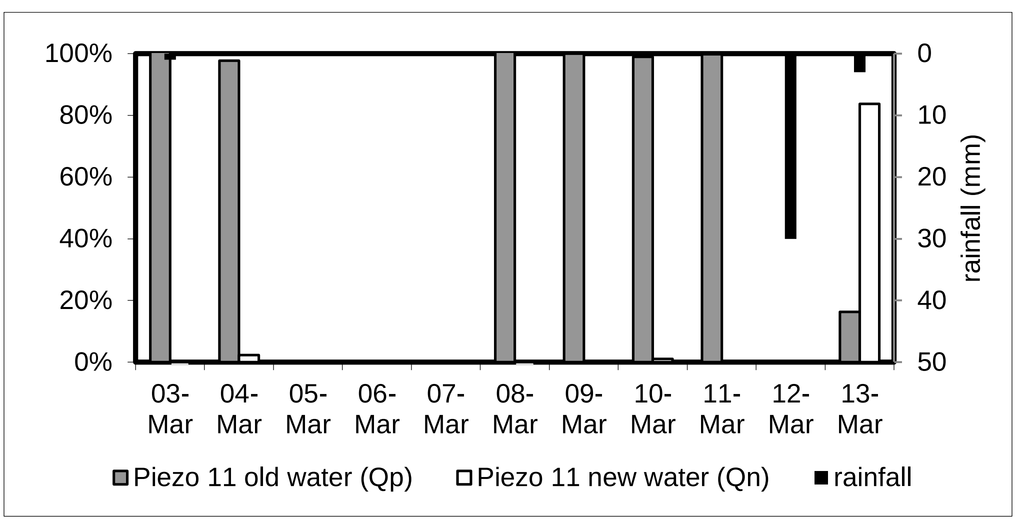


Figure 4.34 Hillslope 1, riparian nest 13, event and pre event contributions

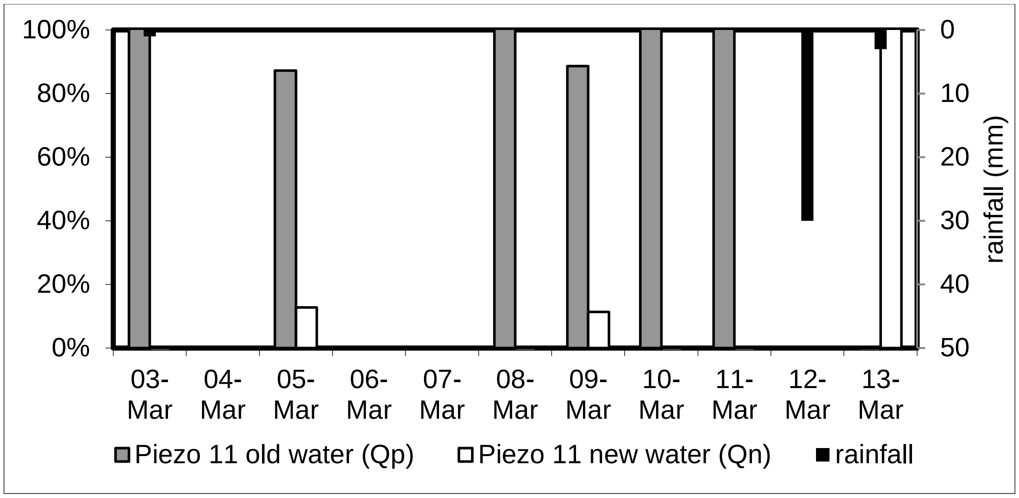


Figure 4.35 Hillslope 2, riparian nest 11, event and pre event contributions.

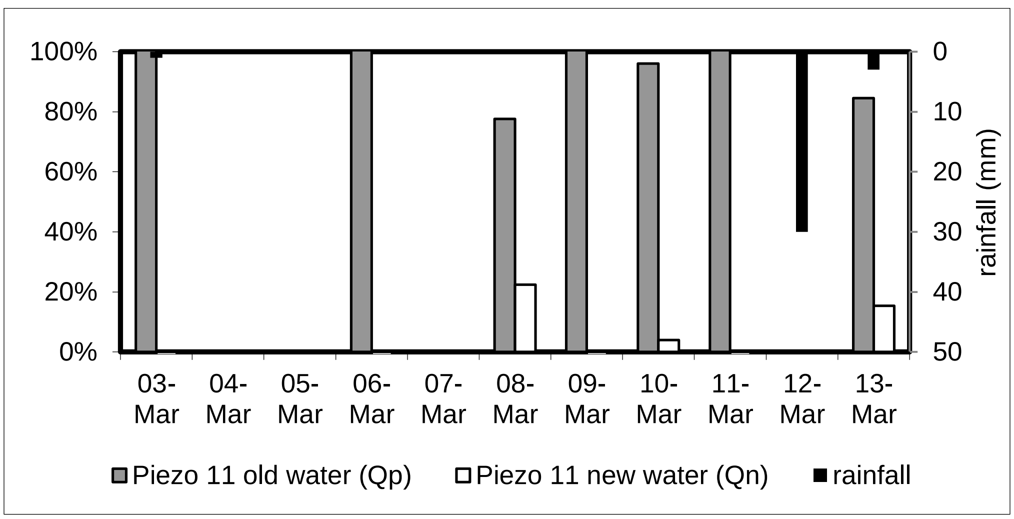


Figure 4.36 Hillslope 3, riparian nest 2A, event and pre event contributions.

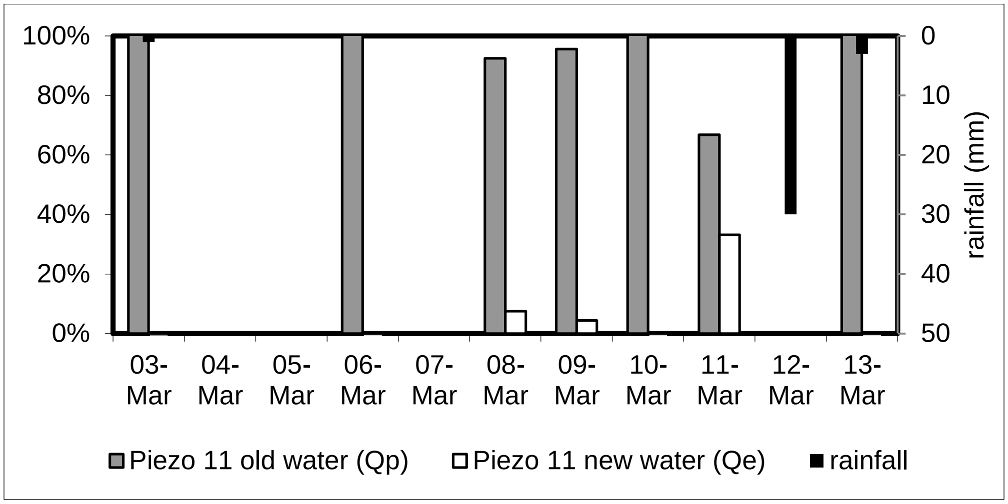


Figure 4.37 Hillslope 4, riparian nest UC 3/4, event and pre event contributions.

As no surface runoff was observed at any of the hillslope USLE runoff plots (Figure 4.1) event water either recharges vertically very slowly or moves laterally downslope within the shallow part of the soil horizon in-between the soil surface and the level of the perched water table. Given the heavily stratified nature of the sedimentary derived soils, it is highly likely that event water is rapidly transported downslope via lateral near surface movement.

Similar conclusions can be drawn from the piezometer scale hydrograph separations to those of the hillslope descriptions in Section 4.3. Upslope positions show the dominance of older hillslope water, the depleted and attenuated signal of the upslope positions observed in the δO^{18} values is further perpetuated in the hydrograph separations. This is evident in the high pre event component that makes up at least 70% of all soil/bedrock interface water in the hillslope and riparian soils. The high pre event contribution during the post event period further demonstrates the lack of rapid vertical recharge at the upslope positions.

4.9.2 Catchment scale hydrograph separations

Catchment scale hydrograph separations were carried out for the period 24-31 January using the mass balance equation (Equation 3.3 and Equation 3.4). This period was chosen as it contained the most complete and detailed record of rainfall and streamflow for a continuous series of events. For the purposes of the calculation, total streamflow δO^{18} isotope value (C_t) is taken from the water gauged and sampled at the LC weir (Figure 3.1). Pre event water δO^{18} isotope value (C_e) is the previous streamflow sample (n-1), and event water (C_e) is the δO^{18} isotope value of sampled rainfall near nest LC 01.

The dominance of event-derived streamflow, 30-80 percent (Figure 4.38), suggests the majority of catchment runoff is derived from the riparian soil adjacent to the stream in the lower parts of the catchment. These soils are shown to hold a high percentage of event derived water very shortly after the event as discussed in Section 4.9.1. The pre event water contribution, 15%-70%, can be attributed to the upper catchment area in which the riparian soils adjacent to the stream are shown to be dominated by older hillslope water

The effect of antecedent soil moisture conditions becomes apparent when soil water tensions and event water contributions are compared, Figure 4.39. Under dry antecedent soil moisture conditions, pre event water dominates the streamflow hydrograph. Prior to the 25 January 2010 rainfall event, antecedent soil moisture conditions are relatively dry. Pre event contributions to the streamflow hydrograph range from 55%-71%. Under wet antecedent soil moisture conditions event contributions outweigh pre event contributions with values ranging from 34%-100%

Under wet antecedent conditions, event water is the dominant contributor to streamflow. The stable nature of the 450mm tension indicates that the top soil is the dominant factor in the initiation of surface and shallow sub surface flows. The correlation between event water contribution and topsoil tension is further evidence of streamflow generation through infiltration excess overland flow on the riparian soils adjacent to the stream.

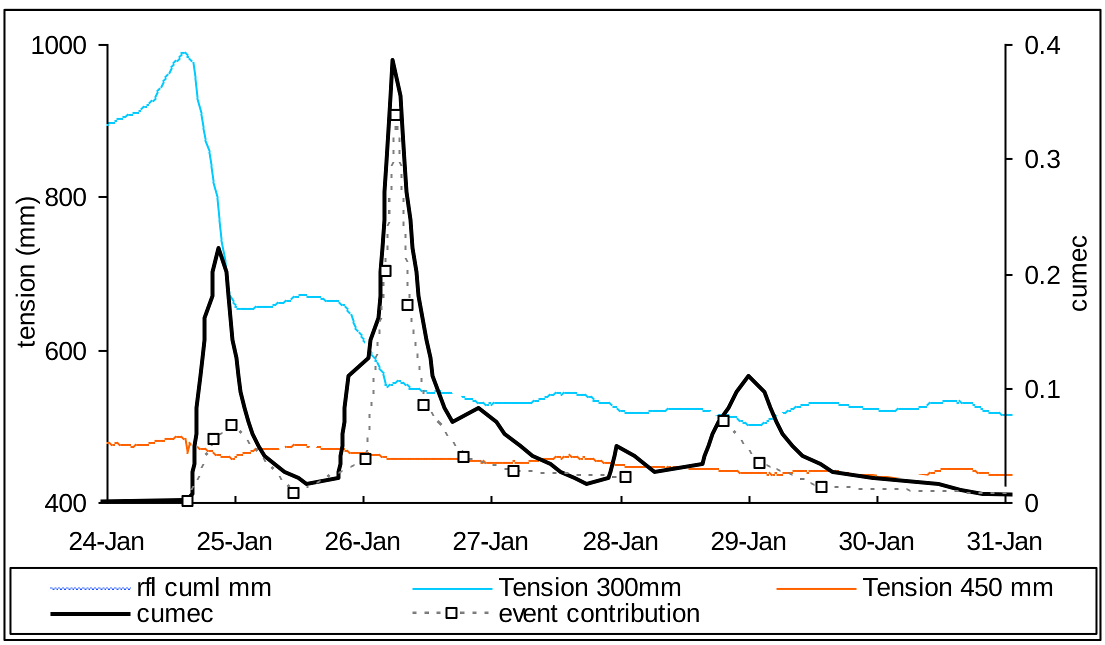


Figure 4.38 Weatherly 2 component δO^{18} Hydrograph separation and upper catchment (UC 03) riparian soil water tension (300mm and 450mm).

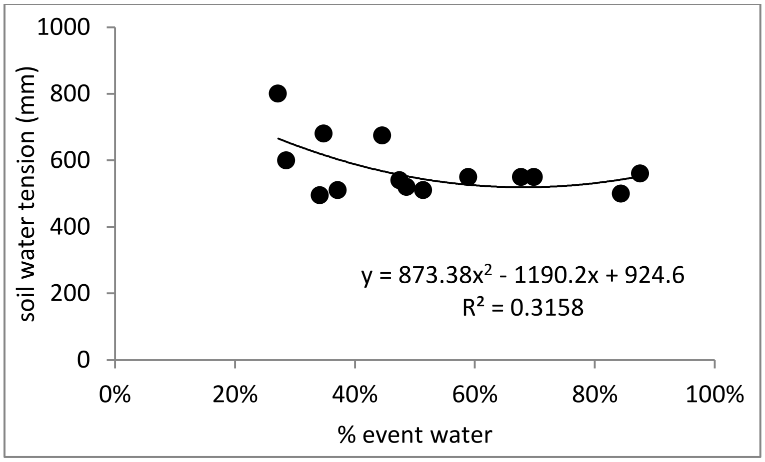


Figure 4.39 Event water contributions in relation to upper catchment riparian soil water tension 300mm depth.

4.10 Advection Dispersion Equation (ADE) Simulations

The purpose of the Isotope Dispersion model simulations was to calibrate the ACRU Intermediate zone model to represent the drainage characteristics of the different hillslopes in terms of the Dispersion coefficient (D_p) and the mean response time (τ), through the application of observed tracer data.

The isotopic response of the different hillslopes was simulated with a two-step algorithm, applying Equation 3.5. Initially the δO^{18} values of the infiltrated rainfall recharging the soil/bedrock interface are estimated. δO^{18} response at the hillslope discharge point is then simulated with the convolution integral by applying the infiltrated rainfall recharging the soil/bedrock interface as excitation time series data for the convolution integral. The time series rainfall data has two different monitoring periods in regard to the sampling of isotopes. The initial period extends from 2009/01/26 to 2009/02/22, and the second from 2009/10/15 to 2010/03/17. These periods will be used as time series inputs for Equation 3.7 and ultimately as input for Equation 3.5.

4.10.1 Input Function

The initial step is to adjust the input rainfall to represent the contributing fraction of the pre event soil or hillslope water using the Equation 3.7. 126 (N) rainfall samples were considered for analysis, each representing an equivalent depth of 7.5 mm rainfall (P_i). Observed ground water values from the individual hillslopes were used as initial δ_{gw} values, slight adjustments were made in order to improve the correlation between simulated and observed data. These values were generally depleted (δO^{18}<-4.0) in comparison to the rainfall average (-2.0).

Results of the application of Equation 3.8 show a strong event based signal for a period of days after a series of large events. This is seen in the depletion observed from 2009/02/04 to 2009/02/10, 2009/02/14 to 2009/02/21 (Figure 4.40) and from 2009/10/26 to 2009/11/18 (Figure 4.41) in both the simulated recharge and event water δO^{18} values.

The results obtained from the application of Equation 3.8 for each hillslope will be used as time series based input data in the convolution integral simulating hillslope discharge isotope responses. This parameter is represented by δ_{in} in Equation 3.5.

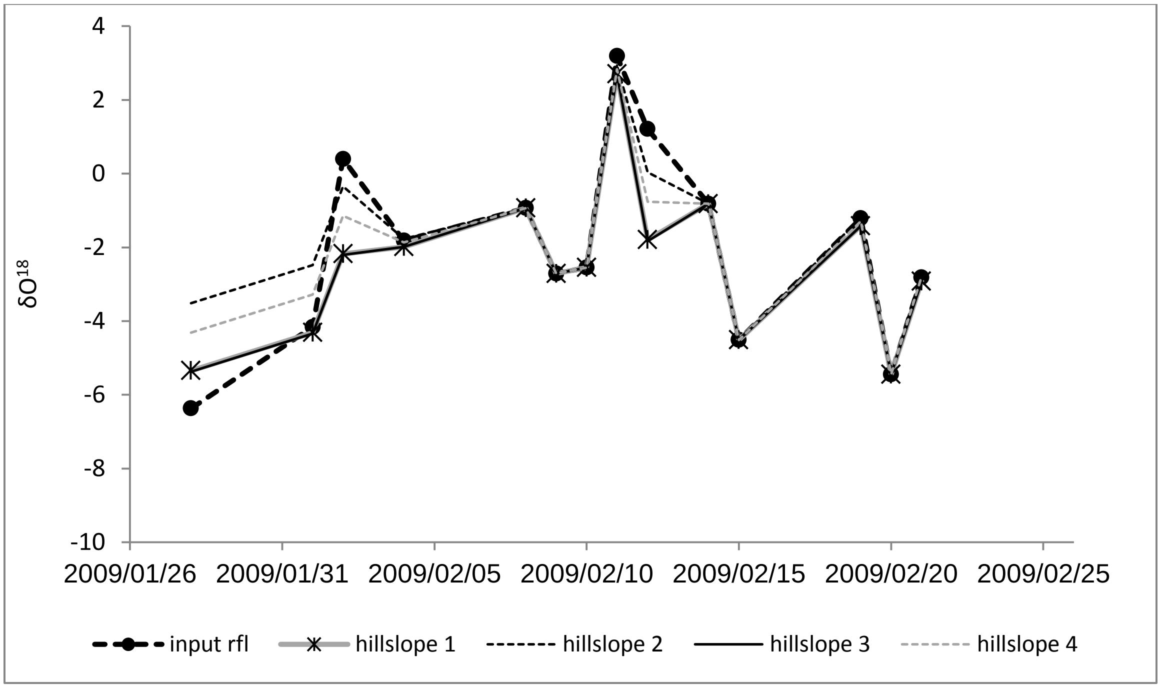


Figure 4.40 Transformed rainfall δO18 data adjusted by ground water δO^{18} values, January and February 2009.

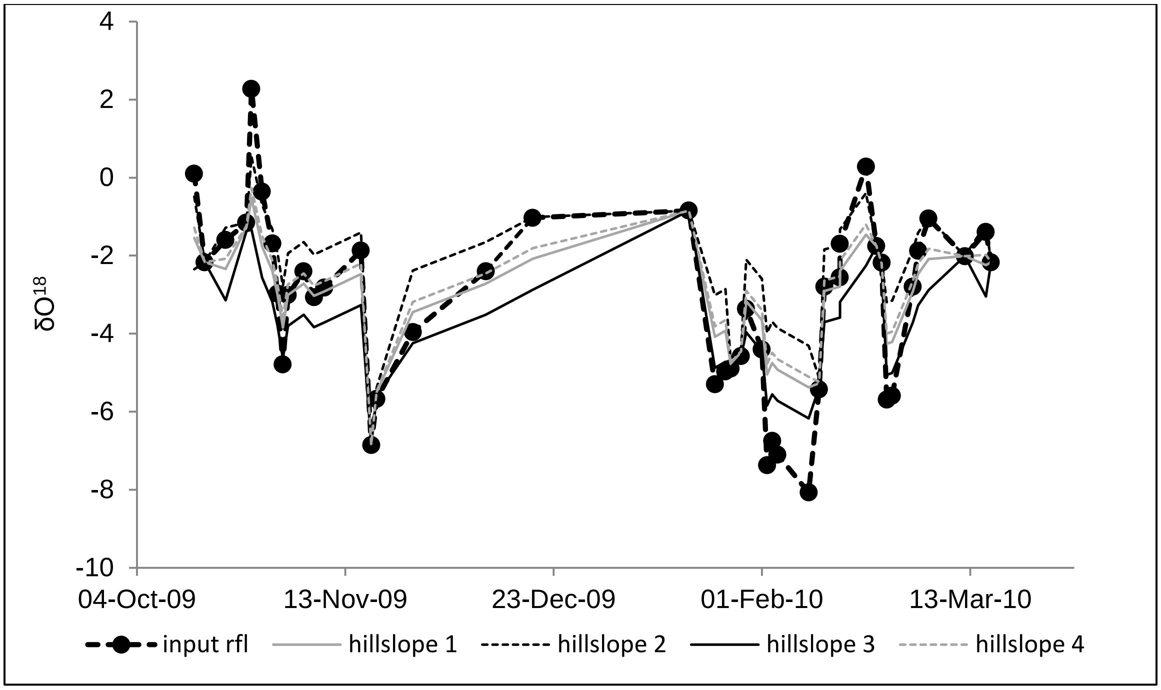


Figure 4.41 Transformed rainfall δO18 data adjusted by ground water δO^{18} values, October 2009-March 2010.

4.10.2 Hillslope scale ADE simulations

The aim of the ADE modelling was to generate representative values of the Dispersion coefficient D_p and the mean response time τ. These values are used as general descriptors of the entire range of surface sub surface processes operating at the specific scale applied, similar to the hillslope Péclet number discussed in Section 2.11.1, and will be used to calibrate the respective routines in the ACRU Intermediate zone model controlling the initiation of lateral sub surface water movement.

Adevection Dispersion Function (ADE) (Equation 3.5) simulations were carried out on each of the four different hillslope transects. The input function for this simulation was derived by estimating the isotopic value of rainwaters recharging the soil water (Section 4.10.1). The isotopic response at the outlet of the hillslope is simulated using different values for D_p and τ, attempting to achieve best fit with observed piezometer and surface seepage δO^{18} values. Unfortunately, the piezometer data from Hillslopes 2, 3 and 4 was not of sufficient scale to be representative and thus was omitted from the results.

The section of Hillslope 1 simulated extends from LC 01 through LC 04. While upslope piezometers LC 01, LC 02 and LC 03 show no evidence of a sustained soil/bedrock interface water table, the piezometers situated near the rocky outcrop near LC 04 show sustained water levels. Surface seepage allows for a unique opportunity to directly sample hillslope discharge. Seepage is observed responding over the rocky outcrop near LC 04 for extended periods during the wet season. These factors combined to produce an array of observed data against which simulations can be verified.

The simulated response of Hillslope 1 is well represented by the hillslope seepage isotope values during both simulation periods. This is with reference to the drop and rise in LC 04 seepage δO^{18} values 2009/02/09 to 2009/02/19 (Figure 4.42) during the first period, and 2010/03/06 to 2010/03/13 during the second (Figure 4.43). The best fits of observed and simulated data were achieved with a Dispersion coefficient (D_p) of 0.002 and a mean response time (τ) of 18 days for the first period, January and February 2009. For the second period, February to April 2010, values of D=0.003 and τ=12 achieved best fit (Table 4.7).

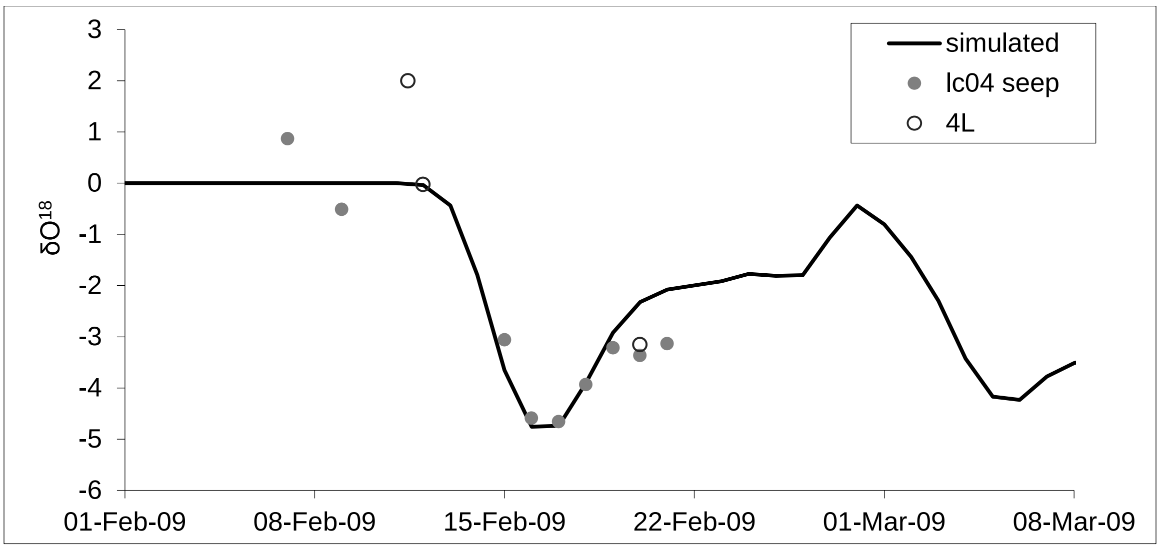


Figure 4.42 Weatherley hillslope 1, simulated and observed δO^{18} isotope values, February to March 2009.

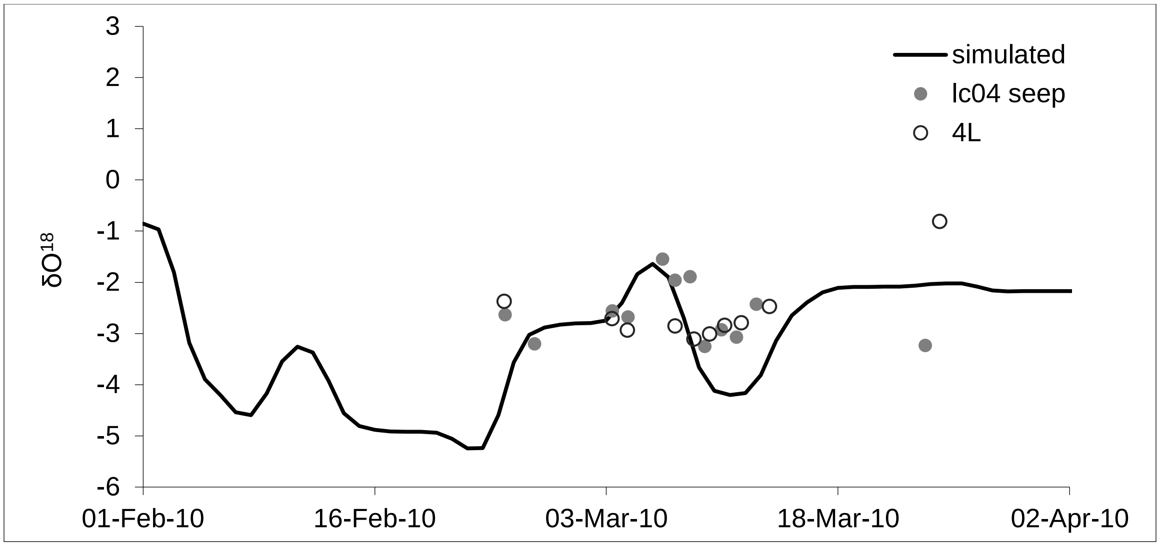


Figure 4.43 Weatherley hillslope 1, simulated and observed δO^{18} isotope values, February to April 2010.

Unfortunately, a lack of piezometer data from 2009 prohibited the analysis of Hillslope 2 from the January and February 2009 period. Hillslope 2 results from the February to April 2010 period exceed the range of observed values for most of the simulation period. However, the drop and subsequent rise in δO^{18} values from 2010/02/25 to 2010/03/03 is faithfully replicated (Figure 4.44). D_p and τ values that produced the best fit for Hillslope 2 data were 0.002 and 12 respectively.

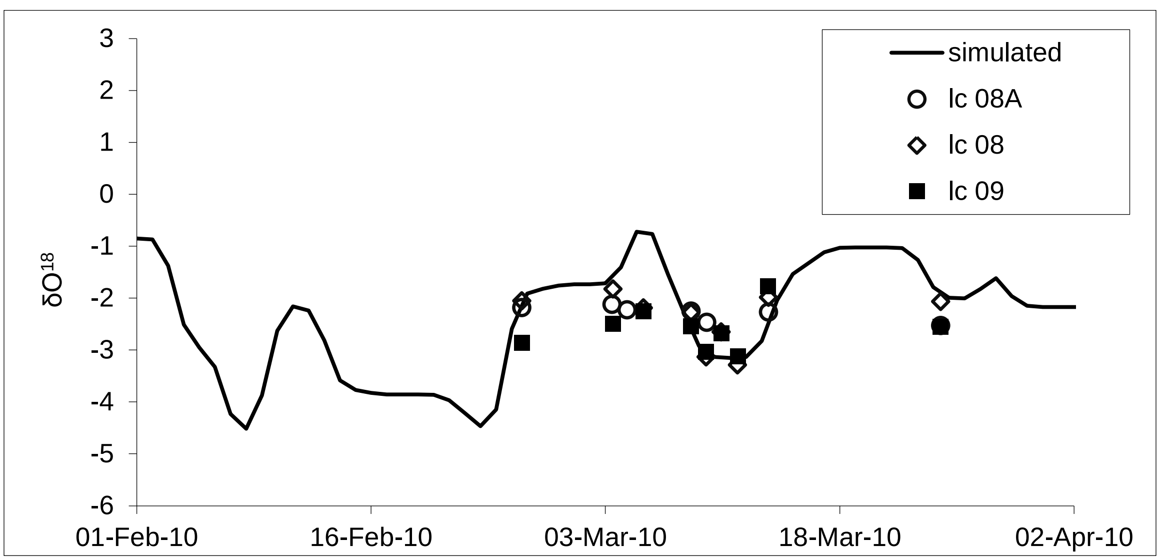


Figure 4.44 Weatherley hillslope 2, simulated and observed δO^{18} isotope values, February to April 2010.

Results from the simulation of Hillslope 3, using D_p=0.30 and τ=10, showed a well-mixed simulated δO^{18} response compared to Hillslopes 1 and 2. The well-mixed simulated δO^{18} response faithfully replicates the δO^{18} values observed in the hillslope piezometers along the transect, particularly piezometer UC 01. The depletion of the piezometer isotope values is well represented by the simulated δO^{18} response.

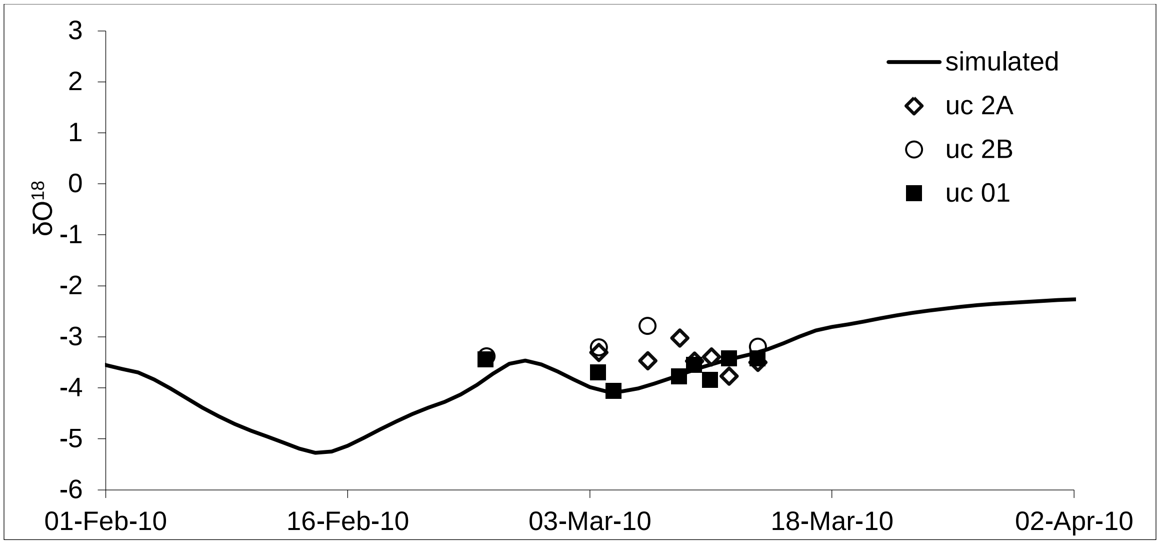


Figure 4.45 Weatherley hillslope 3, simulated and observed δO^{18} isotope values, February to April 2010.

Like Hillslope 3, Hillslope 4 simulated responses show well-mixed δO^{18} values, with very little variation in time compared to Hillslopes 1 and 2. Observed values from piezometer UC ¾ fall consistently on the simulated values (Figure 4.46) indicating that the D_p and τ values of 0.09 and 9 are representative of the hillslope subsurface drainage characteristics.

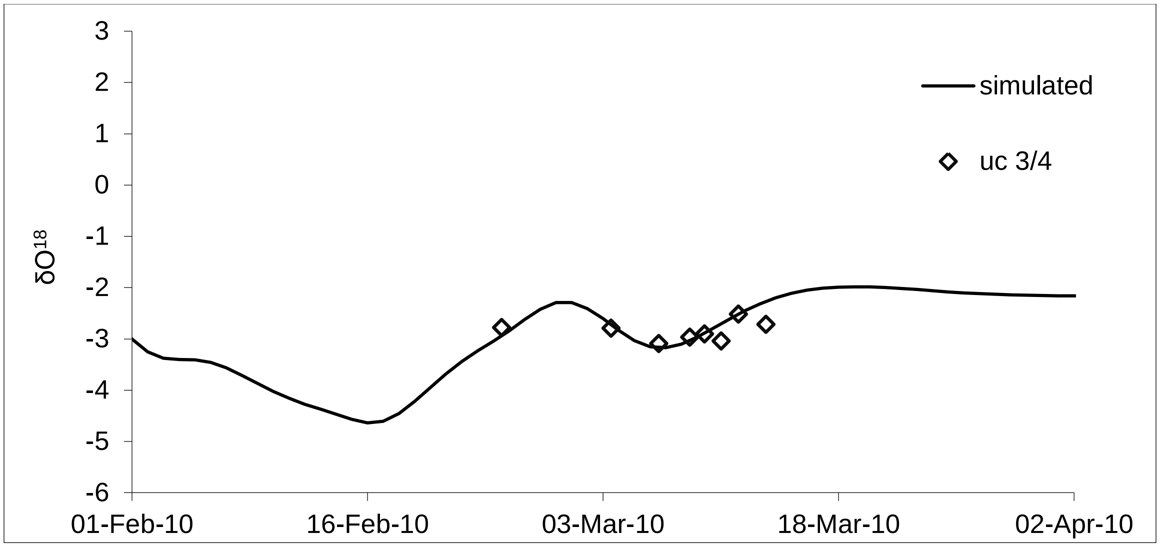


Figure 4.46 Weatherley hillslope 4, simulated and observed δO^{18} isotope values, February to April 2010.

While correlation coefficients (R^2) are low for these simulations (Table 4.7), it is evident from the simulated and observed sequences that the upper catchment hillslopes (3 and 4) respond differently to the lower catchment hillslopes (1 and 2). Upper catchment dispersion coefficients range from 0.09 to 0.3, while mean response times are 9 and 10 days. Lower catchment dispersion coefficients range from 0.0015 to 0.003 and mean response times are 12 and 18 days. It is clear that D_p values are higher in the upper catchment, perpetuating well-mixed conditions, while the lower D_p values of the lower catchment reflect an event derived pulse like response from the hillslopes.

	Hillslope	Site	Date	Dispersion coefficient (D)	Mean response time (τ)	R^2
Lower catchment	1	LC 04	February 2009	0.002	18	0.81
		LC 04	March 2012	0.003	12	0.24
	2	LC 08	February 2009	0.0015	12	-
		LC 08	March 2012	0.002	12	0.27
Upper catchment	3	UC 01	February 2009	0.30	10	-
		UC 01	March 2012	0.30	10	0.19
	4	UC3/4	February 2009	0.09	9	-
		UC3/4	March 2012	0.09	9	0.41

Table 4.7 hillslope scale convolution integral Dispersion coefficient and mean response time values and simulation regression analysis.

4.10.3 Catchment scale ADE simulations

The catchment scale ADE simulations were carried out in order to gauge the drainage characteristics of the riparian soils adjacent to the stream. As discussed in Section 4.3, the stream is surrounded by riparian soils which feed it, therefore any hillslope soil water reaching the stream must pass through the riparian soils. Thus, riparian soils discharge is directly linked to the catchment discharge. This theory is central to the determination of D_p and τ values for the riparian soil routines in the hydrological modelling process that follows in Section 4.11)

The catchment scale ADE simulations applied the convolution integral response model used for the hillslope simulations. Volume averaged rainfall δO^{18} data was used as time series excitation for Equation 3.7, which in turn provided the excitation for Equation 3.5. The simulation results matched the observed δO^{18} time series as plotted in (Figure 4.47). Periods of enriched streamflow appear to be over simulated, which indicates the exclusion of deep ground water characteristics in the simulation process. The relatively depleted period of streamflow (January 2010) shows a faithful correlation between the simulated and observed values. These results were achieved with a Dispersion coefficient of 0.003 and a mean response time of 22 days. On a catchment wide basis the lower catchment hillslopes dominate the streamflow response considering D_p values of 0.0015-0.003 and τ values of 12-18 days. The response time of the catchment scale simulation is higher than any of the hillslopes (22 days), indicating the delayed response of ground water contributions to the stream from the upper catchment hillslopes.

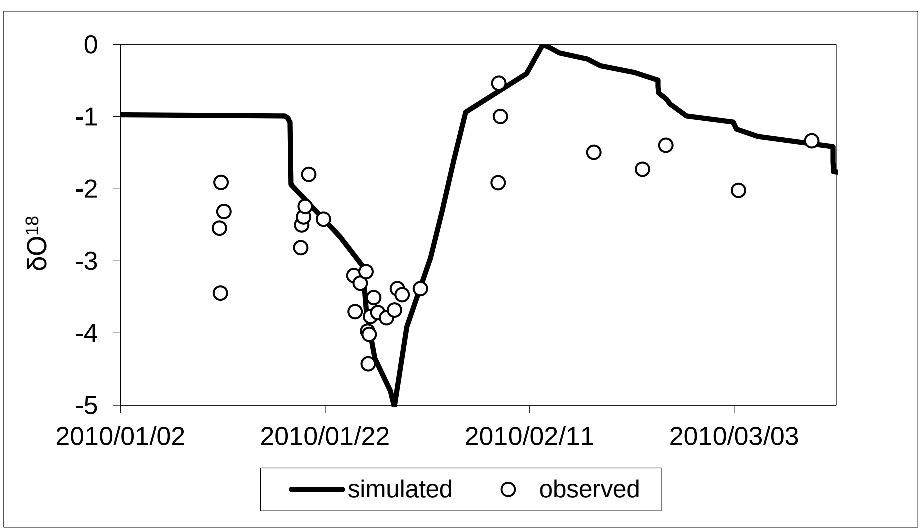


Figure 4.47 Weatherley catchment scale convolution integral response (D=0.003, τ=22 days).

4.11 ACRU 2000 and Intermediate Zone Simulations

The main objective of the modelling exercise was to replicate the dominant subsurface processes observed in the Weatherley catchment. This was achieved by only calibrating the parameters crucial to the simulation of downslope drainage. This is achieved by defining subsurface flow linkages and using the hillslope scale descriptors defined by the convolution integral parameters, D_p and τ, modelled in Section 4.10. In order to assess the ability of the ACRU Intermediate zone model to represent dominant subsurface responses a range of comparative simulations were carried out using the same input data where possible. The comparative ACRU modelling included two simulations. Both simulations considered four sub catchments, three hillslopes sub catchments draining to a riparian sub catchment at the outlet. Observation and analysis of hillslope isotope responses (Section 4.3 and Section 4.10.2) lead to the combining of Hillslopes 3 and 4 into a single sub catchment. Hillslope 3 and 4 riparian δO^{18} piezometer values showed strong pre event values during the post event period (Figure 4.22 and Figure 4.28), indicating the well-mixed nature of hillslope discharge (Figure 4.45 and Figure 4.46). The similarities in simulated and observed responses lead to the amalgamation of Hillslope 3 and 4 into single sub catchment representing the upper catchment area (Figure 3.4). Hillslopes 1 and 2 also portrayed similar isotopic responses, yet the inherently different geological sequences found along the two hillslope transects lead to them being simulated individually (Figure 3.4).

Population of the input files considered generic quaternary data describing climate and land use. Soils data was obtained using the textural data input to the ACRU AUTOSOILS application. The Weatherley catchment soils have a textural classification of sandy clay loam (SaClLm) which generated the simulations soil parameters (Table 4.8). For ACRU 2000 simulations, in which no subsurface drainage routines are active, the catchment was disaggregated based on hydropedological soil types assuming the dominance of Recharge, Interflow and Responsive soils at upslope, midslope and downslope areas respectively. In the case of the ACRU Intermediate zone simulations, subsurface routines were parameterized from descriptions of hillslope responses (Section 4.3) and estimations of D_p and τ (Section 4.10).

The simulation period 1998 through 2002 was used as full data sets of streamflow, rainfall and Neutron probe volumetric water contents were concurrent. The Weatherley catchment was completely under grassland conditions for the duration of the simulation period, allowing for the exclusion of the afforestation impacts on the simulations. Both versions of the ACRU model expresses soil moisture volumetrically (mm/m), thus the sub daily tension data cannot be used to verify model outputs, leaving only weekly, volumetric Neutron probe data.

4.11.1 Model inputs

A baseline simulation using the standard version of ACRU 2000, on which the Intermediate zone version is based, was carried out using identical input data to the ACRU Intermediate Zone simulation, apart from the intermediate zone characteristics given in Table 4.8.

Description	**Model variable**	**Value**
Depth A horizon	DEPAHO	0.250 m
Depth B horizon	DEPBHO	0.500 m
Depth Int zone	DEPINTZ	1.200 m
Wilting point A horizon	WP1	0.100 $m.m^{-1}$
Wilting point B horizon	WP2	0.100 $m.m^{-1}$
Wilting point Int zone	WPINTZ	0.159 $m.m^{-1}$
Field capacity A horizon	FC1	0.254 $m.m^{-1}$
Field capacity B horizon	FC2	0.354 $m.m^{-1}$
Field capacity Int zone	FCINTZ	0.354 $m.m^{-1}$
Porosity A horizon	PO1	0.402 $m.m^{-1}$
Porosity A horizon	PO2	0.402 $m.m^{-1}$
Porosity Int zone	POINTZ	0.402 $m.m^{-1}$

Table 4.8 Weatherley Hydropedological ACRU Intermediate zone simulation soils data.

4.11.2 ACRU 2000 simulation results

ACRU 2000 simulations were parameterized very simplistically. Climate, land use, runoff and soil properties were identical across all four sub catchments used in the simulation. Surface routing was calibrated by routing hillslope sub catchments 1, 2 and 3 into the riparian sub catchment 4, illustrated in Figure 4.5.2. Thus, the poor simulation results can be attributed to the lack of detail contained by the input files.

Results showed that high flow periods were well modelled, with streamflow generation from rainfall events exceeding 20 mm well simulated (Figure 4.48) however the simulation of low flows is poor (Figure 4.48, over simulation of these periods lowers the regression analysis value to 0.6843 (Figure 4.49). Over estimation of streamflow during the drainage periods is sufficient to cause general over simulation for the entire study period (Figure 4.50). The cause of the over simulation of streamflow arises from the inability of the ACRU 2000 routines to replicate a deep soil water store which has a delayed response in respect of the upper soil horizons.

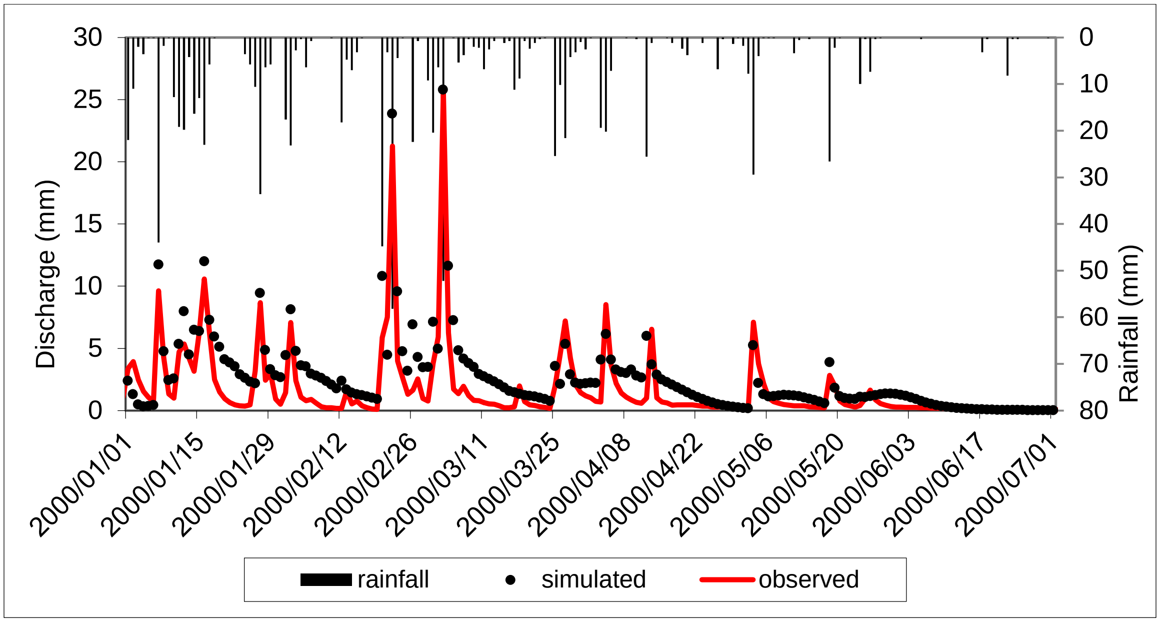


Figure 4.48 Weatherley, ACRU 2000 4 sub catchment hillslope scale simulation, observed and simulated streamflow time series.

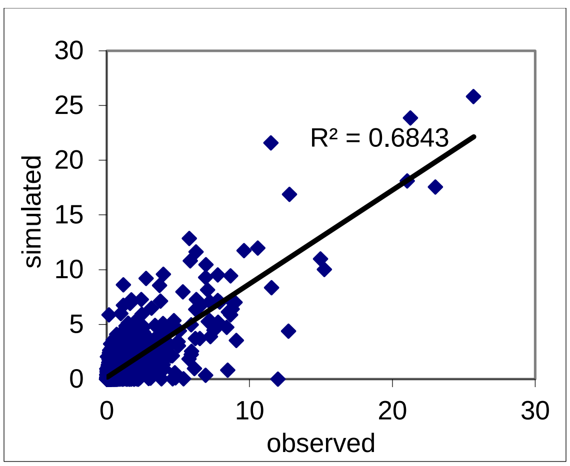


Figure 4.49 Weatherley, ACRU 2000 regression analysis of observed and simulated streamflow.

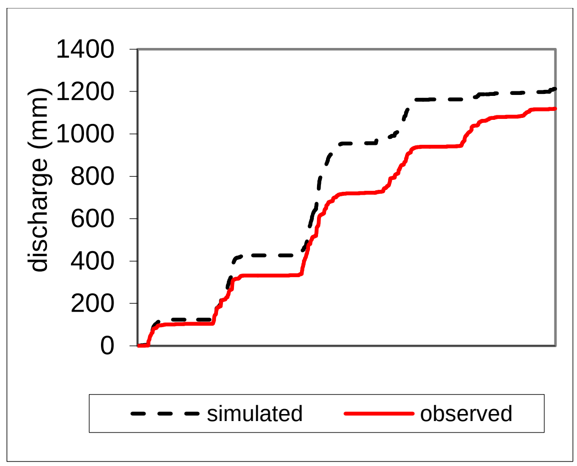


Figure 4.50 Weatherley, ACRU 2000accumulated observed and simulated streamflow.

Volumetric soil water comparisons between simulated and observed data are shown for March 1998 to February 2001, Figure 4.5.1. Simulations of the upper soil horizon faithfully represent the values and trends of the observed data. The absence of a deep soil water store is evident in the observed and simulated volumetric soil water data (Figure 4.5.1). Observed volumetric soil water data at 750mm below the surface shows a sustained and delayed response in comparison to the simulated (Figure 4.5.1, STO2%) data which shows a pulse like response in the rapid recharge and drainage.

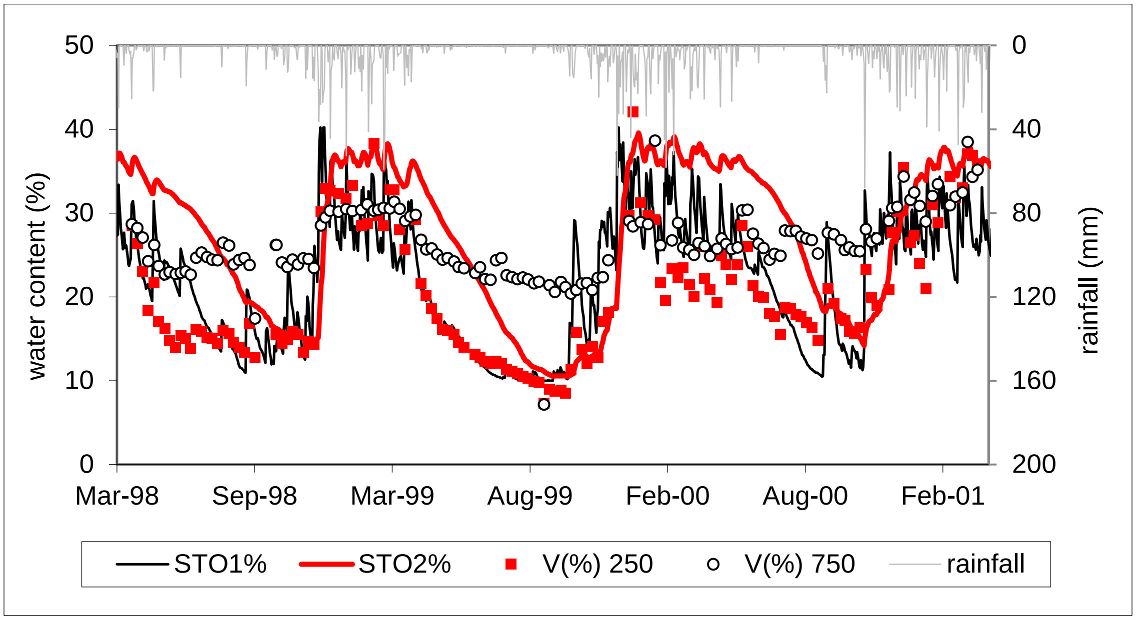


Figure 4.51 Weatherley ACRU 2000, simulated and observed volumetric soil water contents.

The ACRU 2000 simulation results were poor considering all analyses. This was to be expected as the scale of the data used to parameterize the input files was extremely coarse, with identical climate, landuse, runoff and soil data used. With a higher level of parameterization simulation results could obviously improve dramatically. By increasing soil depths, a larger soil water storage capacity could be created. Lowering the coefficient of same day runoff would delay the response of the soils to the stream. However, a primary objective of this study is to develop a non-intensive methodology for parameterizing a hillslope scale model, yielding acceptable results for practical applications.

4.11.3 ACRU Intermediate Zone simulation results

The addition of the intermediate zone routines to the ACRU 2000 model allow for better representation of hillslope scale processes. The new routines allow for the simulation of sub surface lateral responses. Lateral responses can be calibrated to link any soil horizon of the downslope hillslope segment (Figure 2.13). The lateral downslope response is controlled by a threshold response mechanism which can simulate the generation of near surface ground water discharges, separate from the typical ACRU 2000 SCS derived event volume (Section 2.9).

Additions to the model structure include an intermediate soil layer in-between the B-horizon and the ground water store. The intermediate soil layer is parameterized in the same way as the A and B soil horizons with the exception of the threshold response mechanism. The intermediate soil horizon has the ability to simulate downslope lateral responses as governed by the Advection Dispersion Equation (ADE)(Equation 3.6).

Calibration of Dispersion coefficient (D_p) and mean response time (τ) used the values shown in Table 4.9. Hillslopes 3 and 4 were lumped into a single sub catchment as they are underlain by similar geological sequences, and show similar well mixed isotope responses and occur adjacent to each other in the upper catchment (Figure 4.45 and Figure 4.46). Hillslopes 1 and 2 show similar responses in terms of isotope trends (Figure 4.42, Figure 4.43 and Figure 4.44), however they are simulated separately as the geological sequence of the two hillslopes differs. The rocky outcrop on Hillslope 1 near nest LC 04 causes a defined hydrological break in the hillslope, which causes surface seepage over the rocky outcrop. This results in the sub surface routing linking the upslope intermediate zone with the downslope (riparian) B soil horizon, instead of the intermediate soil layer as is the case with hillslope 2 (Figure 4.52).

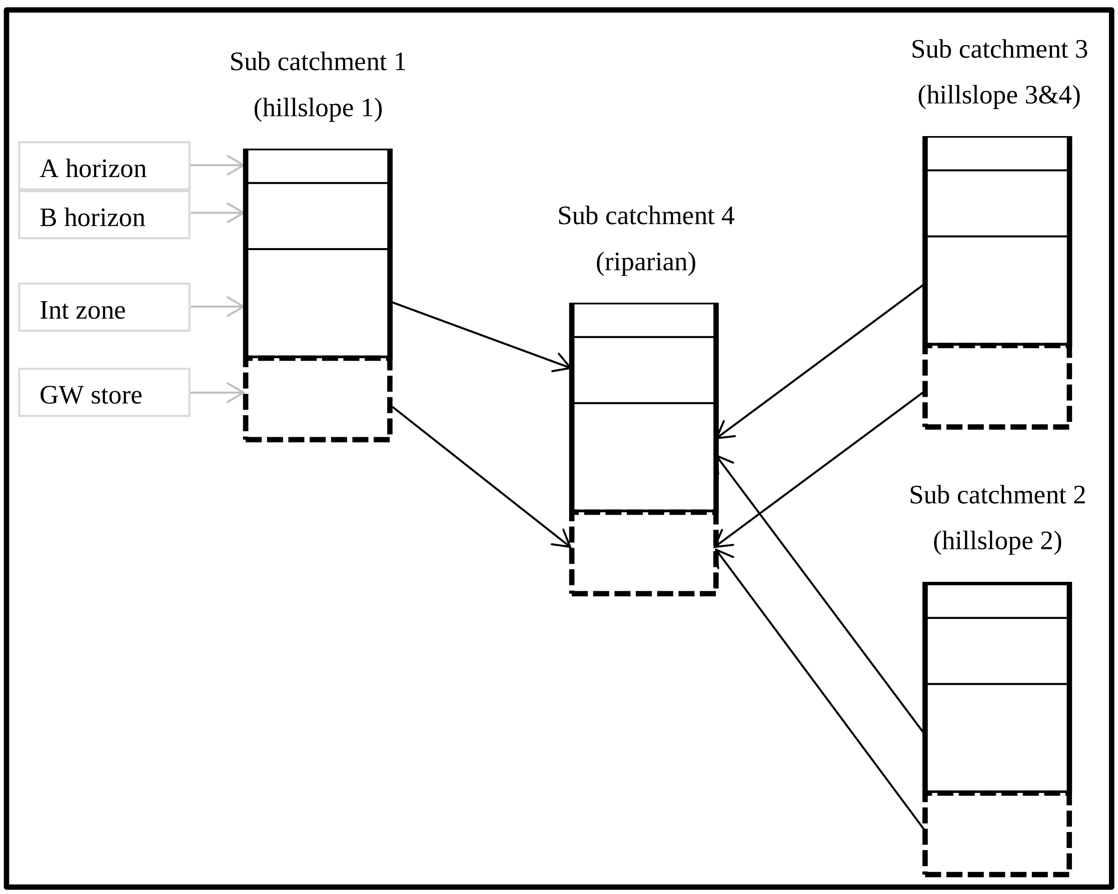


Figure 4.52 Weatherley ACRU Intermediate zone sub catchment sub surface routing.

Sub catchment	Hillslope no.	Dispersion coefficient (D_p)	Mean response time (τ)
1	1	0.003	12
2	2	0.002	12
3	3 and 4	0.09	9
4	Riparian	0.003	22

Table 4.9 Weatherley hillslope scale dispersion coefficient and mean response time variables used in ACRU Intermediate zone simulations.

Simulation results show a vast improvement compared to ACRU 2000. Event based streamflow is well simulated, as is the case with ACRU 2000. This is further evidence of the role that riparian soils play during event periods has been faithfully simulated (Figure 4.53). Riparian soils are simulated as the accumulation of the hillslopes prior to the generation of stream flow (Figure 4.52), therefore the soils will maintain high antecedent moisture levels. This will allow for the rapid generation of infiltration excess conditions, which would result in almost all the effective rainfall on the riparian soils becoming overland flow and responding directly to the stream.

The improvement in the regression analysis (R^2=.07147) was as a result of the improvement of low flow simulations (Figure 4.54). The improvement in low flow simulations is evident in both the time series data and accumulated streamflow data shown in Figure 4.53 and 4.55 respectivley.

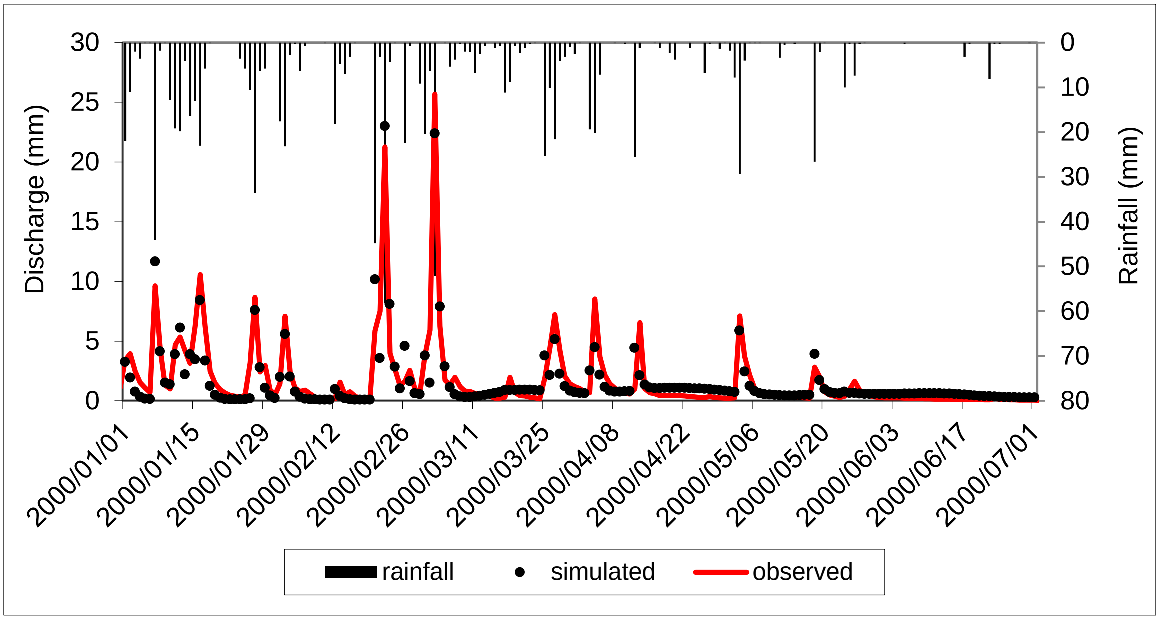


Figure 4.53 Weatherley, ACRU Intermediate zone, 4 sub catchment hillslope scale simulation, observed and simulated streamflow time series.

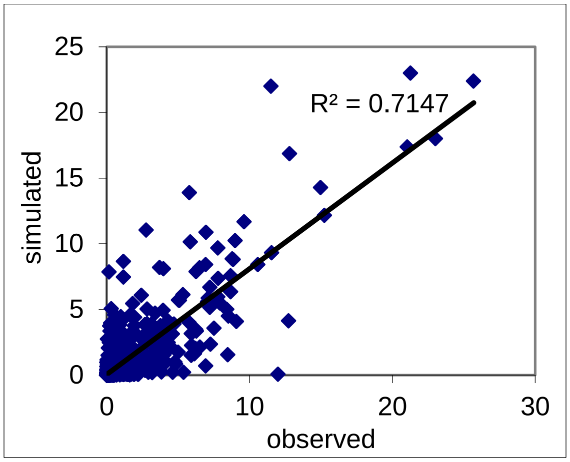


Figure 4.54 Weatherley, ACRU Intermediate zone regression analysis of observed and simulated streamflow.

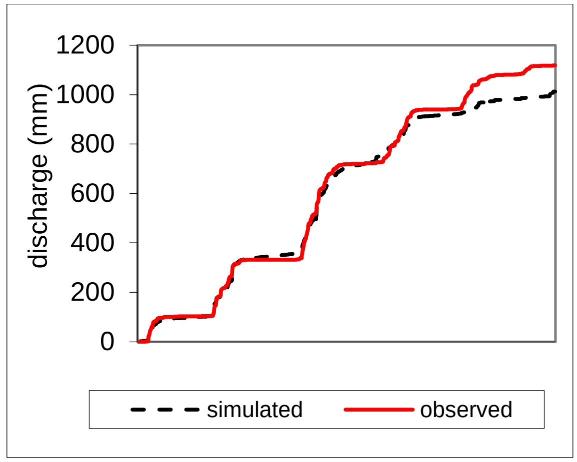


Figure 4.55 Weatherley, ACRU Intermediate zone accumulated observed and simulated streamflow.

Simulated A horizon soil water contents are almost identical to ACRU 2000 results. The simulation of B horizon soil water contents, STO2% (Figure 4.56) improved, showing more sustained water levels than simulated by ACRU 2000. Intermediate zone soil water content simulations displayed a well-mixed, delayed response, showing delayed but sustained recharge during the rainy season, followed by sustained drainage during the dry season (STO3%, Figure 4.56). This compares favourably with the trend of the observed data (V(%)1050, Figure 4.56) which shows a similar delayed, well mixed response in the subsurface. The presence of the intermediate soil layer allows for improved simulation of the delayed response from a catchment during drainage periods. The effect of the delayed response of the hillslope water from the intermediate zone is evident in the improved simulation of low flows (Figure 4.53) compared to ACRU 2000 (Figure 4.48).

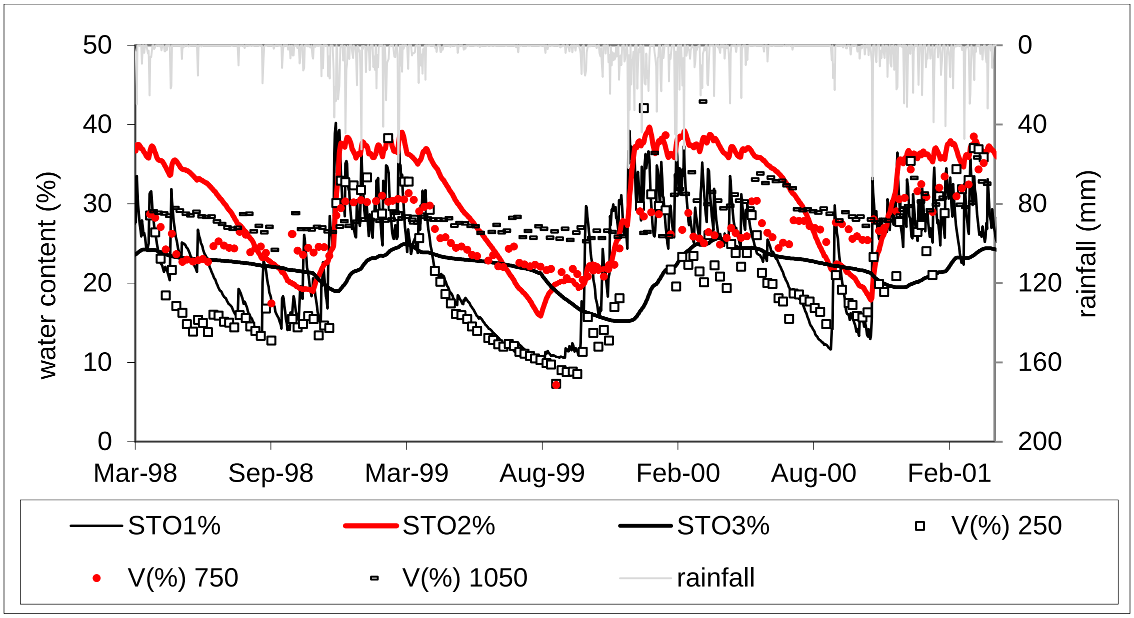


Figure 4.56 Weatherley ACRU Intermediate zone, simulated and observed volumetric soil water contents.

Results showed an overall improvement as a result of the inclusion of the intermediate zone routines. Better ACRU 2000 results could have been achieved by increasing the soil depth of the sub catchments, or calibrating variables pertaining to runoff generation such as the coefficient of baseflow response (COFRU) or the stormflow response fraction (QFRESP). However, these additions to the model detail would simultaneously improve the results of the ACRU Intermediate zone simulations. The intermediate zone routing option allows for a better representation of subsurface linkages between the different hillslope positions with the inclusion actual soil physical properties. ACRU 2000 simulations would require the exaggeration of actual soil physical parameters to improve simulation results, thus not truly representing catchment dynamics.

5 CONCLUSIONS

The study declared four main objectives at the outset in the aim of documenting a methodology in aid of moving closer to prediction in ungauged catchments. In the execution of each objective a dominant relationship has been exposed, aiding the catchment scale modelling process described in Section 4.11.

1. Define the hydrological processes in two distinct hillslopes through hydrometric and tracer observations .

Hydrometric and isotope data from four different hillslope across the Weatherley catchment were analyzed for dominant hydroloigical response patterns at different hillslope positions. Lower catchment Hillslopes 1 and 2 were dominanted by event derived flow, showing large fluctuations in δO^{18} in riparian soil/bedrock interface water, in comparison to Hillslopes 3 and 4. The fluctuations in δO^{18} values is as a result of mixing with event water. This is caused by the presence of the Elliot terrace near nest LC 04 on Hillslope 1 which creates an impermeable hydrological break which forces soil water to the surface. A dolerite dyke in the midslope region interrupts Hillslope 2. Soils around the dyke are highly permeable, which creates the potential for increased soil infiltration rates. Hillslopes 3 and 4 results showed the dominance of the hillslope water signal during pre and post event periods. The well mixed isotope response and the lack of an event based hydrometric response in the riparian piezometer (UC ¾) confirmed this.

Hydrograph separations carried out for each individual piezometer showed the presence of event water in the riparian soils of Hillslopes 1 and 2, while hillslope water remained evident in the upper catchment riparian soils of Hillslopes 3 and 4. These findings are consistent with those of the hillslope descriptions, providing a solid base for the quantification process to follow.

2. Develop typical response functions for discharge from the hillslopes.

Using the rainfall, piezometer and streamflow δO^{18} data, a simplified descriptor of sub surface drainage was developed for each of the four hillslope sections. Initially the rainfall time series was used to estimate the δO^{18} response of water recharge the soil/bedrock interface on each hillslope section (Equation 3.7). This estimate was then used as excitation for the convolution integral (Equation 3.5) in an attempt to simulate the δO^{18} response of the hillslopes discharge, by simulating different values of D_p and τ. Results showed distinct difference between Hillslopes 1 and 2 responses compared to Hillslopes 3 and 4. Hillslopes 1 and 2 had a variable pulse like response, unlike the well-mixed sustained response of the upper catchment Hillslopes 3 and 4. Lower values of D_p and higher values of τ are representative of the pulse like responses of the lower catchment hillslopes. Higher values of D_p and lower values of τ reflect the drainage characteristics of the well-mixed soil water body that drains the upslope area. Specific D_p and τ values for each hillslope were used to calibrate hillslope sub catchments of a distributed catchment scale simulation with two versions of the ACRU model.

3. Integrate the response functions into a catchment model, evaluating the improvement afforded by the hydrological response descriptors.

The hillslopes descriptors, D_p and τ, derived from the convolution integral calculations are used as one of only two parameterizations made to the ACRU Intermediate zone model. The other being the sub surface routing derived from the hillslope descriptions and hydrograph separations. The addition of the intermediate zone routines and subsequent use of estimated values of D_p and τ improved on the simulation results achieved with ACRU 2000. High flow periods were well simulated by both versions of the model. However, ACRU 2000 over simulated drainage periods causing the regression analysis results to deteriorate. The addition of the intermediate soil layer was able to replicate the delayed and sustained nature of the well-mixed response from the upper catchment Hillslopes 3 and 4. Over simulation of streamflow and isotope values is because the influence of the soil/bedrock interface water on the hillslope and catchment response is underestimated.

The ACRU Intermediate zone model can therefore potentially offer a non-data intensive alternative to simulating hillslope scale responses in a catchment scale model, overcoming many of the short comings of scaling when using other data intensive models such as HYDRUS or TOPKAPI.

4. Recommend future direction for catchment response simulations using classed hillslope responses.

Although this objective cannot be fully completed until a wider range of catchments have been assessed in a similar way, it is an initial step with results encouraging enough to speculate that similar trends will hold true when applying catchment trends at regional scale. Results showed that the underlying geology, intrinsic in the soil development process, dictates the presence of certain dominant hydrological responses. Areas underlain by sedimentary geologies will typically form soils that are heavily stratified, while soils developing from finer grained parent material will show more vertical homogeny. Hillslope transects with interrupted connectivity and/or permeability due to geological features show an increased propensity for shallower lateral sub surface processes, while hillslopes with uninterrupted permeability along the transect show that vertical recharge followed by a delayed lateral response on the soil/bedrock interface to the riparian streams. This delayed response is of fundamental importance in determining the timing and magnitude of the streamflow response during the drainage periods.

Hillslope and ultimately catchment geology is a fundamental factor in determining the nature of the hydrological response. Along with climate, these are the key factors effecting soil development and ultimately hydrologic response. This study has applied observations of dominant hydropedological patterns in the soils to isotope-based descriptions, identifying zones of recharge, storage and release, thereby conceptually describing hillslope connectivity for the modeling process. Hillslope scale drainage descriptors were estimated from the isotope data, which in turn allowed for the calibration of the individual hillslopes response in a catchment scale model. A combination of static qualitative field observations combined with numerical descriptions of the responses was used in the simulation process, thus driving numerical experiments with collective field intelligence as suggested by Weiler and McDonnell (2004).

"Numerical experiments with a model driven by collective field intelligence".

6 RECOMMENDATIONS

Deriving a range of typical hillslope responses can be compared to assembling the periodic table of elements. There are a finite number of hydrological response types, yet each one has to be observed and documented separately, as was the case in the discovery of each different elements comprising the periodic table. Once we have discovered a number of different responses, classification based on similar characteristics can occur, much in the same way as metals and non-metals, or noble gasses are grouped on the periodic table of elements. This denotes the application of similar objectives to other study sites in different geological and climatic zones of South Africa. However, this can only be successfully achieved once the relationship between scale and response is well understood. While it is suggested that further studies cover a range of climatic and geological areas, the issue of upscaling from hillslope to catchment to regional and ultimately primary catchment scale should be tackled in areas with similar climate and geology. Evidence in the disparity between catchment and regional scale responses is illustrated in Figure 6.1 where isotopes of the Mooi catchment ($302km^2$) show depletion when compared to those of the Weatherley catchment ($1.57km^2$), this indicates that with increasing scale the effect of hillslope water becomes more pronounced on the catchment response. At this stage one cannot clearly say whether this is due to greater volumes of hillslope water in the system, or as a result of greater contributions of hillslope water to the stream. Through increased sampling resolution at the hillslope, catchment and regional scale, analysed with the methods described in this study, it is believed that the classification of typical hillslope responses for use in PUB can be achieved.

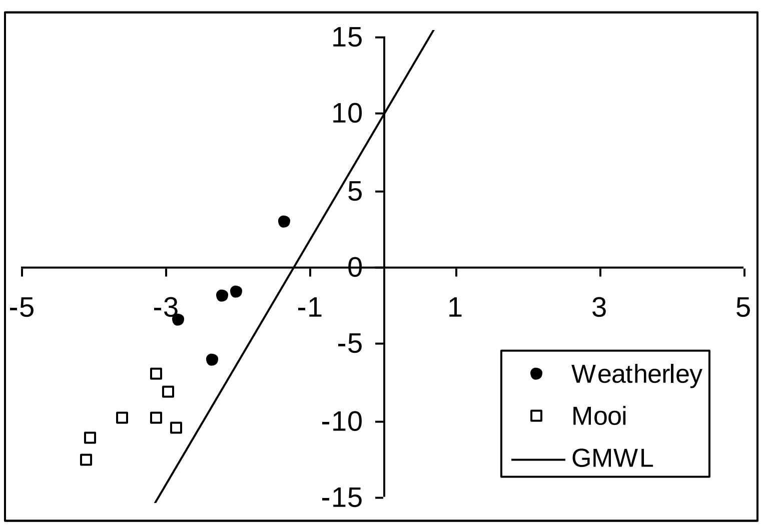


Figure 6.1 Weatherley and Mooi weir δO^{18} and δ^2H isotopes.

7 REFERENCES

Altinors, A. and Oender, H. (2008). A double-porosity model for a fractured aquifer with non-Darcian flow in fractures. Hydrological Sciences Journal, 53(4).

Asano, Y., Uchida, T. and Ohte, N., 2002. Residence times and flow paths of water in steep unchannelled catchments, Tanakami, Japan. Journal of Hydrology, 261(1-4): 173-192.

Ashman, M. and Puri, R . 2005. Essential soil science. Victoria, Blackwell Science.

Berne, A. and Uijlenhoet, R. (2005). Similarity analysis of subsurface flow response of hillslopes with complex geometry. Water Resources Research, 41(9): W09410.

Beven, K. J. 1997. TOPMODEL: A Critique. Hydrological Processes, 11: 1069-1085.

Beven, K. J. 2001. Rainfall-runoff modelling: The Primer, Wiley.

Bogaart, P. W. and Troch, P, A. 2004. On the use of soil-landscape evolution modelling in understanding the hillslope hydrological response. Hydrology and Earth System Sciences, 3: 1071-1104.

Bracken, L. and J, Croke, J. 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominanted geomorphic systems. Hydrological Processes, 21: 1749-1763.

Bronstert, A. 1999. Capabilities and limitations of detailed hillslope hydrological modelling. Hydrological Processes, 13: 21-48.

Ciarapica, L. and Todini, E. 2002. TOPKAPI: a model for the representation of the rainfall-runoff process at different scales. Hydrological Processes, 16(2): 207-229.

D'Odorico, P. and Rigon, R. (2003). "Hillslope and channel contributions to the hydrologic response." Water Resources Research, 39(5): 1113.

Detty, J., M. and McGuire, K, J. 2010. Topographic controls on shallow groundwater dynamics: Implications of hydrologic connectivity between hillslopes and riparian zones in a till mantled catchment. Hydrological Processes, 24: 2222-2236.

DeWalle, D, R,. Edwards, P, J,. Swistock, B, R,. Aravena, R,.Drimmie, R, J. 1997. Seasonal isotope hydrologyof three Appalachian forest catchments. Hydrological Processes, 11. 1895-1906.

Dunne, T. 1983. Relation of field studies and modelling in the prediction of storm runoff. J HYDROL 65: 25-48.

Finsterle, S. and Doughty, C. 2008. Advanced vadose zone simulations using TOUGH. Vadose Zone Journal,7 (2): 601.

Freer, J., McDonnell, J.J., Beven, K.J., Peters, N.E., Burns, D.A., Hooper, R.P., Aulenbach, B. and Kendall, C., 2002. The role of bedrock topography on subsurface storm flow. Water Resources Research, 38(12): 1269.

Grabczak, J., Maloszewski, P., Rozanski, K., Zuber, A. 1984. Estimation of the Tritium input function with the aid of stable isotopes. Catena(11): 105-114.

Helmschrot, J., Lorentz, S., Flugel, W.A. 2006. Integrated Wetland and Landscape Modellng. A Case Study from the Eastern Cape Province, South Africa, Department of Geoinformatics, Geohydrology and Modelling, University of Jena, Germany.

Jensco, K., G,. McGlynn, B, L,. Gooseff, M, N,. Bencala, K, E,. Wondzell, S, M. 2010. Hillslope hydrologic connectivity controls riparian groundwater turnover: Implications of catchment structure for riparian buffering and stream water sources. Water Resources Research, 46, W10524, doi:10.1029/2009WR008818.

Kendall, C. and Caldwell, E, A. 2003. Fundamentals of Isotope Geochemistry, Isotope Tracers in Catchment Hydrology. C. Kendall, McDonnell, J, J., Amsterdam, Elsevier: 51-86.

Kirchner, J. and Feng, X,. Neal, C. 2001. Catchment-scale advection and dispersion as a mechanism for fractal scaling in stream tracer concentrations. Journal of Hydrology, 254: 82-101.

Kollet, S. J. and Maxwell, R, M. 2006. Integrated surface–groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model. Advances in Water Resources, 29(7): 945-958.

Kutilek, M. and Nielsen, R, D. 2007. Interdisciplinarity of hydropedology. Geoderma, 138: 252-260.

Leibunbgut, C. and Maloszewski, P. 2009. Tracers in Hydrology. West Sussex, Wiley-Blackwell.

Lin, H, S. 2003. Hydropedology: bridging disciplines, scales, and data. Vadose zone journal. 2: 1-11.

Lin, H, S. Bouma, Wilding, L. Richardson, J. Kutilek, M. Nielsen, D., 2005. Advances in hydropedology. Advanved agronomy. 85:1-89.

Lin, H. S. 2009. Earth's critical zone and hydropedology: concepts, charcteristics, and advances. **:** Hydrology & Earth System Sciences Discussions 6(2): 3417-3481

Liu, Z. M. and Todoni, M. L. V. 2000. Flood forecasting using a fully distributed model: application of the TOPKAPI model to the upper Xixian Catchment. Hydrology and Earth System Sciences 9(4): 347-364.

Lorentz, S. A. 2007a. Application of the ACRU model to assess water use by different land uses: Application of the revised ACRU model at management scales School of BioResources Engineering and Environmental Hydrology, University of KwaZuluNatal, Pietermaritzburg, South Africa.

Lorentz, S. A. 2007b. Intermediate Layer in the ACRU Model, School of BioResources Engineering and Environmental Hydrology, University of KwaZuluNatal, Pietermaritzburg, South Africa

Lorentz, S. A., Bursey, K, Olufemi, I, Pretorius, J.J, Ngeleka, K. 2008. Definition and Upscaling of Key Hydrological Processes for Application in Models, Water Research Commission. K5-1320.

Lyon, S. W. and Troch, P, A. 2007. Hillslope subsurface flow similarity: Real-world tests of the hillslope Péclet number. Water Resources Research, 43, W07450, doi:10.1029/2006WR005323.

Maloszewski, P. and Zuber, A., 1982. Determining the turn over time of groundwater systems with the aid of environmental tracers. 1. Models and their applicability. Journal of Hydrology, 57: 207-231.

McDonnell, J, J. 2003. "Where does water go when it rains? Moving beyind the variable source area concept of rainfall-runoff response. Hydrological Processes, 17: 1869-1875.

McDonnell, J. J., Freer, J., Hooper, R., Kendall, C., Burns, D., Bevans, K. & Peters, J. 1996. New method developed for studying flow in hillslopes. Eos Transactions American Geophysical Union. AGU, 77(47), 465–472, doi:10.1029/96EO00306.

McGlynn, B. L., McDonnell, J.J. Kendall, C. and Hooper, R.P. 2001. The effects of catchment scale and landscape organization on streamflow generation processes. Chapman Conference on State-of-the-Art in Hillslope Hydrology. Sunriver, OR: Abstracts pg38.

McGuire, K. and McDonnel, J, J. 2010. Hydrological connectivity of hillslopes and streams: Characterisitic time scales and nonlinearities. Water Resources Research 46, WI0543, doi:IO.1029120IOWR009341

McGuire, K. J. and DeWalle, D, R. 2002. Evaluation of mean residence time in subsurface waters using oxygen-18 fluctuations during drought conditions in the mid-Appalachians. Journal of Hydrology 261(1-4): 132-149.

McGuire, K. J., McDonnell, J, J. 2005. The role of topography on catchment-scale water residence time. Water Resources Research, 41, W05002, doi:10.1029/2004WR003657.

Mueller, M, H.,Weingartner, R., Alewell, C. 2012. Relating stable isotope and geochemical data to conclude on water residence times in four small alpine headwater catchments with differing vegetation. Hydrology and Earth System Sciences, 9(4): 11006-11048.

Nourani, V. and Singh, V, P. 2009. Three geomorphological rainfall–runoff models based on the linear reservoir concept. Catena. 01/2009; DOI:10.1016/j.catena.2008.11.008

Ocampo, C. J., Sivapalan, M,. Oldham, C. 2006. Hydrological connectivity of upland riparian zones in agricultural catchments: Implications for runoff generation and nitrate transport. Journal of Hydrology 331: 643-658.

Rodgers, P. and Soulsby, C. 2005. Using stable isotope tracers to assess hydrological flow paths, residence times and landscape influences in a nested mesoscale catchment. Hydrology and Earth System Sciences 9(1-2): 139-155.

Schulze, R. E. 1995. Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System. Pretoria, Water Research Commission. 63/2/84.

Schulze, R. E. 2008. Integrated water resources management as a medium for adapting to climate change: conceptual, scaling, impacts modelling and adaptation issues within a South African context.

Schumer, R., Benson, D, A,. Meerschaert, M, M, . Baeumer, B,. 2003. Fractal, mobile/immobile solute transport. Water Resources Research, 39(10), 1296, doi:10.1029/2003WR002141.

Simunek, J., van Genuchten, M,. Sejna, M. 2008. Development and Applications of the HYDRUS and STANMOD Software Packages and Related Codes. Vadose Zone Journal, 7(2): 587-600.

Singh, B. P, and Kumar, B. 2005. Isotopes in Hydrology, Hydrogeology and Water Resourecs. New Delhi, Narosa Publishing House.

Sivapalan, M. 2003. Process complexity at hillslope scale, process simplicity at the watershed: is there a connection? Hydrological Processes, 17(5): 1037.

Soulsby, C. and Tetzlaff, D. 2006. Runoff processes, stream water residence times and controlling landscape characteristics in a mesoscale catchment: An initial evaluation. Journal of Hydrology, 325(1-4):197-221.

Troch, P. A. and Paniconi, C. 2003. Hillslope-storage Boussinesq model for subsurface flow and variable source areas along complex hillslopes: 1. Formulation and characteristic response. Water Resources Research, 39(11), 1316, doi:10.1029/2002WR001728,

Tromp-van Meerveld, H. J, and McDonnell, J, J. 2006. Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. Water Resources Research, 42(2), W02411, doi:10.1029/2004WR003800.

Uhlenbrook, S. and Leibundgut, C. 2002. Process-oriented catchment modeling and multiple-response validation. Hydrological Processes, 16: 423-440.

Uhlenbrook, S., Didszun, J., Tilch, N., McDonnel, J., McGuire, G. 2004. Breaking up is always difficult – Landscape discretization as a process transfer approach for prediction in ungauged basins. Predictions in ungauged basins. PUB Kick-off . (Proceedings of the PUB kick-off meeting held in Brasilia, 20-22 November 2002). IAHS Publ. 309, 2007.

Uhlenbrook, S. and Didszun, J. 2008. Source areas and mixing of runoff components at the hillslope scale-a multi-technical approach. Hydrological Sciences Journal, 53(4): 741-753.

Uhlenbrook, S. and Roser, S. 2004. Hydrological process representation at the meso-scale: the potential of a distributed, conceptual catchment model. Journal of Hydrology, 291: 278-296.

Uhlenbrook, S., Wenninger, J, Lorentz, S.A 2005. What happens after the catchment caught the storm? Hydrological processes at the small, semi-arid Weatherly catchment, South-Africa. Advances in Geoscience, 2: 237-241.

Van Genuchten, M., T, H, and Sudicky, E, A. 1999. Recent Advances in Vadose Zone Flow and Transport Modeling. Vadosa Zone Hydrology: Cutting across disciplines. M. B. H. Parlange, J, W,. Oxford, Oxford University Press: 155-193.

van Tol, J., J,. le Roux, P, A, L,. Hensley, M,. Lorentz, S, A, L. 2010. Soil as an indicator of hillslope hydrological behaviour in the Weatherley Catchment, Eastern Cape, South Africa. Water SA, 36(5): 513-519.

van Zyl, A. L. and Lorentz, S, A, 2003. Predicting the impact of farming systems on sediment yield in the context of integrated catchment management. Pretoria, Water Research Commission of South Africa. 1059.

Wagener, T. and Sivapalan, M. 2007. Catchment classification and hydrologic similarity. Geography Compass, 1(4): 901-931.

Weiler, M. and McDonnell, J, J 2004. Virtual experiments: a new approach for improving process conceptualization in hillslope hydrology. Journal of Hydrology, 285(1-4): 3-18.

Weiler, M. and McDonnell, J.J. 2007. Conceptualizing lateral preferential flow and flow networks and simulating the effects on gauged and ungauged catchments. Water Resources Research, 43, W03403, doi:10.1029/2006WR004867.

Weiler, M., McDonnell, J.J., Tromp-van Meerveld, I., Uchida, T., 2005. Subsurface Stormflow. Encyclopedia of Hydrological Sciences. M. Anderson, Wiley and Sons, Ltd.

Weiler, M. M., McGuire, K.J. and Mcdonnell, J.J. 2003. How does rainfall become runoff? A combined tracer and runoff transfer function approach. Water Resources Research, 39(11): 1315, doi:10.1029/2003WR002331

Wood, E., F,. Sivapalan, M. Beven, K. 1990. Similarity and Scale in Catchment Storm Response. Reviews of Geophysics, 28(1): 1-18.

Woods, R. and Rowe, L. 1996. The changing spatial variability of subsurface flow across a hillside. Journal of Hydrology, 35: 51-86.

Yang, D. and Herath, S. 2002. A hillslope-based hydrological model using catchment area and width functions. Hydrological Sciences Journal, 47(1): 49-66.