Hydrological Connectivity - a study into representative metrics for a humid temperate catchment in northern England.

WILLIAMS, CHRISTOPHER,JOHN,SELLWOOD

Hydrological Connectivity - a study into representative metrics for a humid temperate catchment in northern England.

Christopher Williams

Abstract

Hydrological connectivity has been identified as a concept which can help hydrology move towards a hydrological approach focussing on homogeneity rather than difference. The method of hydrological connectivity measurement has subsequently developed as key in permitting this concept to reach its potential. Previous studies have focused on topography and soil moisture respectively to solve this problem, generating metrics and indexes in order to predict the potential for connectivity spatially and temporally. This study focused on ascertaining the relative success of these different approaches for a humid temperate catchment in northern England. It was found that simple saturated area based metrics performed better than complex cluster analyses. In addition to this the Topographic Wetness Index was found to struggle to ascertain active areas within the catchment. Subsequently, building upon the Network Index of Lane et al. (2004), a new index was developed in order to combine topographic and soil moisture measurements to give a probabilistic estimation of connectivity over time. This Cumulative Probability Network Index was found to be the most promising method for estimating hydrological connectivity, particularly for upland catchments with shallow soils.

Hydrological Connectivity - a study into representative metrics for a humid temperate catchment in northern England.

By

Christopher John Sellwood Williams BSc

Department of Geography
Durham University
Science Laboratories
South Road, Durham
DH1 3LE,
UK

A thesis submitted for the degree of Master by Research in Physical Geography (MRes.) at Durham University.

2010

Contents

Figures

Tables

List of Abbreviations

AI	-	Aggregation Index	51, 94, 96, 97, 98 100, 114, 115
AMSR-E	-	Advanced Microwave Scanning Radiometer	37
AP	-	Antecedent Precipitation with a number denoting the number of days e.g. AP14 represent the previous 14 days	55, 75, 89, 90, 99 105, 112
C_BUF60	-	Distance Buffered Contributing Area metric at sm60 threshold	99, 101
CA%	-	Percentage proportion of catchment that is Saturated Area	51, 94, 97, 98, 99, 100, 105, 112
CA%70	-	Percentage of Contributing Area metric at sm70 threshold	99, 101
CD_stage	-	Stage in day of survey	89, 90
CHASM	-	Catchment Hydrology and Sustainable Management	30, 46
CONT70	-	Contributing Area metric at sm70 threshold	99, 101
CONT60	-	Contributing Area metric at sm60 threshold	101
CONTAREA	-	Contributing Area metric	50, 92, 94, 96, 97, 99, 100, 105, 111 112
CONTAREA_BUF	-	Distance Buffered Contributing Area metric	50, 97, 98, 99, 100
CoV	-	Coefficient of Variation	54, 98
cp	-	Depth averaged temporal percentile	111
CPNI	-	Cumulative Probability Network Index	56, 102, 103, 104, 118, 121, 122

CRUM	-	Connectivity of Runoff Model	17
DA_1	-	Stage day after survey	81, 90
DEM	-	Digital Elevation Model	46, 47, 48, 56, 57, 58, 60, 61, 62, 63
DGPS	-	Differential Global Positioning System	45, 46, 58, 59, 60, 62
dp	-	temporal soil moisture percentile	85, 87, 92, 94, 95 95, 97, 98, 99, 104 104, 105,111, 115 116
GPR	-	Ground Penetrating Radar	37, 38, 39, 40
GPS	-	Global Positioning System	45
HYSS	-	Hydrologically Similar Surface	8
ICSL	-	Integrated Connectivity Scale Length	56
LPI	-	Largest Patch Index	51, 94, 97, 99, 100 100, 105, 112, 113
LPI70	-	Large Patch Index at the sm70 threshold	99, 101
MSMC	-	Mean Soil Moisture Content	89, 90, 98, 111
PD_stage	-	Stage on day preceding survey	75, 90
RANGE_EW	-	Range of East-West directional semivariogram	95, 97, 100, 104, 107, 111, 115
RANGE_NS	-	Range of North-South directional semivariogram	95, 97, 98, 99, 100, 111, 115
RANGE_OM	-	Range of omnidirectional semivariogram	95, 97, 100, 111, 115
RMSE	-	Root Mean Standard Error	41
SAT70	-	Saturated Area metric at sm70 threshold	101

SATAREA	-	Saturated Area metric	49, 92, 94, 96, 97 97, 98, 99, 100, 105, 111, 112, 116 117
SATAREA_BUF	-	Distance Buffered Saturated Area metric	50, 97, 100
SATCLUST	-	Number of saturated clusters	49, 94, 96, 97, 98 99, 105, 111, 116 117, 123
SCIMAP	-	Sensitive Catchment Integrated Modelling and Analysis Platform	17
SD_stage	-	Stage on the day of the survey	81
SINCE	-	Days since rainfall	89, 90
sm	-	soil moisture percentile	85, 86, 88, 92, 94, 95, 96, 97, 98, 99 100, 110, 111, 112, 114, 115, 116, 117
TDR	-	Time Domain Reflectometry	36, 38, 40, 41
TWI	-	Topographic Wetness Index	47, 48, 106, 107, 108, 110, 112
VSA	-	Variable Source Area	4, 34, 47
WARR	-	Wide-Angle reflection-refraction	37

Declaration

I certify that no part of the material offered in this thesis has been previously submitted by me for a degree or other qualification in this or any other University.

Signed
Christopher Williams

Statement of Copyright

Acknowledgements

I would like to thank my supervisors, Dr. Louise Bracken and Dr. Sim Reaney, for their consistent and helpful advice throughout this thesis. I would also like to thank Dr. Mark Wilkinson, Nick Barber and Vesna Tripkovic of Newcastle University for access to their weather and stage data record for Cumbria and their help regarding field work and site information. My gratitude also goes to Dr. Dave Milledge for his help with CPNI and its application in SAGA GIS which was invaluable. I would also like to state my appreciation to Steve Warton for access to his land. My appreciation also goes to Calum Baugh and I-Hsien Porter for their support using Matlab and the seemingly endless difficulties experienced with GIS. I'd also like to thank my friends and family for their support and putting up with my ceaseless obsessions with this project in one way or another.

1.0 Introduction

The development of hydrology has historically been focussed on the understanding of processes and conditions that make places hydrologically unique. The established formula of specification through empirical or theoretical relationships has resulted in a wealth of understanding surrounding how water behaves in a range of environments and at a range of scales. The problem with such an eclectic accumulation of information is that the task of combining it into one system of understanding, particularly across different scales, has proved elusive. Traditional models of water flow were, for a long time, considered exclusive, infiltration excess runoff and saturation excess runoff were used to understand processes in semiarid and humid climates respectively. This historic schism is a microcosm of the psychological divide that is still present between a number of hydrological conceptions. This divide has been a cause for concern for some time, Dooge (1986; p. 46) identified the need for a "…search for regularities in hydrological relationship…". This is no less pertinent a statement now, with McDonnell et al. (2007) realising that this vision "…remains just as fresh, relevant and, unfortunately, very much unfulfilled…" (McDonnell et al., 2007, p. W07301). They go on to testify that hydrological progression has been driven by largely descriptive studies resulting in a presumption that sufficient detailed studies will result in an understanding of the whole despite distinct conditions and processes, being all too often scale and sometimes even site specific.

The drive for homogeneity rather than the cataloguing of heterogeneity has potential benefits in reframing hydrological problems in order to advance innovative solutions. It has been recognised that hydrological modelling struggles to characterise hydrological variability due to their dependence on small scale physics or theories (Kirchner, 2006). The heterogeneities present in large catchments lead to variation in dominant processes that are not fully understood (Sivapalan, 2003). This leads to intensive parameterisation and problems of equifinality resulting in predicative uncertainty (Beven, 2000). Even at small scales organised soil matrices can result in fundamental modelling principles like the Darcy-Richards equation to break down (Weiler and Naef, 2003). Again these issues are not new with Dunne in 1983 (p. 25) recognising the "… runoff concepts need to be refined, developed and formalized through more vigorous combination of rigorously defined field experiments and realistic physically based mathematical models…". The reactionary approach to concepts and theory for field experimentation only serves to intensify this problem as the importance of the more general large scale is subsumed beneath more easily applicable site specific hypotheses (McDonnell et al., 2007).

The manner in which the consideration of homogeneity in catchment hydrology, particularly regarding the need for a new runoff generation theory (Dunne, 1983; McDonnell, 2003; Ambroise, 2004), has begun to be developed by assessing hillslopes and the degree to which they are hydrologically similar (e.g. Bull et al., 2003) and as a result the potential probability of water connecting to catchment channels. This development in conjunction with the growing recognition for the impact of network pathways at all spatial scales (Clothier et al., 1998) progressed to form the hydrological connectivity concept. This concept aims not only to identify areas where runoff is likely to occur but also focus on when it is likely to connect to the channel network and to what extent. Research on hillslope-channel connection (Harvey, 1996; Michaelides and Wainwright, 2002) has highlighted the significance of hillslope connection on catchment response. The approach attempts to develop this research by linking the physical catchment elements at a range of scales with temporal changes to identify the impact of certain hydrological conditions on different catchments. This concept aims to progress the understanding of runoff response from how it occurs towards the more hydrologically meaningful impacts of how much of the water that enters a catchment connects to the channel and for what duration. This concept has been identified as having a great deal of potential for solving issues surrounding heterogeneity when estimating runoff response (Bracken and Croke, 2007). Subsequently there has been a development in ways in which hydrological connectivity can be predicted both through topography (Network Index, Lane et al., 2004) and soil moisture (Western et al., 2001), however there is some debate about the most effective methods that should be used. This thesis attempts to address this debate by assessing different approaches to estimate hydrological connectivity with the aim of clarifying the most promising solutions to this problem.

The overall aim of this project is "**to test and refine existing methods of estimating hydrological connectivity through a combined soil moisture and topography metric**".

To address this aim 4 key objectives were identified:

1. Identify a set of static (topography) and dynamic (soil moisture and antecedent conditions) connectivity measures.

2. Measure topography and seasonal variability in shallow soil moisture, rainfall and stage at high resolution to give detailed data for connectivity metric assessment for a humid temperate environment in the UK.

3. Test distinctions found in the literature between temperate forested and temperate rangeland catchments in terms of soil moisture, topography and combined soil moisture topography metrics.

4. Identify the critical distribution percentile and absolute soil moisture percentage thresholds for connectivity through significance calculation of connectivity metrics.

5. To develop a revised cumulative probability alternative to the Network Index.

This thesis will address the literature on connectivity to identify the best performing connectivity metrics. The methodology behind how these are estimated will be followed while identifying a test site in the Eden Valley, Cumbria, UK. The subsequent field measurement will provide a detailed data set that can then be used as a base to compare the metrics both in terms of soil moisture distribution and topographically derived flow pathways. The robustness of these metrics will be tested against a series of meteorological, hydrological and temporal data series to ascertain the metrics that best represent all three parameters with the aim to provide clarity to the current research into connectivity prediction and estimation. The literature review will also discuss factors affecting hydrological connectivity and how the concept has been developed. The next chapter will include a comprehensive description of the study site that was selected. The methods of the metrics selected for this study will follow identifying the ways in which the field data was collected and analysed. The results are then described, presenting topographic, rainfall and stage data for the catchment before the connectivity metrics analysis is then presented. Finally these results are discussed and conclusions are draw about the most effective metric performances.

2.0 Literature Review

2.1 Connectivity – Concept and Definition

Connectivity has become an increasingly important tool for hydrology in recent years (Bracken and Croke, 2007). Given a general definition of "the transfer of water from one part of the landscape to another, and the related physical movement of matter through the catchment" (Lexartza-Artza and Wainwright, 2009) connectivity has been identified as a key concept in understanding hydrological systems. Connectivity is important regarding the conveyance of water and sediment spatially and temporally within a catchment (Ward et al., 2002). This influences ecology in terms of leeching and nutrient transfer particularly relating to agriculture (Frey et al., 2009) as well as hydrological (Western et al., 2001; 2004) and geomorphological development (Brierley et al., 2006). The impact of the landscape on connectivity also heavily influences hydrological and sedimentological flowpaths (Michaelides and Wainwright, 2002) which dictates the impact of anthropomorphic and natural changes to the system (Harvey, 2007). Subsequently this highlights the potential benefits this approach can have in analysing more effectively outputs from complex systems within a catchment (Lexartza-Artza and Wainwright, 2009).

This conceptualisation of the hydrological system is a significant contrast to traditional views of Hortonian runoff (Horton, 1933) and the Variable Source Area (VSA) model (Hewlett and Hibbert, 1967) that focus on spatially and temporally specific sites with limited transferability. Previous studies into runoff generation at small scales, notably Morgan (1995) and Cammeraat and Imeson (1999), identified spatial and temporal patterns between areas of varying soil moisture and vegetation. However these studies were based on small scale study plots (for example 2.5 m^2 plots were used by Cammeraat and Imeson (1999)). Previous hydrological research has focused on process interaction with particular importance being placed on physical drivers rather than the broader responses of different landscape units and rainstorm conditions. By contrast the focus of connectivity moves from individual process dynamics towards generating spatial mapping of output conditions based on structural and functional aspects at a broader scale. Thus connectivity represents a shift in approach from a study of heterogeneity towards an understanding of similarity based on patterns identified in space and time. This is perceived as an important step forwards by many hydrologists (McDonnell et al., 2007; Sivapalan 2005) particularly with reference to ungauged catchments.

The concept of connectivity was initially developed in ecology and was used as a key feature in understanding the structure of distribution for population movement (Metzger and Decamps, 1997). In this way early definitions of hydrological connectivity such as "water-mediated transfer of matter, energy, and/or organisms within or between elements of the hydrologic cycle" (Pringle, 2001) were specifically tied to elements of ecological importance. However parts of this definition are also important to hydrological understanding particularly with reference to matter. The identification of water as a medium of transport through a system and the key notion of its complete connection being important for conveyance, albeit of ecological material, has clear benefits.

Currently there is a lot of debate about the exact definition of hydrological connectivity (Bracken and Croke, 2007). Since being taken up by hydrologist a definitive definition of the concept has proved to be elusive. This problem has been widely discussed with little progress being made (Brierley et al., 2006; Bracken and Croke, 2007; Ali and Roy, 2009; Lexartza-Artza and Wainwright, 2009). Lexartza-Artza and Wainwright (2009) identified a general definition of connectivity being "the transfer of water from one part of the landscape to another, and the related physical movement of matter through the catchment" more specifically "the ease with which water can move across the landscape in different ways and in so doing be affected by and affecting different landscape components." Bracken and Croke (2007) in their review incorporated the importance of time and spatial position in the definition of connectivity suggesting that it "describes all the former and subsequent positions, and times, associated with the movement of water or sediment passing through a point in the landscape". Bracken and Croke (2007) also developed the connectivity framework to include static (redefined as structural by Turnbull et al., 2008) and dynamic (functional) aspects. This highlights the two features that dictate hydrological connectivity, that of the physical landscape (structural - topography, land use and geology) and temporal conditions (functional - antecedent conditions and rainfall inputs). They emphasise that it is the spatial and temporal combination of these two aspects that are key for hydrological understanding. However these definitions are by no means definitive.

Ali and Roy (2009) reviewed a number of hydrological connectivity papers in an attempt to clarify the definition of hydrological connectivity. They identified that definitions of hydrological connectivity were specific to the predominant scale under investigation and subsequently the main functional and structural processes at work. Definitions ranged from water cycle scale generalised conceptualisations of the sort introduced by Pringle (2001), structural landscape feature definitions like that of Bracken and Croke (2007) and functional process definitions from Creed and Band (1998) (Table 2.1). Ali and Roy (2009) highlight that this multiplicity of definition provides focus and versatility, something that a unified definition would not achieve. Instead of one overarching standard definition of similarity each definition highlights the important processes to be identified at each specific scale. It is clear from previous attempts at defining hydrological connectivity that only vague indefinite statements can be made to represent the whole spectrum of study. Ali and Roy (2009) emphasise that important drivers change according to scale. For instance Ziegler et al. (2001) highlight the importance of micro topography at the plot scale. Soil moisture and soil structure are also key to hydrological connectivity at this scale (Sole-Benet et al., 1997). By contrast at the hillslope scale vegetation and slope length become more important (Wainwright and Parsons, 2002). Clearly scale plays an important role in defining hydrological connectivity because of the varying range of factors that affect it.

Water cycle	[. . .] An ecological context to refer to water mediated transfer of matter, energy and/or organisms within or between elements of the hydrologic cycle (Pringle 2003)	Watershed scale
Landscape features (STRUCTURAL)	All the former and subsequent positions, and times, associated with the movement of water or sediment passing through a point in the landscape (Bracken and Croke 2007)	Watershed scale
	Flows of matter and energy (water, nutrients, sediments, heat, etc.) between different landscape components (Tetzlaff et al. 2007)	Watershed scale
	The extent to which water and matter that move across the catchments can be stored within or exported out of the catchment (Lane et al. 2004)	Watershed scale
	The physical coupling between discrete units of the landscape, notably, upland and riparian zones, and its implication for runoff generation and chemical transport (Stieglitz et al. 2003)	Hillslope scale
	The internal linkages between runoff and sediment generation in upper parts of catchments and the receiving waters [. . .] two types of connectivity: direct connectivity via new channels or gullies, and diffuse connectivity as surface runoff reaches the stream network via overland flow pathways (Croke et al. 2005)	Hillslope scale
Spatial patterns (STRUCTURAL)	Hydrologically relevant spatial patterns of properties (e.g. high permeability) or state variables (e.g. soil moisture) that facilitate flow and transport in a hydrologic system (e.g. an aquifer or watershed) (Western et al. 2001)	Watershed and Hillslope scale
	Spatially connected features which concentrate flow and reduce travel times (Knudby and Carrera,2005)	Watershed and Hillslope scale
Flow processes (FUNCTIONAL)	The condition by which disparate regions on a hillslope are linked via lateral subsurface water flow (Hornberger et al. 1994; Creed and Band 1998)	Hillslope scale
	Connection, via the subsurface flow system, between the riparian (near-stream) zone and the upland zone (also known as hillslope) occurs when the water table at the upland-riparian zone interface is above the confining layer (Vidon and Hill 2004; Ocampo et al. 2006)	Hillslope scale

Table 2.1: Table of hydrological connectivity definitions taken from Ali and Roy (2009).

However with such fluidity in definition the conceptualisation of hydrological connectivity becomes difficult. It is necessary therefore to diversify the concept in line with this variation in definition whist at the same time maintaining an overall conceptual framing of the whole. The primary delineation that has been made within hydrological connectivity is the distinction between structural and functional connectivity (Turnbull et al., 2008). This distinction was originally made by Bracken and Croke (2007) to begin to distinguish the connectivity concept. They define structural (static in their paper) as "spatial patterns, such as hydrological runoff units, that can be categorised, classified and estimated" (Bracken and Croke, 2007). This element is the easiest to measure and quantify and as a result and been increasingly formed the focus of research. Topography, soil moisture distribution (as a result of variable infiltration capacity), geology and vegetation impact on the potential for runoff response. Lexartza-Artza and Wainwright (2009) highlight that examples of studies that focus on this combination of physical characteristics (e.g. Kirkby et al, 2002) provide a good description of structural connectivity without addressing elements of functional connectivity. Bracken and Croke (2007) also recognise this using an example of Bracken's own work in SE Spain (Bull et al., 2003). They highlight that predicted hydrologically similar areas of high runoff potential estimated from topography, land use and geology might indicate areas of likely runoff but do not identify which will connect with the channel and at what threshold this will occur. Indeed two regions were identified (Figure 2.1) in this study that despite high potential for runoff were disconnected from the channel. The first area (A) was disconnected because the amount of runoff was not sufficient to supersede the volume of the channel. The second area (B) was disconnected by an anthropogenic drainage channel separating the drainage area from the channel network. Bracken and Croke (2007) emphasise that these areas could connect in the right rainfall conditions and that this signifies the importance of considering functional connectivity. Despite further studies attempting to identify these hydrologically similar surfaces (HYSS) in an attempt to begin to understand thresholds present in the landscape between these areas and the channel (Kirkby et al., 2002) the importance of rainfall cannot be ignored. However detailed assessment of hydrological runoff areas, particularly in terms of identifying structural disconnection through topography, geology, pedology or land use can help to understand the potential for connection. Several studies have shown the importance of location when estimating the contribution of these active areas in relation to each other and the catchment channels (Fitzjohn et al., 1998). In the absence of physical connection only areas adjacent to the channel will contribute (Yair, 1992).

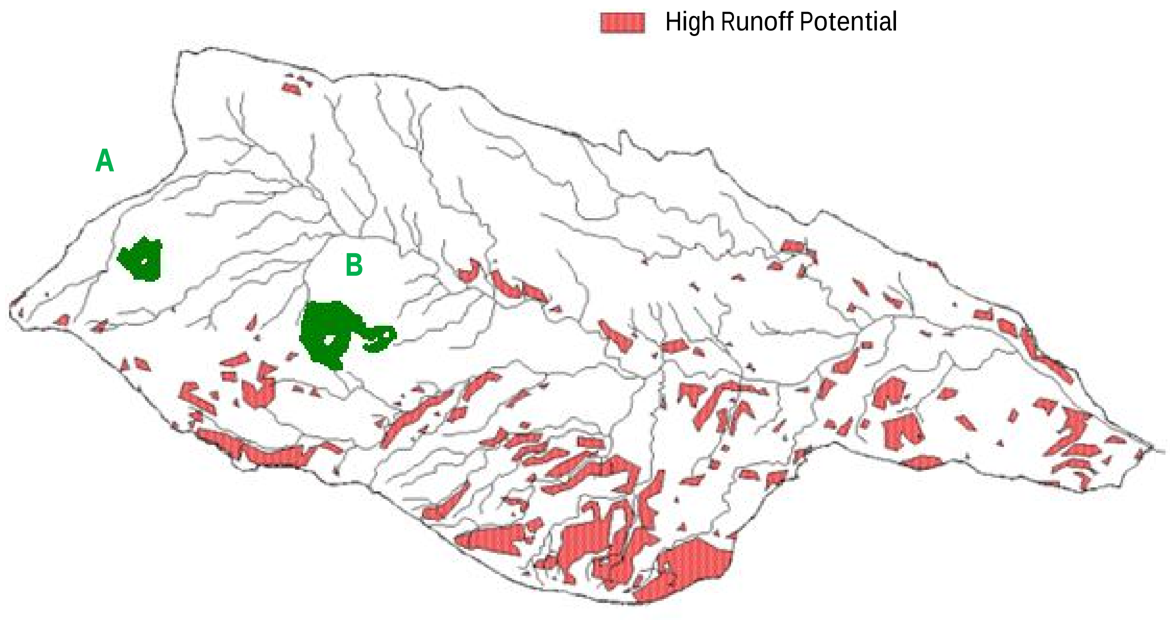


Figure 2.1: Red areas represent high runoff potential for the Rambla Nogalte in SE Spain as predicted using the principle of hydrologically similar surfaces determined by topography, land use and geology. The catchment area is 171 km^2 and the main channel is 33 km long. Green areas represent locations that had high runoff potential but remained disconnected. A indicates a region disconnected by a long drainage distance. B represents an area disconnected by an anthropogenic drainage channel. Adapted from: Bull et al. (2003).

Functional connectivity is, defined by short term variations in rainfall intensity and duration as well as rainfall event frequency. Functional connectivity is very important in understanding when and for how long areas of the landscape are hydrologically connected. Due to the threshold nature of hydrological connectivity where there is limited catchment reaction before the point of connection the understanding of the extent to which antecedent and rainfall conditions are causing structural properties to approach connection is of great importance (Ambroise, 2004). Initial studies recognised that the magnitude of antecedent conditions are important, particularly referring to soil moisture (Leibowitz and Vining 2003). However the frequency, duration, timing and rate of change have also been identified as important for establishing, maintaining and disrupting hydrological connectivity (Ali and Roy 2009; Bracken and Croke 2007). Ali and Roy (2009) argue that the threshold concept is unhelpful in terms of understanding these interactions and instead suggest that spatial linkages should be thought of as probability distributions in time and space. In this way functional connectivity can be assimilated more easily with a physical modelling frame work whilst at the same time it has been shown in wetland environments to be a useful tool in the field. Leibowitz and Vining (2003) found that by using probability, through measuring recurrence intervals of different levels of connectivity, a continuum of hydrological states could be established. It is the combination between these conditions that are important in order to ascertain the extent and persistence of hydrological connectivity. Thus Ambroise (2004) suggests that areas of hydrologic similarity that have the potential for runoff should be termed active areas rather than contributing areas. In addition he highlights the importance of active time periods where conditions are appropriate for connectivity to the channel, the extent of which are dependent on the degree to which active areas are connected. The impact of this can be seen in the "tiger bush" example in Niger where alternate bands of impermeable bare soils and permeable forest soil exist (Thiéry et al., 1995). Here, despite more than half the area being active almost none of the runoff reached the outlet. The water that flowed across the impermeable bands was absorbed by the permeable forested areas. Here is evidence that a combination of physical catchment structure has to be combined with temporal weather changes to fully understand the degree of connectivity and consequently the response of the catchment.

2.2 The Significance of Scale

The nesting of scales is another significant problem for connectivity as well as much of hydrological study (Soulsby et al., 2006). Early examples of runoff estimation were contained by plot measurement (e.g. Poesen et al., 1990) that revealed a great deal about the processes of soil rainfall interaction with elements like microtopography (Ludwig et al., 1995) and the impact of vegetation (Lyford and Qashu, 1969). Yet the results of such small scale detailed plot studies of hydrological response do not scale well to hillslope and catchment scales (Van Giesen et al., 2000). The increased distance of interaction between surface runoff and the soil causes an attenuation of surface flow. This is due to the increased variability in spatial infiltration rates and rainfall distribution, as well as through the soil structure and surface over distance, influenced by topography, geology and meteorology (Lal, 1997; Wainwright and Parsons, 2002). The resulting heterogeneity makes scaling from small field sites difficult.

The solution has been to attempt to estimate the hillslope as a whole hydrological unit through field measurement and hydrological modelling. The main field measurement of physical hillslope hydrological connectivity is the volume to breakthrough. This has largely been used in the estimation of the connection time and volume of runoff from compacted trackways (Croke et al., 1999; 2001; 2002; Hairsine et al., 2002). By measuring the amount of water required for hillslope connection, through applying an accumulating volume to a test slope, under different temporal and functional conditions a stochastic understanding of hydrological connectivity can be achieved. By doing this experiment on a range of hillslopes with different structural properties that represent the catchment an understanding of the whole catchment response can be estimated (Croke et al., 1999a). Although this method is the most effective approach for estimating connectivity it is not without fault. Bracken and Croke (2007) identified that this method does not identify specific hillslope conditions for each breakthrough experiment. This means that although volume to breakthrough can identify the volume required for connectivity of the slope it cannot define its continuity over time or the manner of its disconnection (Bracken and Croke, 2007).

Cameraat (2002) produced one of the first studies identifying connectivity as a sequence of developing patches on a semiarid hillslope that become activated with time presuming a sufficient duration of rainfall at a sufficient intensity. He found that smaller scale plot experiments produced more numerous runoff events than at the hillslope or catchment scale. This impact of flow length has been identified by others showing that connectivity flowpaths also exist at a range of scales depending on very different determining factors. Flow pathways range from subfield features having been identified as a result of different soils, land uses and topographies (Bull et al., 2000; Lane et al. 2009), to hillslope scale variability resulting from the surface water generation and routing of compacted earth tracks (Hairsine et al. 2002). However at the larger catchment scales, where hydrological modelling and estimation is most important in terms of stakeholder involvement and applied significance, these small scale influences are lost often due to a lack of spatial resolution and a lack of detailed investigation. As a result the potential for scaling hydrologically significant flowpaths like trackways are lost.

2.3 Factors impacting hydrological connectivity

A number of elements influence hydrological connectivity. The primary control, as with the majority of other hydrological processes, is climate. The runoff regime is dependent on this. Semiarid environments are driven by high intensity rainfall, generating Hortonian infiltration excess runoff. This means that hydrological connectivity in these regions is largely driven by topography with limits on connectivity being the flow length and the volume to breakthrough. In humid temperate regions long periods of low intensity rainfall are more common resulting in seasonal depletion and recharging of soil water storage. Where heavy rain interacts with pre-existing rainfall saturation, infiltration excess runoff is combined with saturation runoff. It is these events that often prove to be the most reactive conditions in these environments (Vivoni, 2007). The duration of rainfall is relevant both in terms of the length of distinct rainfall events as well as the extent of seasonal precipitation. Both influence the process of soil saturation. These processes are significant in defining conditions for patch scale saturation and subsequent hydrological connection (Guo and Quader, 2009). The pattern in humid temperate regions is more complicated than semiarid environments with a constantly evolving boundary of “active areas” of high soil moisture (Ambroise, 2004).

This is enhanced by constituent features of rainfall intensity, such as increased raindrop size, which reduces the soils capacity to infiltrate, resulting in a greater runoff response (Morin and Benyamini, 1977) and connective potential. The drop size is a driving factor behind soil surface morphology, as it promotes the filling of pore spaces and increases surface compaction (Tackett and Pearson, 1965). Indeed Lang and Mallet (1984) found that the surface runoff of 50% vegetation cover was 54% lower than bare ground, due to the reduced soil surface sealing. This is of primary importance in semiarid areas where vegetation is patchy. Where vegetation exists the potential for connection and runoff is reduced through increased infiltration potential under vegetation (Lyford and Qashu, 1969) and the reduction of impact of rainfall intensity. Other fundamental influencing factors are the characteristics of the soil and the slope. The extent of vegetation in humid temperate environments mean that rainfall intensity has a lower impact with the intensity being more relevant in terms of the net volume over time by comparison to the raindrop size. These climatic drivers are key elements of functional connectivity.

Soil characteristics affect the volume of water that can be infiltrated and define the rate at which this can occur. This consequently defines land-use practices, which then further augments this causal condition. The effect of particle size can be significant, especially for the soils dominated by silts or clays. These soil types have a cohesively bonded structure which result in a much lower infiltration capacity compared to non-cohesive sandy soils. Also, due to the extremely small particle size the pore spaces are negligible, meaning that there is almost no volume for infiltration. Indeed soils with high clay and silt contents are often totally impermeable negating any subsoil and bedrock infiltration capacity (Sharpley, 1985). This results in an increased capacity for hydrological connectivity across the surface. Sandy soils are highly permeable, making them very difficult to saturate or exceed their infiltration rate. These soils promote vertical water flux which in turn promotes subsurface soil flow along impermeable soil layers or along bedrock (Tromp Van Meerveld and McDonnell, 2005). However, there is high variability in the composition of a soil surface even in small catchments (Jury, 1986). This, combined with bedrock permeability, engenders a complex system that makes predicting the soil response to rainfall a big challenge. The permeability of the bedrock is an important underlying factor particularly with respect to upland catchments with shallow soils. Impermeable rock provides a surface for throughflow which often results in return flow at the base of slopes, where the soil becomes saturated due to the high through flow rate (Scherrer and Naef, 2003). Porous bedrock promotes deep percolation into ground water, thereby increasing the draw down of water and reducing lateral water flux (Pearce et al., 1986). As a result areas with permeable aquifers are a lot less likely to develop hydrological connectivity, as the water table falls after rainfall events at a quicker rate. This means that a lower volume of runoff is produced from them when rainfall events occur frequently. Rock permeability is most significant when the soil is thin as the rock can then readily interact with the water at the soil surface (Bertoldi et al., 2004).The thickness of the soil itself is also clearly important as a thin soil layer will allow less infiltration than a thick soil (Bertoldi et al., 2004). However this depends on the soil permeability both spatially and stratigraphically. This is often related to climatic and ecological conditions that combine to determine the potential for vegetation and as a result the extent of organic material available. Thin soils are common in semi-arid areas where vegetation is sparse. This increases the spatial potential for connectivity with the rate of infiltration becoming the key factor in potential for connection. High organic content, which is common to humid and temperate regions, greatly increases the capacity for the surface to infiltrate, which means that the potential for surface runoff is reduced. Vegetation protects the soil from solar and heat generated surface features (like soil crusting) as well as intercepting some of the rainfall and providing a source for soil development. This means that the soil does not need to infiltrate as much water as would be the case in a barren environment. Lyford and Qashu (1969) found that infiltration rates beneath bushes were three times that found in open ground. The spectrum of vegetation can augment the complex organisation of soil characteristics and climate to create areas of high vegetation density to form water sinks limiting connectivity.

Slope characteristics are important for a number of reasons. Gradient is the principal feature regarding the potential for runoff and as a driver for structural connectivity. A higher slope gradient decreases the infiltration rate of the soil as the water flows faster over the surface, which allows less time for the soil to absorb it (Liu and Singh, 2004). This means that saturation runoff is less likely to occur on steep slopes, as it would take longer for the soil to become saturated, but it increases the prospect of infiltration excess runoff. As a result especially in temperate catchments this interaction means that identifying which regime of flow that is occurring at what time is important for understanding the potential for predicting flow and its potential connectivity. This is the main feature regarding traditional methods of predicting soil moisture organisation like Topographic Wetness Index (TWI). The shape of the slope is also important. Areas on a slope with low connectivity and low gradient are more prone to saturation. So slopes with a concave profile or surface depressions are more likely to become active areas in the event of high precipitation than a slope with a straight profile (Talebi et al., 2008). The slope shape can have a great deal of an effect through increasing areas of saturation and disconnecting the slope (Bracken and Croke, 2007). The length of the slope has an important effect on connectivity. A number of field studies have shown that the runoff per unit area decreases as a function of slope length (Lal, 1997; Van de Giesen et al., 1996). This is important regarding infiltration excess runoff, because areas prone to saturation provide a threshold response. Infiltration excess runoff production is dependent on variable infiltration and surface storage (Van de Giesen et al., 2000). Van Giesen et al. (2000) found during their study in the Côte d'Ivoire that the influence of slope length on the total runoff during large storm events was as high as 78%. This highlights the importance of spatial variability and connectivity of antecedent soil conditions and hillslope characteristics, since precipitation falling on longer slopes interacts with the surface for a greater distance and period of time and therefore is more prone to local hillslope variability.

2.4 Measuring Hydrological Connectivity

There has been great deal of debate surrounding the potential for the use of soil moisture in aiding hydrological connectivity estimation. However there is no consensus as to how it should be used. Saturation excess has long been considered to be the main form of runoff in temperate climates and with the development of the variable source area concept soil moisture patterns were increasingly identified as an important variable in the estimation of runoff in a catchment. This, in conjunction with the increasing belief that spatial flow pathways are important in runoff prediction and that they are not always constantly connected, led to increasing measurement of soil moisture to estimate the degree of connectivity of a catchment. The first attempt at measuring soil moisture with a view to resolving hydrological connectivity was led by Western (Western and Blöschl 1998; Western et al., 2001; Western et al., 2004) in the temperate Tarrawarra catchment in southwestern Australia. They found that soil moisture patterns could be seen to change over time and that the spatial organisation of the soil moisture produced alternating patterns of connection and disconnection to the catchment outlet (Western et al., 2001). Through the use of topographically corrected semivariograms bounded by an integrated connectivity scale the varying degrees of connectivity could be identified.

However this approach has been challenged in recent years. The limited consideration for throughflow dynamics in the method of Western is the main cause for concern which was identified by Tromp van Meerveld and McDonnell (2005). Western's approach to estimating soil moisture was to take a soil moisture reading at a average depth of 30 cm. Tromp van Meerveld and McDonnell (2005) argued that soil moisture can be a passive reaction to connectivity, particularly regarding subsurface flow. They argued instead that it is, in fact, transient saturation at the soil - bed rock interface or at a layer of reduced permeability in a duplex soil that represents the causal mechanism for subsurface flow. This was identified through experimentation by Tromp van Meerveld and McDonnell (2006) in the subtropical Panola Test

Catchment in Georgia, USA. However despite the relevance of identifying the importance of subsurface impervious layers the shallow nature of the soil in this experiment lended itself as a credible alternative to Tarrawarra.

Studies in temperate forested catchments have also found fault with the Western conclusions. James and Roulet (2007), through a detailed shallow soil moisture survey (20 cm) and long term monitoring in forested temperate catchment of St. Hilaire in Quebec, identified a significant relationship between hydrological connectivity and hydrological response. However the use of shallow moisture measurement did not identify regime change in the catchment. Unlike Western, James and Roulet (2007) found that organised patterns of soil moisture persisted across regime thresholds suggesting that is was not an appropriate method of connectivity identification in forested catchments compared to the clear conclusions identified on rangeland by Western. St. Hilaire was also prone to shallow bed rock, seen by Tromp van Meerveld and McDonnell (2005) in their study area, and the rough surface microtopography identified in other studies (Ali and Roy, 2010) highlight the increased potential for subsurface throughflow. The high variability seen in the depth of soils above bedrock in combination with complex microtopography and intermittent frangipans resulted in a complex soil-rainfall interaction that is absent at Tarrawarra. It has been statistically identified that semivariograms do not distinguish between microtopographies (Antoine et al., 2009) which in addition to bed rock variability minimises their effectiveness. In addition the impact of the forest canopy reduces the range of soil moisture that limits the effectiveness of the Western method of connectivity estimation.

This debate has led to a number of review articles (Bracken and Croke 2007; Ali and Roy, 2009) but only two address different connectivity ‘metrics’ experimentally. Antoine et al. (2009) used statistical analysis on three computed microtopographic surfaces, without incorporating soil moisture. Ali and Roy (2010) completed a comprehensive review of a range of connectivity metrics at a range of soil moisture depths at Hermine in Quebec. This study made an attempt to review a range of connectivity metrics identified in the literature over the last ten years in conjunction with measurement of soil moisture at multiple depths to ascertain the influence of the confining layer (in this case soil rather than bed rock). Here they found limited variability in soil moisture by comparison to Western et al. (2001). However in contrast to Antoine et al. (2009) the most suitable metrics were the directional semivariograms, especially in response to meteorological and outflow discharge; the two key factors in determining catchment discharge. Ali and Roy (2010) conclude a similar response to James and Roulet finding that lateral throughflow is important for the Hermine catchment in wet conditions and echo their earlier review in highlighting the continuum of connectivity rather than the distinct threshold of Western et al. (2001). At the same time Ali and Roy (2010) identify distinctions between Hermine and the subtropical Panola catchment.

Analysis of previous published literature suggests that there is a clear divide between forested and rangeland catchments, where rangeland appears to display greater variability in soil moisture response through more consistent microtopography and reduced vegetation cover. There is also a great deal of debate as to whether directional semivariograms have the potential to distinguish between hydrological connection or not. The distinction here is not clear even between meteorologically similar forested catchments of Waldstein (Lischied et al., 1998) and Plastic Lake (Buttle and House, 1997). Also the use of an integrated connectivity scale as characterised by Western et al (2001) has shown a range of success between two similar catchments; proving to be useful in defining different connectivity regimes in St Hilaire yet falling short when tested at multiple depths in Hermine. Shallow surface moisture has been considered to be too shallow to be representative of the subsurface flow in the three catchment groups and is suggested by Ali and Roy (2010) not to show high significance. Ali and Roy (2010) identify a range of potential thresholds to test the significance of their range of tests. This is an approach that has not been attempted before in the other test catchments and represents a promising approach at identifying significance.

Modelling also struggles to adequately define hydrological connectivity. The earliest modelling attempts using the Soil Conservation Service Curve Number method (e.g., Beasley et al., 1980; Savard, 2000; Brocca et al., 2009) did not address connectivity itself instead estimating the continuity of runoff through statistical estimations of hillslope factor interaction. Simple weighted delivery approaches of water and sediment subsequently developed as a function of slope distance which led to the beginning of physical estimation of connectivity within modelling (Johnes and Heathwaite, 1997; Munafo et al., 2005). With the development of fully distributed, physically based models, physical formulaic relationships are solved for vertical and lateral water flows across the landscape (e.g. De Roo and Jetten, 1999). At these larger scales, detailed information about topography, soil characteristics, antecedent conditions and vegetation elements like density and type are lacking (McGuire et al., 2007) with some models using resolutions of as much as 1 km^2 (Adams et al., 1995) despite typical control structures for connectivity in the landscape being less than 0.0025 km^2 (Blackwell et al., 1999; Lane et al., 2009). This is further undermined by using physical models at greater spatial scales than they can adequately represent, given spatial difference at that resolution (Lane et al., 2009). The reasons for such coarse resolution are twofold. Firstly the demands of modelling for data at this resolution in order to calibrate them is such that often it is unavailable despite recent improvements in data collection (Heathwaite, 2003). Even if they are available the volume of information makes modelling these catchments accurately time consuming and difficult to verify. Indeed it is clear that with the evidence of the importance of subscale connectivity features and the high temporal variance it represents is very difficult to achieve (Lane et al., 2009). There is potential for improvement particularly through airbourne laser altimetry which has been identified as sufficient for hydrological analysis (Milledge et al., 2009) however this is specific to topographically driven systems. Lane et al. (2009) highlight the need to recognise that the amount of physical simplification that is necessary should be in line with the data available and the aims of the model results.

Lane et al. (2004; 2009) propose that hydrological modelling has a role in hydrological connectivity. Lane et al. (2009) argue that modelling can be used to represent temporal variation and structural connectivity presuming the limits of modelling is recognised and understood. The strength of modelling is through topographic estimation as this is the easiest parameter to be measured at high resolution. For catchments that are defined by shallow soils and impermeable bed rock, which can be characterised by topography, modelling is an invaluable tool. Lane et al. (2004) have developed upon the Topographic Wetness Index (TWI) in order to better characterise connectivity. TWI is a function of contributing area and slope creating a cumulative index deriving a topographically based method of estimating areas of high soil moisture (Beven and Kirkby, 1979). Lane et al. (2004) have simplified TWI in order to ascertain the threshold for connectivity. The Network Index identifies the lowest value for the flow paths across the catchment using the theory that the lowest value determines the potential for connectivity. This representation of the likelihood of physical connection indicates not only a probability of structural connection but also the probability that flowpaths with lower potential to connect are likely to be less frequent and for a shorter period of time (Lane et al., 2009). This has been suggested as a tool for land management that involves changes in the distribution and development of saturated zones and their connection to the drainage network, however this is limited to land areas where subsurface flow is not present (Lane et al., 2009). The Network Index has already begun to be incorporated into modelling as part of the Sensitive Catchment Integrated Modelling and Analysis Platform (SCIMAP) which aims specifically to represent hydrological connectivity as part of hydrological modelling in order to improve management of flood sources, water quality and sediment transport problems (Lane et al., 2003).

In addition to this other innovative methods are being developed in order to better understand how water flows across a catchment and how it is represented in models. Reaney (2009) developed a hydroAgent feature to the Connectivity of Runoff Model (CRUM) that attempts to map the flow pathways of individual water agents across the catchment reacting to the conditions of the physical, distributed hydrological model. This has been applied to a semiarid catchment in

SE Spain and proved effective not only in estimating surface flow pathways but also the extent of their connection over the duration of a storm event. It is developments like this in modelling that can progress the catchment scale estimation of both structural and functional hydrological connectivity.

Ali and Roy (2009) have identified a series of issues that the combination of scale and definition diversity creates in relation to measuring hydrological connectivity. Initially the challenges to topographically derived connectivity appear to be relatively limited. The use of surface topography has been a corner stone of estimating flow pathways in hydrological modelling as well as identifying active areas (Harvey, 2001). It has been identified that slope length is an important factor in connectivity (Aryal et al., 2003) with longer slopes increasing the potential for reinfiltration of surface runoff, thus reducing the chances of hydrological connection (Lane et al., 2003). However there has been increasing evidence that suggests that subsurface flow connectivity is better represented by bedrock or impermeable soil subsurface topography and subsurface soil permeability variability (Tromp Van Meerveld and McDonnell, 2006). Tromp Van Meerveld and McDonnell (2006) have suggested, particularly in humid temperate environments, that surface topography is not sufficient to represent the subsurface interaction. Figure 2.2 shows the potential disparity that can occur highlighting the considerable subsurface variability in contrast to surface topography. This variability can result in subsurface flow that is derived more from impervious soil horizons and bedrock topography resulting from transient water table, than from the surface topography (Stieglitz et al., 2003). This highlights the need to consider the depth of soil permeance and subsurface topography (Ali and Roy, 2009). There is potential to do this both in the field and through remote sensing. Ground penetrating radar has proven to be good at identifying bedrock depths and impermeable soil horizons (Galagedara et al., 2005). This is, however, somewhat time-consuming and the data is difficult to process. There are also suggestions that remote sensing can be developed to assess this, however this has not been adequate tested (Robinson et al., 2009).

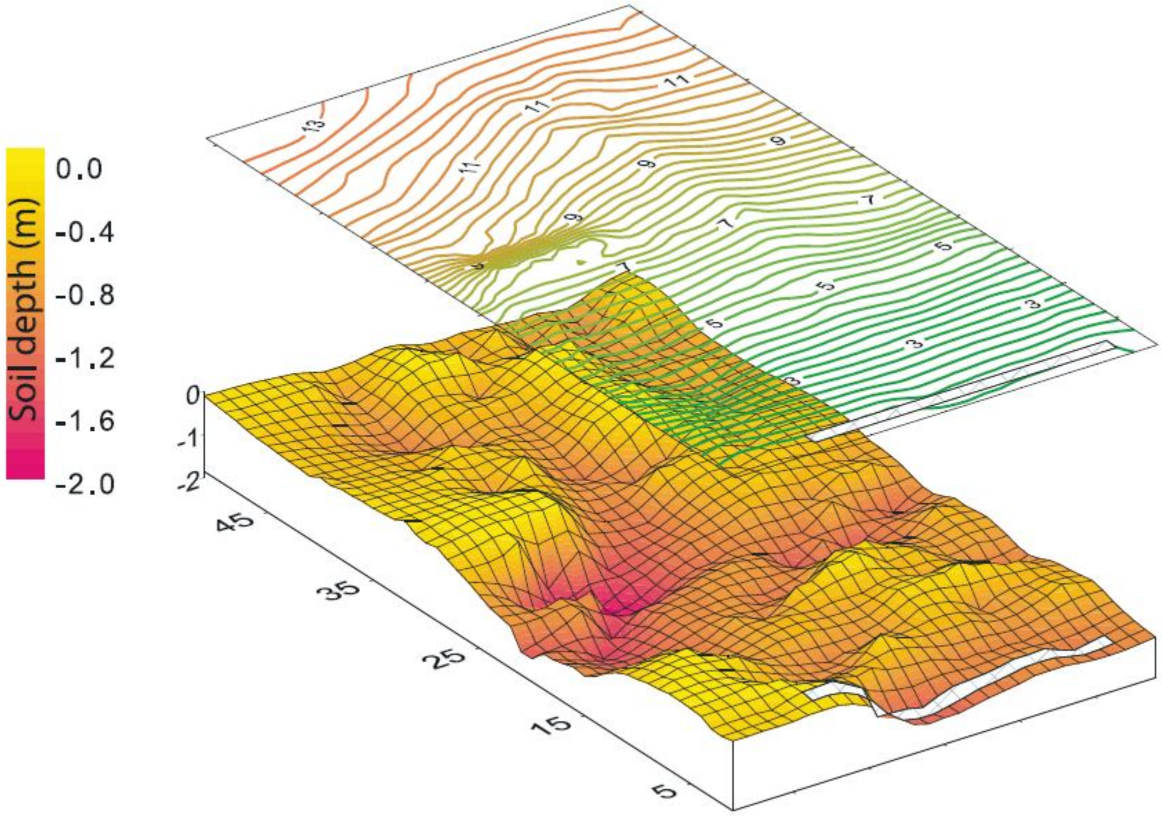


Figure 2.2: Example of the disparity between the surface and subsurface topography taken from Tromp Van Meerveld and McDonnell (2006). All values are measured in meters..

The measurement of dynamic connectivity is difficult. The best representation of the change that antecedent conditions manifest on the catchment is through the direct measurement of catchment discharge itself or through a measurement of soil moisture (Fitzjohn et al., 1998). The primary issue of measuring catchment flow is that it is only possible at the patch and hillslope scale. Beyond this, the inclusion of channels diffuses the representation of hydrological flow. The limitation of dynamic flow measurement to smaller scales is due to the manner in which flow is measured. The study of subsurface storm flow is measured using trench excavations of a maximum length of 60 m (Woods and Rowe, 1996). Although this method can give detailed information of various subsurface flow pathways, it is site specific with little potential for scaling up to catchment scales short of identifying important parameters for flow inception. This is particularly relevant to soil specificities which are often considerably spatially variable and as a result do not scale very well whilst also not being easily measured. Ali and Roy (2009; p. 375) state "…This technique cannot be deployed on the whole catchment area to fully capture the processes that trigger subsurface stormflow and their scaling properties…". This has been the principal method of subsurface storm flow measurement for a number of years. There is a prospective development in measuring the presence of active subsurface storm flow paths using geochemical signatures of stream and soil water (Weiler et al., 2005). Locating this form of measurement has to be carefully considered. However this method shows a combined measurement of a number of sources without differentiating subsurface flow parameters and as a result provides limited flow information.

An alternative method for this is the use of natural and artificial tracers, which can give detailed information about flow pathways and transit times (McGuire and McDonnell, 2006). There has been speculation that diatoms could be used as a biological tracer for hydrological connectivity (Pfister, 2009). Different diatom species in a stream discharge water sample can indicate areas of the landscape that have become connected (Van Dam et al., 1994). This idea is still in its infancy with limited results to prove its efficacy raising some question marks over how much spatially specific information this method can achieve and how it reacts to seasonal variation (Tetzlaff et al., 2010). The use of tracers can provide new insights into systems and chart connectivity flow pathways. For example Burns et al. (2005) used oxygen isotope analysis to assess the influence of urbanisation on baseflow pathways and residence times. These give information about the length of time water is in transit for. They found that the results of the three sites with varying levels of urbanisation, fit the same model curve. As a result urbanisation appeared to have no effect on the baseflow, which led them to conclude "lack of measurable differences in the mean residence time of water among these three catchments suggests that human alteration of the landscape studied here is not great enough to significantly affect this variable." (Burns et al., 2005). It is in this way that tracers are useful because residence times are an important part of estimating connectivity of different areas of a catchment that are difficult to measure. However identifying spatial specificity is still a major challenge especially at the catchment scale.

Soil moisture represents the main alternative to terrain based connectivity estimation. The disparity between connectivity measurement in semi arid catchments and temperate catchments is significant here. In semiarid catchments factors of key importance are rainfall intensity and duration, especially given the low level of vegetation and the frequent presence of soil crusting. The main source of water movement in these catchments is through Hortonian surface runoff. As a result surface features like soil and rock permeability are the primary factors identifying areas of higher or lower infiltration (Lexartza-Artza and Wainwright, 2009). The primacy of surface runoff in these conditions mean that surface topography is an important driver. In temperate climates there is a further complication. The presence of throughflow particularly in deep permeable soil horizons is the major connectivity route in these catchments (Anderson and Burt, 1990). Subsequently the antecedent conditions become of significant importance as the point to which the soil is wetted up will have a crucial bearing on the extent to which the catchment is connected (Stieglitz et al., 2003). As a result of a series of structural factors a mosaic of soil moisture forms that is constantly changing with meteorological drivers (McNab, 1991). The combination of high rainfall intensity (where the majority of storm runoff and spatial connectivity occur) and the interaction with this soil moisture mosaic can impact greatly on the areas of the catchment that connect and those that remain disconnected. There have been a number of attempts made to estimate areas where higher moisture regions are likely to occur and what extent of saturation is required to result in their connection (Burke, 2009). The difficulty with this is that a great deal of data is required in order to adequately estimate these factors particularly with regards to estimating the probability of connection based on a complex combination of physical factors and antecedent conditions that result in a continuously shifting pattern (Fitzjohn et al., 1998).

Western et al. (1998) theorised that the pattern of soil moisture could be used to identify active areas and that through monitoring, the spatial wetting up and drying out of the catchment could be observed complete with high saturation flow pathways. It has previously been recognised that the incorporation of hydrological connectivity into antecedent moisture mosaics can have a significant effect on runoff simulation even when the continuity of the moisture pattern is constant (Bronstert and Bardossy, 1999; Grayson et al., 1995). This has also been seen to be important in subsurface through flow, where areas of high hydraulic potential produce preferential flow paths (Sánchez-Vila et al, 1996). Western et al (2004) assert that soil moisture measurement represents topographically driven subsurface flow. This method presumes a high level of saturation to enact flow (throughflow or surface runoff) which makes it an inappropriate method for semiarid catchments dominated by Hortonian infiltration excess runoff. Western et al. (1998) through a spatial survey of soil moisture at a depth of 15cm on a hillslope in the Tarrawarra catchment, found a distinct organisation of soil moisture. In seasonal wet months soil moisture showed organised spatial patterns of saturation. This systematically broke down with reduced rainfall and increased evapotranspiration towards a pattern or random moisture distribution (Figure 2.3). Western et al. (1998) hypothesised that instead of attempting to measure water flow across and through the soil that the soil moisture acts as a signal for that water movement and that that can be used to estimate the extent to which a catchment is connected. This represents a development of the preferential states hypothesis defined by Grayson (1997). This hypothesis states that there are two contrasting soil moisture states. The dry state has a disorganised pattern defined by local physical factors (e.g. soil, vegetation and slope). This is dominated by vertical percolation and infiltration processes. The wet state has an organised connected pattern dominated by larger scale hillslope factors like contributing area that generates lateral flow variation.

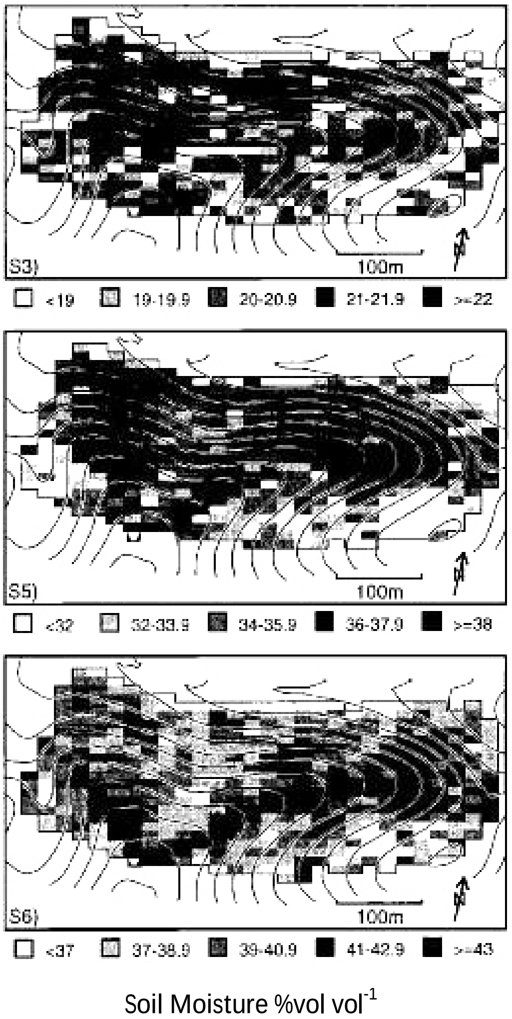


Figure 2.3: Diagrams of the development of mean soil moisture patterns (top 30 cm) showing the different degrees of connectivity between February and April 1996 at the Tarrawarra catchment. Contours show surface topography at 2 m intervals. Taken from Western et al. (2001).

This theory has been challenged by Tromp Van Meerveld and McDonnell (2005) who argue that a uniform estimation of soil moisture at any given depth does not adequately represent the subsurface flow processes. They argue that soil moisture "can be a passive signal between that of rainfall input and the subsurface stormflow output that drives streamflow response" (Tromp Van Meerveld and McDonnell, 2005). Soil moisture often co-varies with subsurface flow, however this is not necessarily a causal factor in subsurface flow or transient saturation (a factor Tromp Van Meerveld and McDonnell (2005) identify as the saturation measurement that accurately represents subsurface flow). Using the example of work undertaken at the Panola gauged catchment in Georgia, USA they make two important assertions. Firstly they show that at Panola the relationship between median soil moisture does not represent the areas of subsurface saturation which indicates lateral flow (Figure 2.4). Secondly that this disparity is important as many studies have found that transient saturation has been seen to have a strong relationship with subsurface flow in temperate environments (McGlynn et al. 2002). However Western et al. (2005) have argued that these assertions are not in conflict with the finding of their own research. They suggest that although it might be the case that transient saturation shows causation in Panola that this is not necessarily representative of catchments elsewhere with different soil conditions. The threshold nature of through flow with connection that has been seen by both Western et al., (2001) and Tromp Van Meerveld (2005) is suggested to be determined by the presence of saturation in the soil profile especially at the hillslope scale. The spatial pattern of soil moisture is an indicator of the connectivity, that Western et al. (2005) argue "is the cumulative result of the fluxes of water into and out of a volume of soil.".

Western et al. (2001)'s method has a number of exponents. Ali and Roy (2009) highlight that this method of data collection maximised the strengths of geostatistics particularly due to the density of soil moisture sample points. Doubts raised by Tromp Van Meerveld and McDonnell (2005) have also been ameliorated by subsequent studies by taking measurements throughout the soil continuum (Ali and Roy, 2010; James and Roulet, 2009). In this way further soil information is achieved subsequently identifying the critical depth at which analysis of continuity and cluster connection through geostatistics best represent hydrological connectivity.

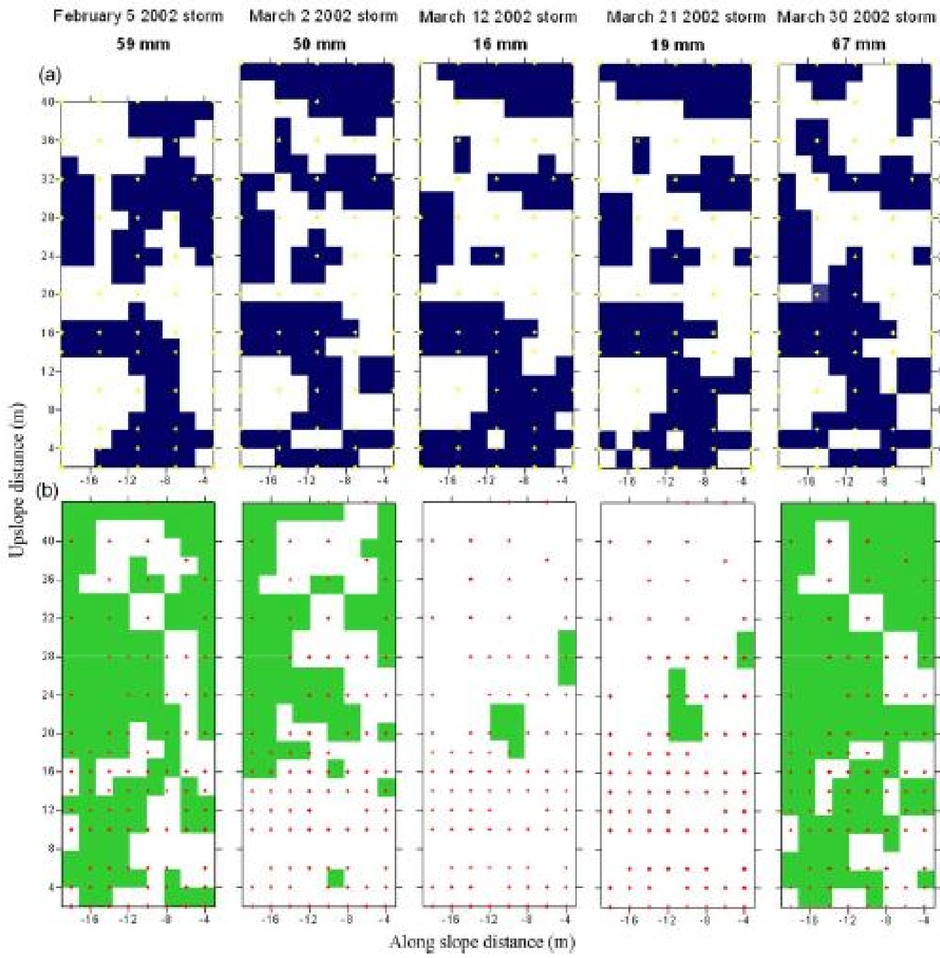


Figure 2.4: Map of the location of above median soil moisture (blue, a) and subsurface saturation (green, b) for 5 storms in 2002 at the Panola test catchment Georgia, USA, identifying the disparity between subsurface saturation and surface soil moisture. Yellow dots in (a) represent soil moisture measurement locations; red dots in (b) show the postions of maximum rise wells for water table detection. Taken from Tromp Van Meerveld and McDonnell (2005).

There are some question marks over the density of sampling that is required for this method to succeed at larger scales. Western and Grayson (1998) required 250 person days in the field to sample between 500 – 2000 points. Although there are a number of papers that have suggested that as few as 150 would adequately represent soil moisture in tests for geostatistical continuity (Webster and Oliver, 1992) such a small number would reduce the effectiveness of estimating connectivity. That said with the increased potential for remote sensing regarding soil moisture (Ulaby et al., 1996) this method could be used reliably in the future. The important element to recognise is the temporal persistence of this approach. Due to the field nature of this method and the intrinsic functional connectivity impact on soil moisture, the variability is strongly related to rainfall dynamics that structural connectivity estimation methods cannot easily predict. Thus the inclusion of soil moisture is important if such temporal factors are to be included in hydrological connectivity measurement.

2.5 Metrics and Their Use

The difficulty of estimating both structural and functional hydrological connectivity is very clear. There have been a number of field and modelling approaches with varying degrees of success. In addition to a series of structural modelling indexes soil moisture has emerged as a good parameter that can be used to represent the temporal variability of antecedent conditions and rainfall (Western et al., 1998; Western et al., 2001; James and Roulet, 2007). The problematic nature of measuring hydrological connectivity has led to an increase in statistical estimations rather than process driven modelled solutions. The use of geostatistics has increased to meet this statistical need (Grayson et al., 1997; Western et al., 1998b). This has led to a number of reviews of the use of geostatistics trying to ascertain which characterise catchment connectivity (James and Roulet, 2009; Ali and Roy, 2010). The focus of these metrics is predominantly on soil moisture and topography due to their relevance to structural and functional connectivity. From these studies a number of metrics have been identified as showing potential for connectivity estimation. Entropy has been considered as a potentially valuable metric (Knudby and Carrera, 2005; Antoine et al., 2009). Connectivity represents order in a catchment system, which means that entropy, which measures disorder, should be increasingly negative with an increase in connectivity. However Antoine et al. (2009) found that entropy was incapable of distinguishing microtopographical order at the patch scale. Further tests at catchment scale using soil moisture also found that entropy was a poor indicator for estimating the extent of connection (Ali and Roy, 2010).

Another metric that has been used extensively is the semivariogram which has been used to assess continuity of soil moisture pattern, with and without topographic bias (Western et al., 1998b). Semivariograms describe the variance between two points as a function of the distance between them (Cressie, 1993). In effect the range of a semivariogram indicates the maximum distance that spatial correlation affects the soil moisture distribution. The incorporation of topography makes this method a useful initial statistical method of estimation in order to ascertain the relationship between soil moisture and topography. Despite studies finding that this assessment of continuity correlates well with soil moisture change and resultant hydrograph variability it has been noted that semivariograms do not accurately represent connectivity itself (Western et al., 1998b). Thus although they prove useful to distinguish different soil moisture conditions it has not been ascertained how this continuity relates to connectivity.

Subsequently connectivity statistics have seen the most rigorous assessment. These estimate the probability of wet locations being connected by either arbitrary or topographically derived continuous pathways to other wet areas (Allard, 1994). Western et al. (2001) developed the integral connectivity scale, which estimated the average distance over which patches of high soil moisture are connected together. This scale can be calculated omnidirectionally and through topography to restrict these connections between high moisture locations to slope orientation (Western et al., 2001). There is some contention as to the efficacy of integrated connectivity length. Western et al. (2004) found that it identified the difference between connected and disconnected catchment conditions. By contrast James and Roulet (2007) used the same metric on a temperate, forested catchment in Quebec but found it to be inconclusive. This might be explained by the forested nature of the Mont St. Hilaire catchment by contrast to the rangeland condition of Western et al. (2004) Tarrawarra catchment. However another extensive comparison of connectivity metrics by Ali and Roy (2010) found that in a similar temperate, forested catchment at Hermine in Quebec, it was not only effective in describing the temporal and spatial variation of soil moisture but proved to be better than other comparative metrics. This discrepancy is likely to be due to the soil moisture sampling method. The Tarrawarra catchment is range land and as a result has a more continuous soil moisture distribution than that seen in James and Roulet (2007) Mount St, Hilare catchment. Ali and Roy (2010) resolved this issue by taking detailed soil moisture measurement at a range of depths throughout the soil medium by contrast to James and Roulet (2007) who took only one measurement depth (20cm). This shows the importance of selecting the correct sampling method for the catchment under investigation and for the flow regime present (Ali and Roy, 2009).

Traditional geostatistic approaches such as semivariograms use the whole spectrum of actual values. However metrics of connectivity itself work on a threshold principle of high (connected) and low (disconnected values) (Journel, 1983). The concept of thresholds in hydrological response are well documented (Kirkby et al., 2002). However it is important that these thresholds are correctly identified (James and Roulet, 2007). Given the use of a binary response map for thresholds for integrated connectivity scale length this becomes even more important. Ali and Roy (2010) identified that the use of different absolute soil moisture and multivariate percentiles thresholds not only differed greatly but had significantly different efficacy. The use of percentile thresholds in the temporally varying soil moisture distribution were found to be far less effective than volumetric percentage thresholds of soil moisture. It was also the case that significant differences were also found between different soil moisture thresholds themselves (Ali and Roy, 2010). It is important therefore not only to select the correct metrics and the correct sample method but also to find the right threshold for connectivity. The approach to sampling and analysis is outlined in the following chapter.

3.0 Methods

3.1 Study Site

The study site is a small ephemeral catchment of the River Eden. The Eden Valley lies to the east of the Pennine Hills with the Lake District to the south and west (Figure 3.1). Measuring an area of 2288 km^2, the catchment represents a third of the land area of the county of Cumbria extending from the river's headwater in the Yorkshire Dales flowing north and then northwest through the towns of Kirkby Stephen and Appleby Westmoreland. The Eden joins the rivers Petteril, Irthing, and Caldew before flowing through Carlisle and then into the Solway Firth and the Irish Sea (Figure 3.1). The River Eden has two significant tributaries, the Eamont and the Lowther. The large town of Penrith is situated on the River Eamont.

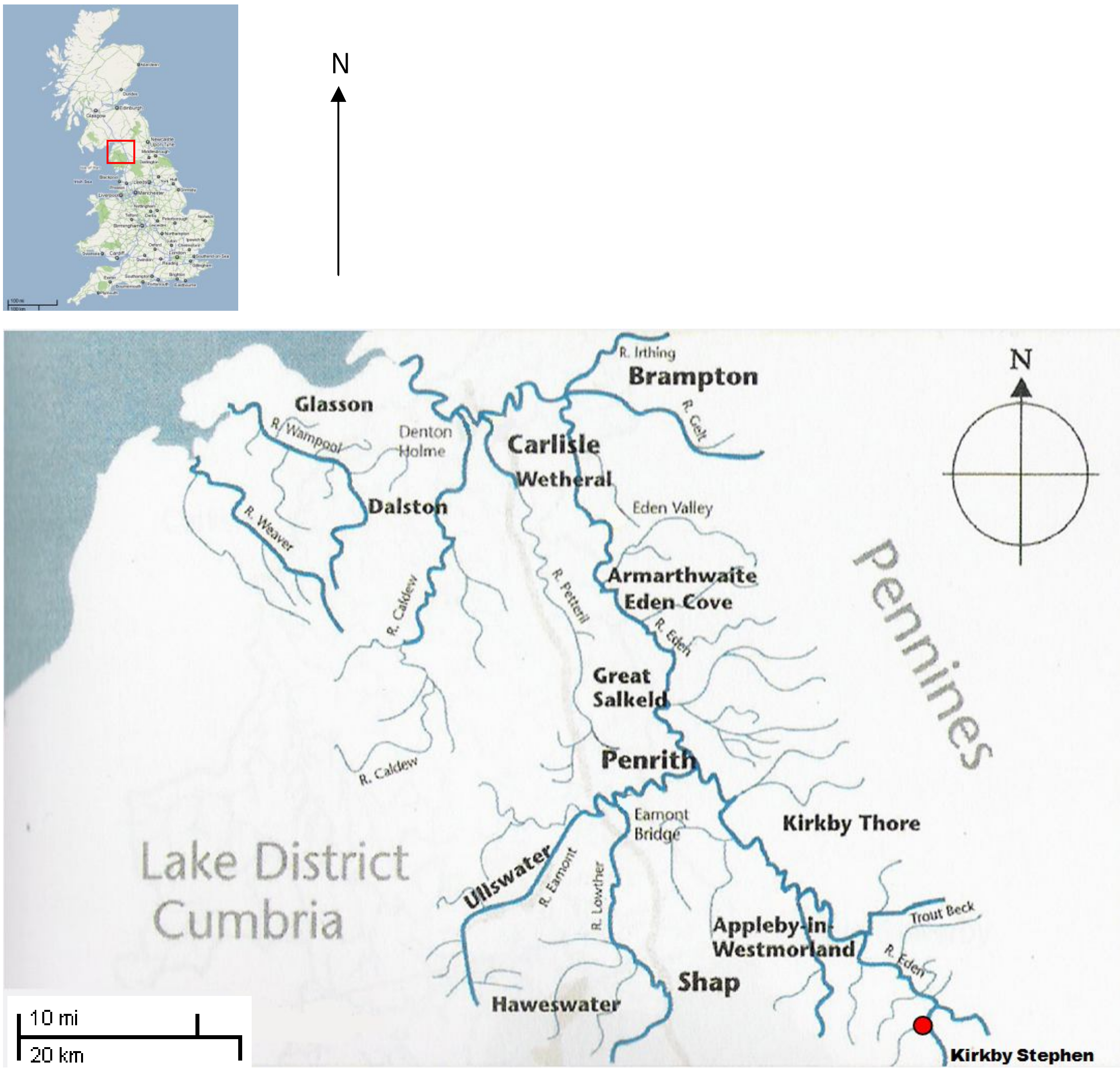


Figure 3.1: Map of the Eden catchment in Cumbria, Northwest England. Red Circle denotes site location north of Blind Beck. (Adapted from Glover, 2005)

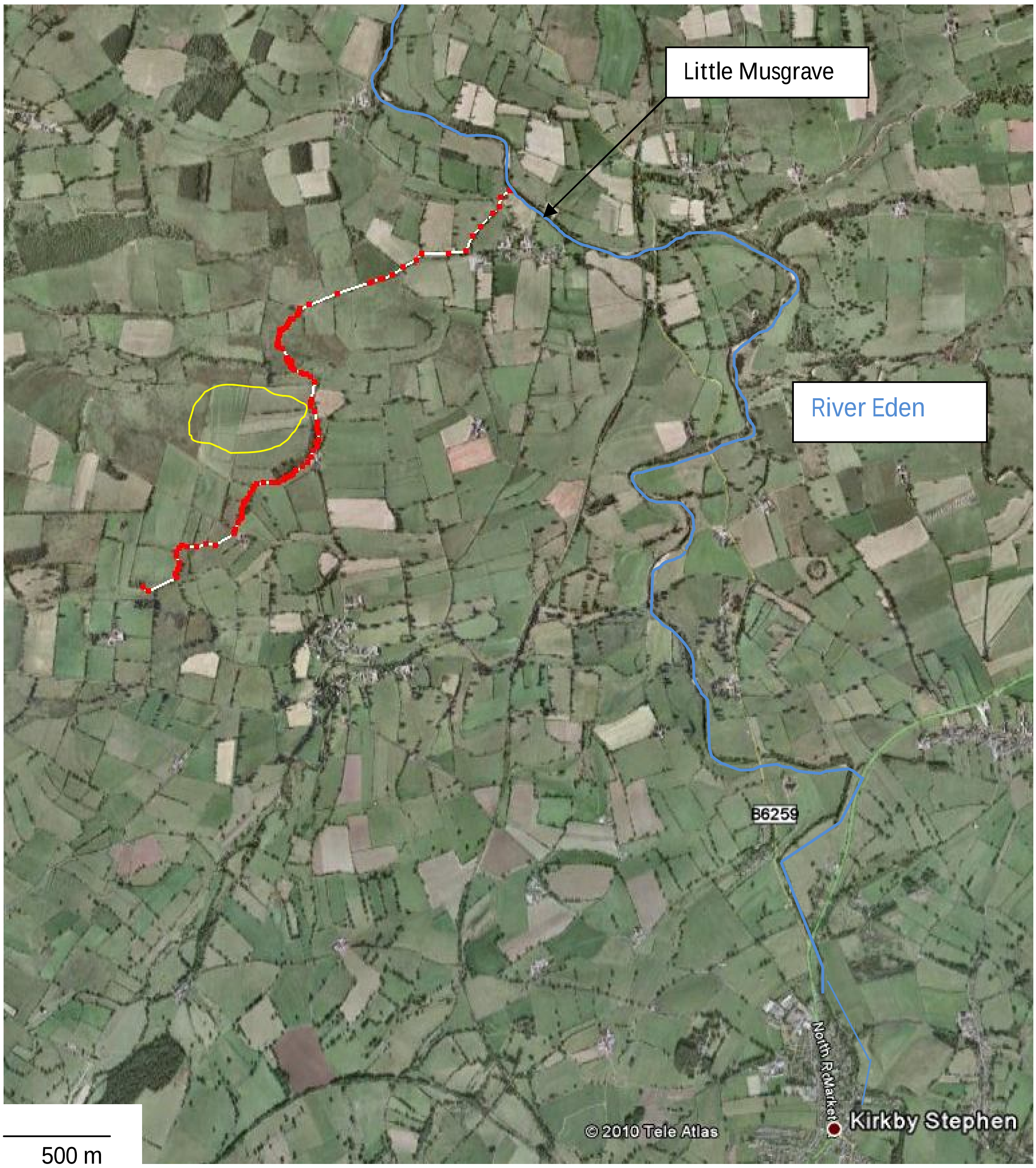


Figure 3.2: Map showing the test catchment (yellow) draining into the unnamed stream (red and white) which subsequently drains into the River Eden (blue) Kirkby Stephen is marked for orientation. Derived from Google Earth.

The Sykeside Farm site is a 3 hectare site of a 10 hectare ephemeral catchment that flows into an unnamed stream that itself flows 2 km north-eastwards through Little Musgrave to join the River Eden, 4 km northeast of Kirkby Stephen (Figure 3.2). It is located in the upper reaches of the Eden Valley. This area of the Upper Eden catchment is typified by Carboniferous limestone in upland areas and Lower Penrith Permian Sandstone within the lowland valley (Ockenden and Chappell, 2008). The site itself is located in the valley on the Permian Sandstone. The soil largely consists of Boulder Clay as a result of the glacial history of the area. This glacial past also impacts on the land features with a number of glacial landscape features evident across the catchment. The lowlands of the Eden Valley are characterised by relatively low relief hillslopes. Precipitation is consistent with the average for the rest of the UK with an annual average of 945 mm (Glover, 2005). This is far less than the neighbouring Lake District to the southwest (2540 mm). The distribution of annual rainfall for the local Keswick weather station is shown in Figure 3.3. It can be seen from this graph that there is considerable variation interannually but that there is no increasing or decreasing trend. Rainfall clearly averages around 900 mm yr^{-1}. Historically this region has been dominated by livestock farming. Sheep are the main animal reared here due to the rough terrain, poor weather as well as poor soil. The majority of the catchment today is still rural farmland. Due to its northerly location and poor soil arable farming is still limited here with the majority of agriculture being sheep and cattle farming. The site is typical of the Upper Eden Valley being exclusively used as pasture for sheep and cattle grazing.

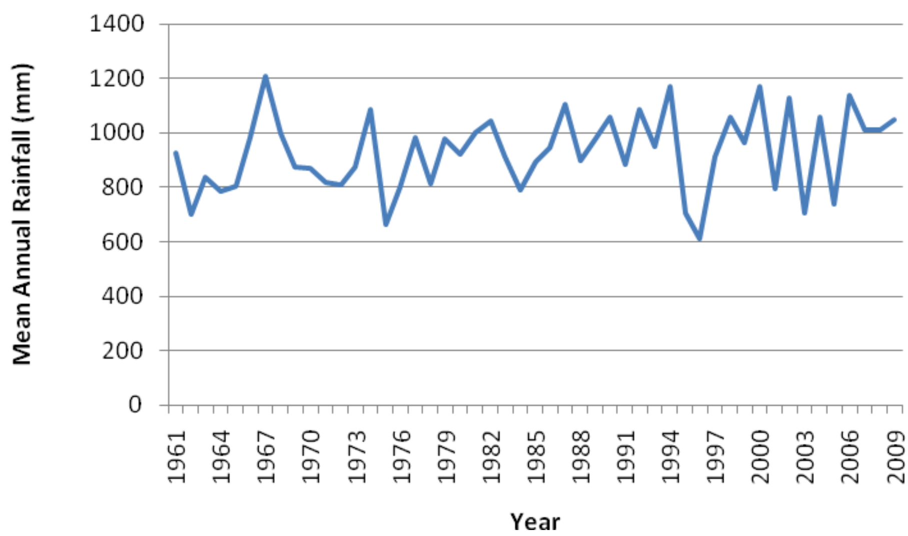


Figure 3.3: Mean Annual Rainfall record for Keswick between 1961 – 2009.

The site at Sykeside Farm was chosen for field monitoring. It is a field measuring 400m by 100m tapering to 80 m at the downstream end of the field (Figure 3.4). The field exhibits a small valley form with an ephemeral channel with interlocking spurs. Approximately a third of the drainage area of this channel is constrained to the study site. Figure 3.4 shows that the channel persists westwards for a further 100 m and the catchment extends to the north and west of the study site boundary. The channel slopes gently from west to east joining the unnamed stream at its eastern end. The soil here is consistent with the Upper Eden Catchment consisting of glacial boulder clay. The impermeability of this soil has resulted in the study site being very wet. As a result of this the site has a field drain running the length of the field underneath the channel at a depth of 1 meter. This drain dates to the 1920s and as a result of its age is broken in a number of places. This has resulted in holes being cut out of the channel above the area where the pipe is broken. These holes present potential for increased connectivity along the channel (Figure 3.5). This catchment has been monitored previously to this project as part of the Catchment Hydrology and Sustainable Management (CHASM) project (O'Connell et al., 2007). As a result long term monitoring has occurred in this catchment for a number of years. Rainfall and other weather data has been monitored in the catchment since 2004 through a weather monitoring station and rain gauge. In 2009 a sump and V notch weir were constructed at the outflow of this site to measure the flow level generated from this small sub-catchment using a pressure barometer (Figure 3.6). This site was selected for this historic record of rainfall and stage data as well as its contained nature with complete valley form.

Figure 3.4: Study site at Sykeside Farm (red) in relation to the ephemeral catchment watershed (yellow) and the unnamed stream (blue). Little Musgrave is marked for orientation. The location of the V notch weir and rain gauge is identified by a purple square. (Derived from Google Earth).

Figure 3.5: View upstream of the channel from the sump showing drain excavations as a result of the broken drainage pipe.

At 60 cm the silt based soil is underlayed by hard lacustrine grey clay. It was identified that in wet conditions the active layer of soil moisture is limited to the top 10 cm of top soil with a rapidly decreasing soil moisture to a shallow impermeable horizon. This indicates that not only is there a very shallow impermeable layer in the soil, identifying this catchment as likely to elicit a response more in line with upland mountain catchments with shallow soils than a valley catchment, but also that the active layer of the soil is limited to the surface 10 cm of the top soil.

In addition there is an indication that the surface soil moisture is spatially organised. This is identified from the vegetation distribution seen in the catchment (Figure 3.7). The majority of the catchment surface is dense grass pasture. However there are significant clearly delineated areas of moss indicating consistent concentrated soil moisture. These factors in this catchment show that not only is shallow soil moisture spatially distributed here, but that it is important for the mobilisation of water across it.

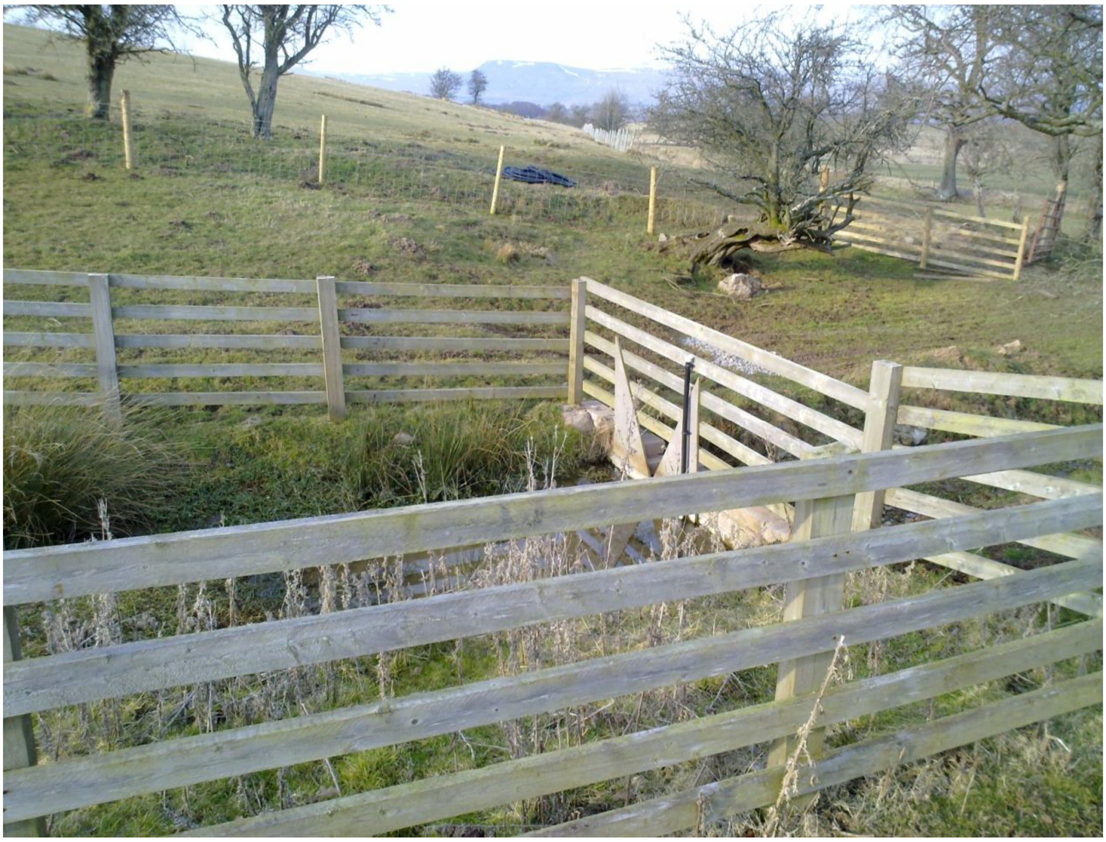


Figure 3.6: Image of V notch weir and sump.

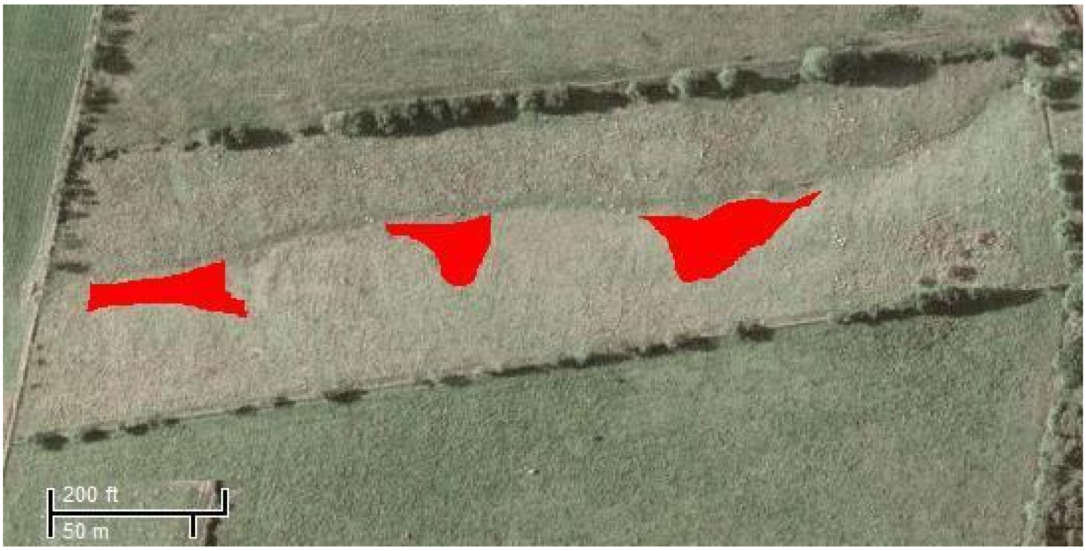


Figure 3.7: Map showing areas of the Sykeside Farm catchment that contain high densities of moss highlighted in red.

3.2 Field Methods

3.2.1 Soil Moisture Methodologies

The focus for measurement in this study is on soil moisture as a proxy for connectivity. This is because of its key role in defining runoff through the VSA concept. There are a number of ways in which this can be achieved, particularly with recent technological developments which have made this area of data collection a dynamic field for investigation. The main field and remote sensing methods will be identified and discussed. Through this process the most appropriate approach will be developed and justified.

The physical state of water in soil is expressed in two main ways: volumetric and gravimetric moisture content (Robinson et al., 2009). Volumetric measurement (θ_v) is an estimate of the difference in volume between the original soil and the constituent water content volume measured as a ratio m^3m^{-3}. Gravimetric measurement (θ_g) is a similar ratio based on the mass of a sample against the mass of water in that sample, usually in the form of g g^{-1}. These measurements are related by the equation:

$$\theta_v = \theta_g \left(\frac{\rho_b}{\rho_w} \right)$$

where ρ_b is soil dry bulk density and ρ_w is the density of water.

Gravimetric moisture is usually identified with thermogravimetric soil moisture measurement as part of laboratory experimentation. Thermogravimetric analysis is the earliest example of soil moisture identification. For this method the water from a soil sample, of 100g or less, is evaporated by baking it in an oven at 105 °C for between 10-24 hours (Topp and Ferré, 2002). This method is still used today particularly as a reliable method of calibration for other field devices and remote sensing (Robinson, et al., 2009). Gardner (1986) notes however that the temperature selected for this method represents a compromise between water being eradicated from the sample (160 °C is the temperature at which crystalline water is vaporised within clay soils) and maintaining the integrity of organic material in the sample (i.e. preventing organic vaporisation). This method is effective for individual samples however it is not applicable for large sample sets. The process of removal of individual samples makes this method time consuming and disturbs the soil surface. Although it does not represent an in situ measure it is still the only real method of obtaining an absolute value of soil moisture despite the concerns raised by Garner (1986). It is for this reason that thermogravimetric sampling is still often incorporated in soil moisture projects for the purpose of calibration or remote sensor testing (Walker et al., 2004). Other methods of soil moisture estimation use characteristics of the water molecule rather than the physical mass to estimate the ratio of water volume to soil volume. These will be discussed in full.

Neutron thermalisation

The original method for the use of thermalised neutrons for the estimation of soil moisture was proposed in the 1940s (Pieper, 1949). The emission of a stream of neutrons towards a soil surface results in a series of molecular collisions. Collisions with different atoms result in different energy losses (Gardner et al., 2001). However when a neutron collides directly with a hydrogen atom the neutron loses all of its energy and becomes thermalised. These molecular collisions also result in a change of direction such that over time a proportion of the emitted neutrons will return to a detector proximal to the emitter. Thus the proportion of thermalised neutrons returned to the detector over a period of time represent the number of hydrogen nuclei and as a result can be calibrated to estimate soil moisture (Bell, 1987). Calibration for this method is straight forward due to the linear relationship between the ratio of thermalised neutrons and soil moisture. However due to increased restriction being placed on the use of radioactive material as well as the slow rate of data collection compared to newer methods the use of neutron probes for surface soil moisture has been reduced. Given the number of samples required for this project as well as the limitation of the restrictions of this method it is not appropriate for this study.

Electrical Conductivity

Electrical conductivity is a method that has been suggested as a method of soil moisture measurement for many years (Briggs, 1899). However the overall bulk electrical conductivity is dependent on both the soil moisture volume and the conductivity of that soil moisture. The impact of salinity has led to electrical conductivity being used for testing nutrient content (Wraith et al. 1993) and transport (Dagan, 1987). The conductivity of the moisture notwithstanding further contributing factors to the overall bulk electrical conductivity including the absorption of ions by charged particles in clay or silt, stratigraphy interference and most importantly the impact of temperature (a change of as much as 2% $°C^{-1}$ (Rhoades, et al., 1999)) renders electrical conductivity a difficult method to calibrate. This is especially problematic given the great spatial and temporal variability that is present in these contributing factors making their compensation from the soil moisture signal difficult to define. This has resulted in interest being diverted towards other methods, predominantly dielectrics. However with the increasing research into geophysical techniques, which have the potential for high mobility while at the same time using electrical conductivity to generate a soil averaged bulk electrical conductivity over multiple depths, the interest in electrical conductivity has been renewed (Robinson et al., 2009). This geophysical technique is called Direct Current Resisitivity and although is still limited by the same problems as other forms of electrical conductivity, its potential in soil monitoring not only the soil moisture but also salinity and soil structure over time has become of great interest (Michot et al., 2003). This is especially so when used in conjunction with water content sensors. However the range of interactions that impact on electrical conductivity make it inappropriate for this study. In particular due to the changing conditions over the period of investigation the sensitivity to temperature makes this method unreliable.

Dielectrics

Dielectric properties are used by a number of devices to estimate soil moisture. Due to the shape of water molecules the oxygen atom draws electrons towards it. This results in the oxygen atom becoming partially negatively charged and the hydrogen atoms becoming positively charged to form a permanent dipole (Hasted, 1973). This dipole is naturally high compared to other naturally occurring soil composite materials which results in a relative permittivity of ~80 compared to air which is 1 and most soil minerals which are ~5 (Robinson et al., 2009). The significant distinction between the permittivity of water with other soil materials gives this method a great deal of promise and a number of different techniques have been developed to measure it. There are 4 main approaches to consider:

- Time Domain Reflectometry (TDR) - emits a high frequency electromagnetic wave (typically above 0.5 GHz) into the soil. Greater soil moisture results in higher relative permittivity of the soil and greater reflection of the electromagnetic wave in a manner similar to radar. A lot of emphasis has been placed on this method as through this approach the bulk conductivity of the soil can be estimated as well as the soil moisture providing information on nutrient content of the soil (Dasberg and Dalton, 1985; Dalton et al., 1984) Example: TDR 100.
- Impedence probes - also use an electromagnetic wave at a lower frequency (~100MHz). The probe compares a length of fixed transmission line that extends into a central electrode with three electrodes surrounding it. The soil moisture in the soil alters the relative permittivity of the known characteristic impedance of the electrodes creating a standing wave. The discrepancy between the wave form and the known impedance is used to estimate soil moisture (Gaskin and Miller, 1996). Example: Theta probe.

- Ground Penetrating Radar (GPR) - uses varying frequencies of electromagnetic waves to estimate soil moisture through relative permittivity. The variability in the transmission signal gives GRP great potency in making soil moisture estimation at multiple depths. There are many methods of measurement and interpretation of GRP data. However as a result this makes this technique a very specialised method to use (Robinson et al., 2009). Example: Wide-Angle reflection-refraction (WARR).
- Remote sensing is the largest scale method for measuring soil moisture. There are both active and passive approaches that measure either naturally emitted (passive) microwave or backscatter response to a microwave signal (active) (Robinson et al., 2009). It has been found that soil moisture has a strong relationship with microwave emission (Hallinkainen et al., 1985) Example: Advanced Microwave Scanning Radiometer (AMSR-E).

Robinson et al. (2009) highlight the importance of understanding the soil permittivity in order to preserve the accuracy of dielectric measurement and this is key to identifying the best approach. To estimate the relative permittivity of the soil all of these methods use electromagnetic waves to excite the dipoles in the soil. Debye (1929) recognised for a homogenous solid or fluid the main potential for energy loss is heat when applying an electrical field in this way. The main contributing factors in this energy loss were material ionic conduction (and subsequent charge transport), the refractive index of the material and the inherent static relative permittivity of the material itself. However Sihvola (1999) recognised that although this provides a useful dielectric model for homogenous materials soil behaves differently to its composite nature. This led to the addition of faradaic diffusion and ohmic conduction by Knight and Endres (2005) who also identified that it is not possible through measurement to distinguish dielectric from conduction. However at high frequencies (100 MHz or above) faradaic diffusion is assumed to be zero and ohmic conduction is assumed to be equal to ionic conduction. However the assumption that high frequencies will be sufficient to counteract soil permittivity has been challenged by a number of studies which show that clay minerals show distinct dielectric dispersion (Ishida et al., 1999). Figure 3.8 shows the frequency dependence of clay relative permittivity dispersion by comparison to a quartz soil.

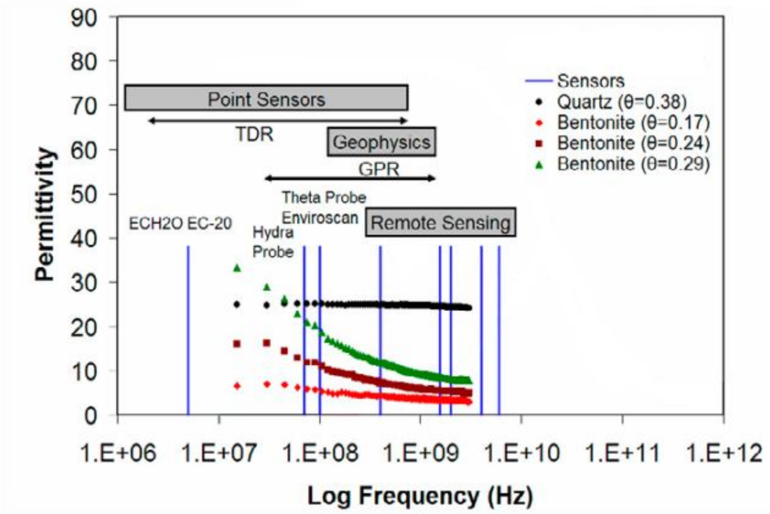


Figure 3.8: Showing frequency dependence of clay dielectric dispersion at different saturations. Also identified are ranges of dielectric sensors that identify frequency bounds within which this dispersion is represents a challenge. Taken from Robinson et al. (2009).

Figure 3.8 highlights the potential difficulties of the relatively low frequency impedance sensors that have the potential to be susceptible to clay relative permittivity dispersion. This also indicates the higher operating frequencies (0.5-1GHz) of TDR are most successful at limiting these effects of the in situ methods. GPR compares well to TDR due to the large frequency range. The use of high frequency microwaves limits interference by clay dielectric dispersion for remote sensing.

Remote sensing appears to be the most stable electromagnetic approach of the four methods originally suggested however the prospect for the use of remote sensing for estimation of soil moisture is currently limited and beyond the scope of this project. Although both active and passive have a great deal of potential the benefits presented by microwave sampling are counteracted by calibration complications. For example passive remote sensing depends on the relationship:

$$T_B = eT$$

Where T_B is the brightness of the soil, e is the emissivity of the soil and T is temperature of the soil. Although emissivity has a strong relationship with soil moisture this relationship depends on whether the soil temperature is known (Robinson et al., 2009). Further difficulties arise when the consideration parameters that affect the scatter of the microwave signal (for example vegetation and soil roughness) which can decrease the accuracy of the brightness to soil moisture relationship (Choudhury et al., 1979). These difficulties are enhanced when active remote sensing using microwave emissions are used as added complications such as antenna characteristics and geometry become important. Active remote sensing also require a greater consideration of problems that have already been identified like backscatter diffusion due to soil roughness, the interference of vegetation and the emission depth of the transmitted signal (Jackson et al., 1998) due to the requirement to calibrate the effect on the transmitted signal as well as the backscattered returning signal. Despite the difficulties in calibrating remote sensing it is undoubtedly the method with the most potential given the accuracy that can be attained at fine resolutions over large areas. However the challenges in calibration mean that care needs to be taken when analysing its results. The limited size of the study area as well as the problems with access and calibration rule out the use of remote sensing for this project, however the importance of the use of remote sensing for similar studies at larger catchment scales cannot be underestimated.

GPR presents a versatile method with the capability of multiple depth soil moisture estimation. There have been a number of methods identified in the literature which use GRP to determine soil moisture for example offset profiling (Lunt et al., 2005), estimation of ground-wave velocity (Hubbard et al., 2002), common midpoint measurements (Greaves et al., 1996), and surface reflectivity (Serbin and Or, 2004). All of these methods measure soil moisture in one of two ways: either through changes in travel time of the electromagnetic wave or the amplitude of the reflected wave. Both of these methods are problematic. The measurement of travel time disparity in electromagnetic waves is challenging due to the variation in the true sample depth as a result of the test frequency and the soil moisture. This can vary between a few centimetres to tens of meters (Galagedara et al., 2005) and is a key issue for depth continuity across a range of soil moisture conditions. The amplitude method has shown some positive results collected by suspending antennae above the ground however there is some doubt as to the depth layer that is sampled using this method (Chanzy et al., 1996). Ground penetrating radar is high resolution and non-invasive however it requires a high degree of user knowledge to operate. There are also some limitations in saline soil. This method does have potential however these issues have limited its use.

3.2.2 Soil moisture measurement approach adopted

From this range of methods a soil moisture sampling approach had to be selected for this study. The capacitance depth of the soil is important for estimating the flow regime of the catchment. A small catchment was selected with a shallow capacitance layer in order to omit the need for multiple depths of soil moisture measurement. This was verified by driving a gouge core into the ground until refusal. 15 random samples were taken to identify the spatial variability of capacitance. The depth was consistently between 60 and 65 cm for all of the sample measurements. As a result the need for remote sensing methods is unnecessary as the scale of the site is relatively small. Also remote sensing requires a great deal of calibration that ultimately increases the chance of error by comparison to other similar methods. GPR is rejected for similar reasons. Due to the shallow nature of the active layer in the soil horizon (0-10 cm) the need for a method that can measure across the whole horizon is unwarranted. However this method would prove very useful for deeper, active soils with a greater degree of lateral flux and deep moisture storage as well measuring transient soil moisture in subsurface flow dominated catchments. However the difficulty involved in measurement and analysis of the raw data make it a very specialist approach. Neutron thermalisation is cumbersome and slow. Also due to the use of radiation this technique is often restricted and as a result has been rejected for use in this study in favour of a more modern alternative. Electrical conductivity is difficult to use to measure soil moisture due to the range of soil factors that can affect the conductivity reading. In order to use this method a number of other factors like salinity and temperature are required to make an estimation of soil moisture. Something that is unnecessary for dielectrics. Thus two principle methods of field based soil moisture measurement remain: dielectric based TDR and impedance probes. TDR is the method that has been used by previous studies measuring soil moisture to assess hydrological connectivity (Western et al., 2001; James and Roulet, 2007). It has been used due to its broad spectrum to overcome dielectric dispersion (Figure 3.8). Randomly sampled soil samples taken from the 5cm top soil from the study site at Sykeside Farm (Figure 3.9) indicates that approximately 20% of the soil surface is likely to be affected by this dispersion. The percentage range of clay is 7% is a small fraction of the soil distribution and the variation in the volume of clay is not considered to be significant.

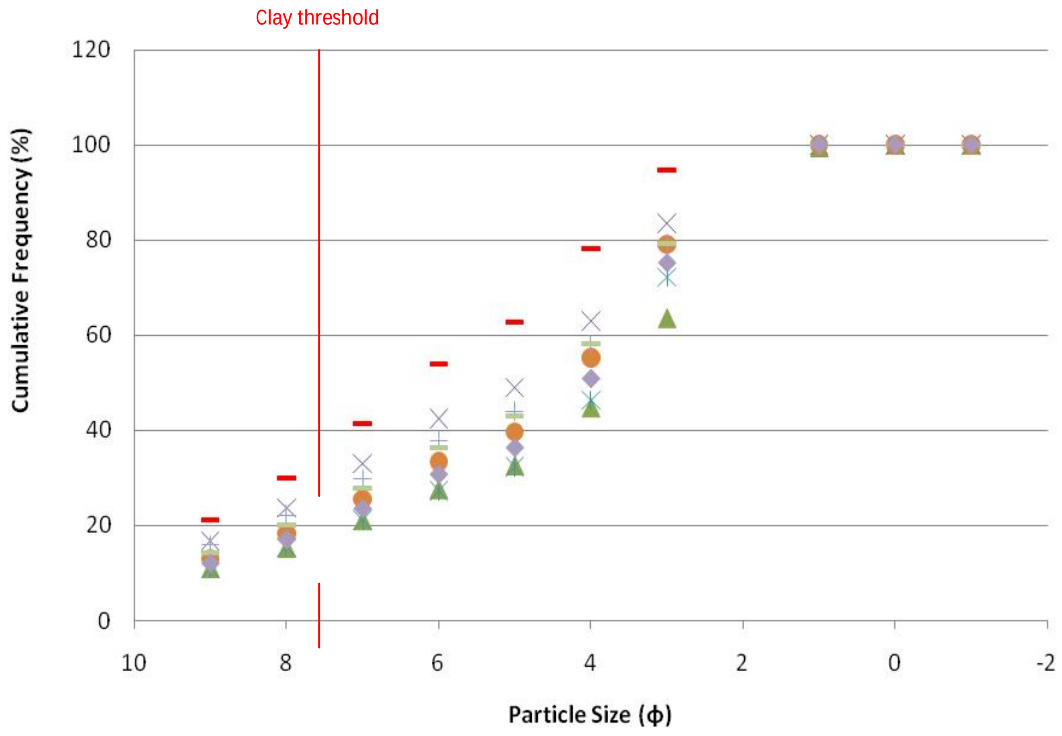


Figure 3.9: Particle size distribution of 8 random soil samples from the Sykeside Farm field site.

Despite this Robinson et al. (2009) identify that the capacitance probe, Theta, has better root mean standard error (RMSE = 0.017) and offset error results to those of TDR (0.022). It was decided that the error of the instrument as a whole was more important than the potential dispersion seen for 20% of the soil horizon. The performance of the Theta probe was tested against absolute oven dried gravimetric soil samples of the same sample volume as that measured by the probe (4cm wide by 6 cm long). The laboratory gravimetric soil moisture results were converted to volumetric measurements and compared to the Theta probe measurements. As a result Figure 3.10 shows the calibration between laboratory gravimetrically tested soil moisture taken at a range of saturations and impedance Theta probe volumetric soil moisture for 15 soil samples. This graph shows the accuracy of the probe over a representative spectrum of soil moistures. The close relationship between the probe and laboratory tests suggest that the probe results are accurate and are a good estimation of the shallow soil moisture despite the concerns of clay dielectric dispersion. The RMSE of this distribution was 0.02 which is representative of the value found by Robinson et al. (2009) and still above that found for TDR. It was therefore concluded that the Theta probe was a good method of measuring soil moisture and that it can be assessed with some confidence.

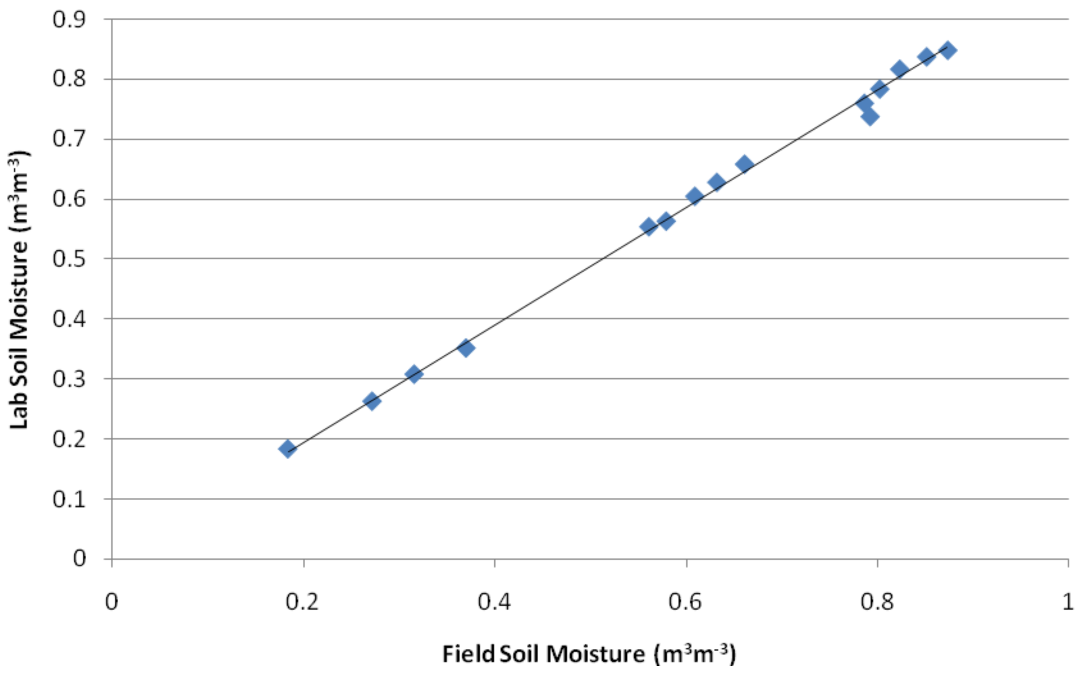


Figure 3.10: Scatter graph showing gravimetric calibration of Theta probe. The line is 1:1.

3.2.3 Soil Moisture Data Collection

The sampling approach that was adopted for the soil moisture measurements was in line with previous studies looking at soil moisture and hydrological connectivity (Western et al., 2001; James and Roulet, 2007; Ali and Roy, 2009). The lots of points (LOP) approach is considered the most effective method for gaining a representative distribution of catchment soil moisture (Grayson et al., 2002). Previous studies have taken 300 measurements on a 10 m grid in a 5.4 ha catchment (James and Roulet, 2007) and 500 points on a grid of 10 m x 15 m grid in a 10.6 ha catchment (Western et al., 2001). This study's catchment at Sykeside Farm measured 3.5 ha. Due to its small size the resolution was scaled up so that soil moisture measurements were taken on a 5 m grid resulting in ~1400 point survey. For each point on the grid three soil moisture measurements were taken to obtain an average for that point in order to ensure that the soil moisture measurement is representative of that sample location. This resulted in each survey being made up from over 4100 individual measurements. This was considered a robust volume of measurements to adequately represent the soil moisture of the catchment. This is an important consideration as the accuracy of geostatistics is dependent on having a large data set with small data pair spacing (Ali and Roy, 2009). It is noted, however, that this method is time and labour intensive and that it would not be appropriate for larger scale catchments. For catchments of this scale it is recommended an alternative method of soil moisture measurement is used.

The grid was measured in 21 transects across the catchment sited at each end by permanent stakes driven into the ground. Each transect was measured by stringing a rope with 5 m marked intervals between each pair of transect posts (Figure 3.11). It is recognised that the rope would stretch over time however the degree of this was not considered great enough to alter the grid point location over the distance of the catchment. In this manner a consistent grid could be measured over the study period.

Figure 3.11: Image of marked rope strung between permanent transect stakes used to locate 5 m grid points. 5 m rope mark is highlighted by a red circle.

The depth of the soil moisture measurement is very important. It has been identified that the depth of representative soil moisture measurement for hydrological connectivity depends on the regime of catchment flow (Western et al., 2005). Tromp Van Meerveld and McDonnell (2006) suggest that transient saturation along bedrock or impermeable soil horizons is the important condition in measuring soil moisture that is relevant to hydrological connectivity. However Western et al. (2005) suggest that shallow soil moisture measurements are representative of deeper soil moisture movement as “the hydraulic conductivity reduces so quickly as the soil desaturates that water will only move over significant (e.g. hillslope) distances if at least part of the soil profile is saturated” (Western et al., 2005, p. 313). Other studies have made multiple depth measurements which result in a better understanding of the soil profile and its moisture distribution (James and Roy, 2007; Ali and Roy, 2010). This is clearly contentious and depends primarily on the flow regime that is present. Permeable soils will result in the need for bedrock saturation measurement by contrast to surface runoff dominated systems.

The Sykeside catchment has fine grained silt soils as a result of its glacial past. Subsequently infiltration is limited across the catchments. A random sample of gouge core measurements to find the capacitance level of the soil was limited to 60 cm across the catchment. Of this 60 cm only the top 10 cm is active due to the low permeance of the soil. This effectively limits the store volume of the soil to a thin surface layer. As a result the runoff in this catchment is likely to be dominated by surface runoff as a result of saturation excess runoff as well as the potential for infiltration excess events at time of high rainfall intensity. Subsequently the top soil surface was decided as the layer most relevant for hydrological connectivity. As a result the Theta probe measurements for the soil moisture surveys were taken for the top 5 cm of soil which is a representative depth for this active soil layer.

Between 8th March 2010 and 5th May 2010 a series of six soil moisture surveys were conducted. They were taken at regular intervals throughout the two mouth period. The aim of assessing the drying out period from wet winter conditions to dry late spring conditions was achieved through regular surveys. As a result the surveys represent the meteorological condition over this period as a whole. The only proviso on the completion of each survey was that no rainfall fell on either of the two days of the survey or the night between. It was considered that rainfall would have an impact on soil moisture quickly due to the shallow soil moisture measurement which over the course of the survey could result in significant discrepancies between the beginning and the end of the survey. This is especially important as the survey required two days to complete. Limited evapotranspiration was predicted between the days of the survey due to the cold conditions of the study period permitting such an extended period of soil moisture measurement.

3.2.4 Differential Global Positioning System

The measurement of the topography of the site was achieved through a Differtial Global Positioning System (DGPS) survey using a Leica GPS1200. A 5 m survey of the site was taken along the same transects as the soil moisture measurement. In addition to this sub grid features like the outwash drains in the channel and distinct breaks in slope were sampled. The survey was taken using a standard DGPS method. A base station was set up on high ground unobscured by trees. This was made up of a GPS unit, an antenna and a radio transmitter. This base station represented a temporary datum point taking constant measurements of its location to get a highly accurate location and altitude measurement. The survey was taken using a rover GPS unit on a range pole. This also had an antenna and a radio transmitter. The rover took a reading of altitude and position in relation to the base station. The base station measured the distance and difference in altitude between it and the rover, to generate measurements accurate to 5 cm. The data was post processed to correct it to ETRS89. This was done by processing the base station relative to the local OS active stations at Carlisle, Ambleside and Richmond to triangulate its position in the catchment. Subsequently the rover data was co-ordinated with that to correct the whole survey. This was then converted to OSGB36 using the grid conversion program Grid Inquest. The data was converted to OSGB36 format so that it could be projected in ArcGIS.

3.2.5 Rainfall and Stage Measurement

In addition to regular soil moisture surveys catchment stage and rainfall were continually measured over this period. Rainfall was measured using the tipping bucket rain gauge ARG100 (Environmental Measurements) and was located within the sump enclosure at the catchment outflow. It was located here so that it would be protected from livestock and because it is in open ground with no interference from vegetation. The small scale of the catchment meant that one rainfall gauge was considered to be sufficient. Its location at the outflow also means that it is situated in the valley of the catchment where wind is at its lowest velocities. The accuracy of this rainfall gauge is 0.2 mm. The rainfall sampling method was incremental with increasing rainfall. The low rainfall sampling time interval was an hour. However if more than 0.2 mm was recorded within a 15 minute or 30 minute interval then the volume was registered at that time interval. Thus when there is little or no rainfall, rainfall was measured at hourly time steps. However during rainfall events this sampling time interval was reduced to 15 minutes in order to gain a more detailed distribution of the rainfall over short intensive rainfall events. The rainfall gauge was installed as part of the Catchment Hydrology and Sustainable Management (CHASM) project in 2004. This provided a 5 year record with which to compare the study period's rainfall. Although this is not an extensive rainfall record it was useful as an indication of how representative the antecedent conditions for the study period were by comparison to recent years. Tipping bucket gauges have been used extensively for measuring rainfall and the AGR100 is accurate and is a common instrument used in hydrology (Teklehaimanott et al., 1991; Asdak et al., 1998; Heppell et al., 2002).

Stage was measured using a pressure transducer diver (Eijkelkamp Agrisearch Equipment). This instrument measures water pressure and uses that to calculate the depth of water at a point. The sump at the outflow of the catchment was excavated so that a diver could be installed to measure temporal variation in the water that flowed into it. The diver was suspended from steel wire in a tube that ran down to the bed of the sump. At 15 minute time intervals the diver recorded the water pressure to measure the stage depth of the water in the sump. The diver was installed in October 2009. This allows a detailed catchment stage reaction to the rainfall for the whole of the winter period of 2009/2010. This provides useful information about how the catchment reacts to various rainfall events across the winter period affording a useful backdrop to the conditions of the study period. The diver has a ±1% accuracy. Pressure transducers are common in estimating stage data especially in small catchment channels (Wigington Jr. et al., 1996; Mongomery et al., 2007; Harmel et al., 2006).

3.3 Topography Analysis

The data collected from field measurement techniques were analysed using ArcGIS, a geographical information system (ESRI). ArcGIS is a spatial data management and manipulation package that is one of a number of programs that are used to analyse geographical data. This was used to analyse the DGPS data of the topography of the catchment to develop an understanding for its structural connectivity.

3.3.1 Digital Elevation Model

The first step was to generate a Digital Elevation Model (DEM) of the catchment on which to base further analysis. The topographic data was measured using the same 5 m grid as soil moisture. In order to predict the terrain between the measurement points ordinary kriging was performed to interpolate a DEM of 1.5 m spatial resolution. Kriging works on a principle of linear least square algorithm to estimate unobserved areas between measurements. A semivariogram model is fitted to the data and on the basis of that model and the number of neighbouring measurements that are taken into account the subscale topography is estimated. There is some debate about the efficacy of kriging especially at large scales and on variable surfaces (Todini, 2001; Todini et al., 2001) however it has been used widely particularly for topography with smooth slopes of limited variation. (Desmet, 1997). For the Sykeside catchment the topography is already densely measured and so there is limited potential for error assuming that the main breaks in slope have been measured. As a result this is a secure method to use.

3.3.2 Slope, Aspect and Flow Direction

Subsequent analysis of the DEM was based on slope angle, aspect and flow direction. These are very simple methods of identification of the difference in topography between pixels. Slope is calculated through simple trigonometry between pixels where difference in topographic high is used to calculate slope angle. Aspect and flow direction relate this slope angle to a compass direction that represent the direction of that part of the catchment as well as the structural flow direction. Previous discussion about the relevance of surface topography shows that this might not be sufficient to predict flow direction (Stieglitz et al., 2003). However the nature of this catchment shows that this is not the case here and that flow direction is dependent on surface topography.

3.3.3 Flow Accumulation and Topographic Wetness Index

The justification for the use of surface topography to determine flow direction also permits calculation of the Topographic Wetness Index (TWI) to represent areas susceptible to soil moisture and potential flowpaths. TWI is the structural topographically derived index for predicting areas susceptible to soil moisture that is used by TOPMODEL (Beven and Kirkby, 1979) and is an important feature to many VSA based physical hydrological models.

$$TWI = \ln\left(\frac{a}{\tan\beta}\right)$$

TWI is a function of upslope contributing area (a) and tan of slope angle (β). As a result this function predicts that areas which have a combination of high upslope contributing area and low slope areas will result in areas more likely to become saturated. This method also aims to identify channels as the lowest slope angles with high contributing areas. This method ignores the importance of transient saturation and so is only relevant to systems where this is not an important driver. However it also presumes there are no other forms of driver on soil moisture creation and connectivity other than topographic forcing. This has been identified as an unsatisfactory approach to hydrological connectivity (Bracken and Croke, 2007). However due to the shallow reactive soil layer seen at the Sykeside catchment, it was a good place to ascertain whether TWI can represent areas of soil moisture. In order to calculate TWI firstly flow accumulation had to be estimated.

Flow accumulation calculates the cumulative contributing areas identifying flow pathways through accumulating the number of pixels that are up slope of each pixel that would contribute to it. Again this ignores the potential for infiltration along the route and given it is the accumulation of the number of pixels this should be recognised as potential pathways. These potential pathways are useful to show the potential extent of connection during high rainfall events during occasions of uniform saturation. The low infiltration capacity of the soil in this catchment indicates that this is likely during winter months. The DEM has to be filled as a preparation to flow accumulation. TWI was then calculated as a series of functions on ArcGIS from flow accumulation.

3.4 Metrics

The metrics that were selected for this study are based on those identified as successful or contentious in previous studies (Western et al., 2001; James and Roulet, 2007; Ali and Roy, 2010). However in addition to this a key element identified by James and Roulet (2007) and investigated in forested catchments in Quebec by Ali and Roy (2010) are thresholds. Thresholds have been identified across hydrological flow regimes (Devito et al., 1996; Martinez-Mena et al., 1998). These have largely been identified using small scale patch assessments of flow with only the volume to breakthrough (Hairsine et al., 2000) representing measurement at hillslope scales. The importance of thresholds in hydrology and the challenge of scaling up plot scale investigations mean that there is a gap that needs to be filled. This resulted in Ali and Roy (2010) using the geostatistical connectivity metrics and applying a range of thresholds in order to ascertain the effectiveness of statistically estimating thresholds. Three types of thresholds were identified: The first is a simple time variable percentile of the distribution of the soil moisture survey as a whole, spatially (dp10, 25, 50, 75, 90). The second type was a multivariate time variable distribution percentile, based on depth. The third was an absolute soil moisture percentage threshold (sm20, 30, 40, 50, 60, 70). Due to the soil moisture sampling method of this study and the nature of the catchment flow regime, multivariate time variable depth percentiles are not relevant to this catchment. However the other two approaches clearly had the potential to define the connectivity limit of the soil moisture of the catchment. Although the percentiles of soil moisture distribution were found to perform poorly by Ali and Roy (2010) it was decided that their inclusion was important. Ali and Roy (2010) used this approach in a forested catchment. The grassland nature of the Sykeside catchment is likely to respond differently to that of Ali and Roy (2010) as a result the spatial percentile was included. The metrics themselves are grouped as statistical cluster analyses, geostatistical metrics and flow path estimation metrics.

3.4.1 Statistical Cluster Analysis

When the soil moisture distributions are subjected to the range of 11 thresholds a series of 66 binary distributions of connectivity are generated. These are calculated through Spatial Analyst in ArcGIS. The pixels that satisfy the threshold to register as connected form clusters across the surface. The first metrics assess the number (SATCLUST) and area (SATAREA) of these clusters. This is achieved by removing the disconnected 0 values to leave only the clusters itself by converting the raster to a polygon and designating 0 as NODATA set. As a result the subsequent areas are then calculated using Spatial Analyst producing an Attribute Table of cluster areas. The total saturated area is calculated for each of the 66 binary distributions as well as the number of clusters.

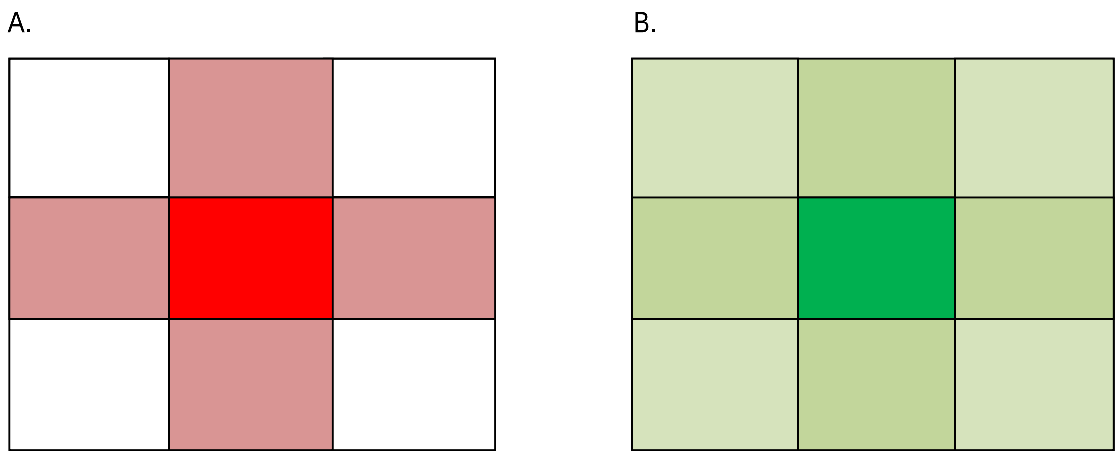


Figure 3.12: Representation of cluster identification by ArcGIS including only adjacent pixels (A) and the common 8 neighbour cell commonly used in hydrological modelling (B).

A key problem of using ArcGIS is that a cluster, as defined by the program, only includes adjacent cells (Figure 3.12). This means that diagonal cells are not considered despite them evidently being connected. Thus an additional derivation of these two metrics was calculated. To overcome this issue a buffer value of 5 cm was added to the clusters cells so that the polygons overlap. The polygons were then merged. This resulted in different values for some of the distributions. These were added as metrics in their own right in order to ascertain the effect that buffering had. These were listed as (SATAREA_BUF).

Contributing area was then estimated (CONTAREA). This metric was calculated by identifying the channel from the flow accumulation raster. This channel was mapped by adding a line feature along its length. This channel was of a broken nature as a result of subsurface drainage excavations along its length. For each of the binary distributions the clusters within 1 m of the polyline of the channel were identified as contributing area. Inclusion of topography to these contributing areas was unnecessary due to the simple form of the catchment with the strong potential for lateral flow pathways to the channel. Again this form was buffered to ensure the whole contributing areas was included (CONTAREA_BUF).

3.4.2 FRAGSTATS

These methods of cluster analysis were seen as relatively simple cluster metrics calculating only total area. To develop beyond the metrics used by Ali and Roy (2010) an advanced cluster analysis program was used to develop a more detailed understanding of the clusters themselves. FRAGSTATS is a specialised program designed to enact metrics and methods of advance cluster relationships as well as identification of individual cluster magnitude and importance (McGarigal and Marks, 1995). This program uses the 8 cell neighbour approach that is lacking in ArcGIS (Figure 3.12). These metrics were selected as a series from FRAGSTATS options and enacted to all 66 binary thresholds using a batch file in the form:

File location, cell size (in meters), background integer*, no. of rows, no. of columns, input data type

* = Background integer: number used to designate values outside of area to be analysed. For this study 0 was used.

Input data type: these are coded as follows with the data format used in this study highlighted:

- IDF_ARCGRID

- IDF_ASCII
- IDF_8BIT
- IDF_16BIT
- IDF_32BIT
- ERDAS
- IDF_IDRISI

The initial metric was a calculation of the percentage of the area that was saturated above the given threshold (CA%). This represents an alternative to SATAREA to see if a proportion is a better representation.

$$LPI = \left(\frac{\max(a_{ij})}{A(100)} \right)$$

The Largest Patch Index (LPI) takes CA% metric further and represents the largest individual patch as a percentage of the total area, where a_{ij} is the area (m^2) of the patch and A is the total landscape area (m^2). This attempts to ascertain the impact of the largest patch on the threshold binary distribution.

$$AI = \left[\frac{g_{ij}}{\max \rightarrow g_{ij}} \right] (100)$$

Aggregation Index is a metric that ascertains the proportion of cell adjacencies (joins) present as a percentage of the total number of possible cell adjacencies in the catchment. The metric is distributed between 100% representing a single completely compact patch with no breaks within it to 0% representing a situation where none of the cells present are in contact with any other (maximally disaggregated). This metric attempts to estimate the proportion of connected cells as a function of total cell contiguity.

$$DIVISION = \left[1 - \sum_{j=1}^{a} \left(\frac{a_{ij}}{A} \right)^2 \right]$$

DIVISION is a proportion of how distributed the cells are, where the patch area (a_{ij}) is divided by the total area (A) with the value squared and summed across all of the patches and then taken as a proportion from 1. This metric attempts to estimate the probability that two random cells in the landscape are not situation in the same patch. DIVISION is distributed from 0 being a catchment containing a single patch to 1 being completely disaggregated, represented by a single isolated cell in the catchment.

$$COHESION = \left[1 - \frac{\sum_{i=1}^{m} p_{ij}}{\sum_{i=1}^{m} p_{ij}\sqrt{a_{ij}}}\right]\left[1 - \frac{1}{\sqrt{A}}\right]^{-1} .(100)$$

The final FRAGSTATS metric is COHESION where (p_{ij}) is patch perimeter, (a_{ij}) is patch area and (A) is the total catchment area. This metric calculates the connectedness of the distribution of patches in the catchment. The relationship between patch perimeter and area gives an indication of the size of the patch and that is summed for all of the patches present and represented as a function of the total catchment area. This metric is a manifestation of the degree to which patches are spatially connected across the catchment.

3.4.3 Semivariograms

It has been noted by Western et al. (2001) and Antoine et al. (2009) that the method by which semivariograms estimate spatial dissimilarity is incompatible with the notion of hydrological connectivity. Western et al. (2001) and Antoine et al. (2009) identified that semivariograms cannot decipher between connected and disconnected landscapes. This is due to the semivariogram method being based on Euclidian distance between the points which ignores any non-Eucildian connected flow formations. Indeed not only is the conceptualisation space a problem but also the assumption that the only variable that influences the distribution of the data is the separation of the points themselves (Western et al., 2001). Inherently within connectivity is the concept of the connection of space through a series of conditions or process which does not sit comfortably with this principle. Western et al. (1998) recognised that the multi-Gaussian approach that kriging methods use, based on semivariograms, presume a normal distribution of disorder set within a Euclidian distance framework. The threshold nature of systems like soil moisture distribution do not fit this normal distribution. This led Western to develop indicator semivariograms whereby thresholds were identified as statistical percentiles and a series of sermivariograms are generated as an interval distribution to show the change between each threshold. This method is a good first step into recognising the spatial subtleties that soil moisture contains.

The structure of semivariograms can be described as follows:

> *"The main features of the semivariogram are the sill, the range (or correlation length) and the nugget. If a stable sill exists, the spatial field is stationary and the sill can be thought of as the variance between two points separated by a large distance. The range is the maximum distance over which spatial correlation exists. It is the distance (separation or lag) at which the semivariogram reaches the sill. The correlation length is the average distance of spatial correlation and it is closely related to the range. The numerical value of the correlation length is about one-third of the range, depending on the shape of the semivariogram. The nugget is the variance between two points separated by a very small distance. It is the value at which the semivariogram intersects the y-axis. The semivariogram is a measure of the spatial continuity of the field. Semivariograms of smooth, or highly continuous, spatial fields have a large range, while semivariograms of discontinuous, or rough, spatial fields have a short range." (Western et al., 1998b, pg. 1852)*

The details of this explanation are illustrated in Figure 3.13. There are two types of semivariogram that were calculated as connectivity metrics, omnidirectional (isotropic) and directional (anisotropic). The binary threshold maps were multiplied with the original soil moisture maps to generate maps showing the soil moisture variation over each threshold. Each of these were subject to a standard semivariogram method, where the variance between each point is calculated and displayed as a function of distance. This resulting semivariogram was fitted with an exponential model and the resulting range from this model was used as a metric. Anisotropic directional semivariograms are the same as omnidirectional semivariograms only the continuity between the points is defined by a plane of reference. Thus for the north-south orientated semivariogram the continuity between point is limited to the vertical plane, and similarly east-west is limited to the perpendicular. Beyond this the method is the same and the range was used as a metric in the same way as omnidirectional.

Figure 3.13: Indicator semivariogram labelled with range, sill and nugget.

3.5 Metric comparison

Each metric generates results for each of the 11 thresholds for each of the soil moisture surveys. The representativeness of these thresholds for hydrological connectivity, meteorological drivers and discharge was tested. Ali and Roy (2010) were the first to attempt to make this comparison. So that the results are comparable to this study the metric analysis methods are largely the same. Three methods were identified to analyse the metrics in relation to catchment drivers.

The first method of analysis was the coefficient of variation. This method assessed the temporal variation of each threshold for each metric across the six surveys. The coefficient of variation is a simple calculation where σ is the standard deviation and μ is the mean.

$$CoV = \frac{\sigma}{\mu}$$

This analysis gives a percentage derived from the ratio between the standard deviation and the mean for each threshold.

The second methods of analysis was a Spearman's rank analysis of each threshold against mean soil moisture and two measurements of average catchment stage. Both short term (0-2 days after survey) and medium term (3-7 days after survey) stage were considered in this analysis. This method assessed the relationship between the metric threshold and catchment responses.

The first two methods of analysis are the same as those used in Ali and Roy (2010). The third method assesses the metric response to meteorological drivers and was adapted in order to fit with the conditions seen at this catchment. Ali and Roy (2010) conducted a three way variation partitioning analysis using current rainfall (in the day of the survey), potential evapotranspiration and antecedent rainfall. However for this study given the shallow nature of the soil moisture measurements it was decided that days on which rain was falling would affect the continuity of the survey due to the period of time that they took to sample. In addition to this it was considered that using a simple ratings curve for evapotranspiration would not accurately represent it. Also at the time of year that the study was being conducted evapotranspiration would be limited and relatively consistent. Therefore it was decided that the third method of analysis for this study would focus on antecedent rainfall. A variation partitioning was not done for rainfall however due to the lack of rainfall during the study period resulting in an inconsistent record from the previous 1, 2, 5, 7, 12 and 14 days before the survey. As a result the antecedent precipitation value that generated the best Spearman's Rank r value with mean soil moisture was used. This transpired to be AP14 ($r_{spearman}$ = 0.71). Thus the final method of analysis was the extent to which each metric correlated with AP14 as a value of R^2.

A satisfaction score for each of these analyses was identified (Table 3.1) in the same manner as Ali and Roy (2010). These were added to give the combined satisfaction score for each metric threshold out of a total of 9.

Qualitative Criterion	Quantitative Criterion	Score = 1	Score = 2	Score = 3
Temporal variability	X1 = Temporal coefficient of variation	X1 < 50%	50% ≤ X1 < 100%	X1 ≥ 100%
Influence on short or medium term catchment stage	X2 = Spearman rank correlation between connectivity metric and discharge	X2 < 0.5	0.5 ≤ X2 < 0.7	X2 ≥ 0.7
Dependence upon antecedent rainfall	X3 = Best performing R2 value	X3 < 0.5	0.5 ≤ X3 < 0.7	X3 ≥ 0.7
OBJECTIVE FUNCTION = Score(X1) + Score(X2) + Score(X3)				

Table 3.1: Computation table of satisfaction scores for connectivity metrics.

3.6 Network Index and Cumulated Probability Network Index

The final method of assessing hydrological connectivity was an alternative to the integrated connectivity scale length (ICSL) used extensively by Western et al. (2001) and others. ICSL was a method developed by Western et al. (2001) that identifies patches of soil moisture above a specified threshold and identified connection length omnidirectionally and topographically. An alternative approach to this is the Network Index developed by Lane et al. (2004). Using the presumption that for catchments with a uniform shallow soils, soil saturation controls when a non-contributing area becomes connected, such that the lowest value of the topographic index along a flow path controls the connectivity for that point to the surface network (Lane et al., 2009). This is then attributed to soil moisture to show the progression upstream of soil moisture impacts on connectivity pathways.

In order to use this method the soil moisture data had to be rescaled. Each soil moisture survey was converted to an ASCII format and the NODATA values were substituted with 0 to prevent leeching into the model. This data was then converted to a probability scale of connection. Below values of 0.3 m^3m^{-3} soil moisture were considered to have no chance of connection. Values above 0.7 m^3m^{-3} were considered to be certain to connect. The intervening values were put on a linear scale of connectivity between 0 and 1. This process was completed through Matlab script. The Network Index was calculated using SAGA GIS (an open access alternative to Arc GIS). In order to run this model an outlet raster had to be identified from channel accumulation rasters, and a filled DEM of the catchment. The presence of the drainage pipe along the channel of this catchment resulted in drier than predicted soil moisture. As a result the soil moisture connection probability rasters were adjusted to take this into account. Cells with a contributing area of 5000 m^2 or larger were given a values of 1 for complete connection, given the assumption that the field drain would facilitate the water out of the catchment. This was incorporated into all of the soil moisture connection probability rasters.

The Network Index was developed further by accumulating the probability of connection attributed by the Network Index. This Cumulative Probability Network Index (CPNI) takes the probability of the Network Index and multiplies it together along topographically derived flow paths. Through multiplying the probability from cell to cell along the flow paths derived from the model an accumulated probability of connection based on topography and soil moisture is attained. The flow pathways with high soil moisture register higher accumulation and thus likelihood of connection for that pathway is considered to be high. This method is a better approach to ICSL as it considers the connection along a pathway to be a probability function of soil moisture rather than an absolute binary result. CPNI results in a probability of connection which is far more representative of the impact of soil moisture on hydrological connectivity (Ali and Roy, 2009). This model was also run in SAGA GIS from the same DEM, outlet and soil moisture connection probability rasters as the Network Index.

The methods outlined in this chapter were used to characterise the catchment and its temporal conditions including topography, rainfall, stage and soil moisture data. Subsequent metrics used this data to analyse the hydrological connectivity portrayed by this soil moisture signal were analysed according to the objectivity function outlined here. In addition spatial characterisations were modelled using the Topographic Wetness Index, Network Index and Cumulative Probability Network Index in order to ascertain the most promising metric for hydrological connectivity prediction. The next chapter presents the field results. Chapter 5 then presents the analysis of the metrics.

4.0 Field Results

4.1 Topographic Surveys

Topography was initially estimated through historic cartographic sources. In this area of the UK the best topographic resolution is 10 m from the OS Land-Form (1:10000). Figure 4.1 shows the best topographical estimation of the site sourced from EDINA Digimap.

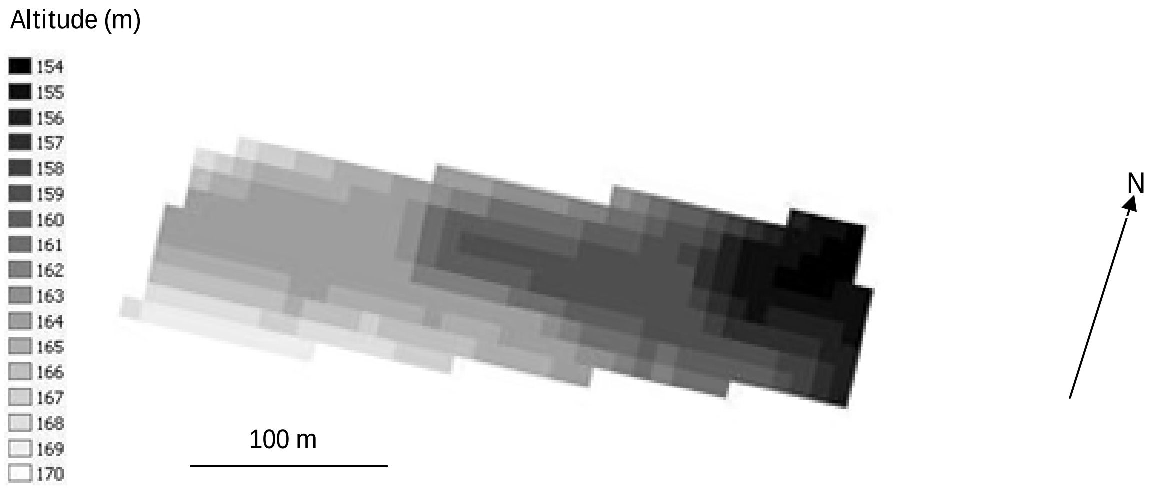


Figure 4.1: Remotely sensed Digital Elevation Model (DEM) of Sykeside Farm at 10 m resolution. The coarse resolution makes identifying important submeter topographic variation impossible showing archive data for this site is not appropriate for this study. © Crown Copyright/database right 2010. An Ordnance Survey/EDINA supplied service.

The overall valley shape was identifiable yet channel features and valley slope variability was poorly defined. Given the small scale of the site and the potential for high soil moisture variability this DEM resolution was insufficient and does not capture the subtle topography thought to drive the connectivity response. This resulted in the need for a DGPS (Differential Global Positioning System) survey which resulted in a DEM with a resolution 1.5 m (Figure 4.2). This improved level of resolution better defines the topographic distinctions of the catchment. The northern slope is 20 m shorter than the southern slope and does not reach the same elevation as the southern slope (3 m lower). However both northern and southern slopes have similar profiles and maximum heights. The outflow of the catchment is in the northeast corner. The ephemeral channel bisects the catchment in a gently meandering manner with a relatively low fall in altitude of 2 degrees across the catchment. There are a number of disruptions in the valley bottom that identify zones of erosion due to broken subsurface drainage. The channel broadens at the channel outflow as the southern slope curves away to the southeast and the catchment joins the stream. The topography is smooth and undulating with few abrupt breaks.

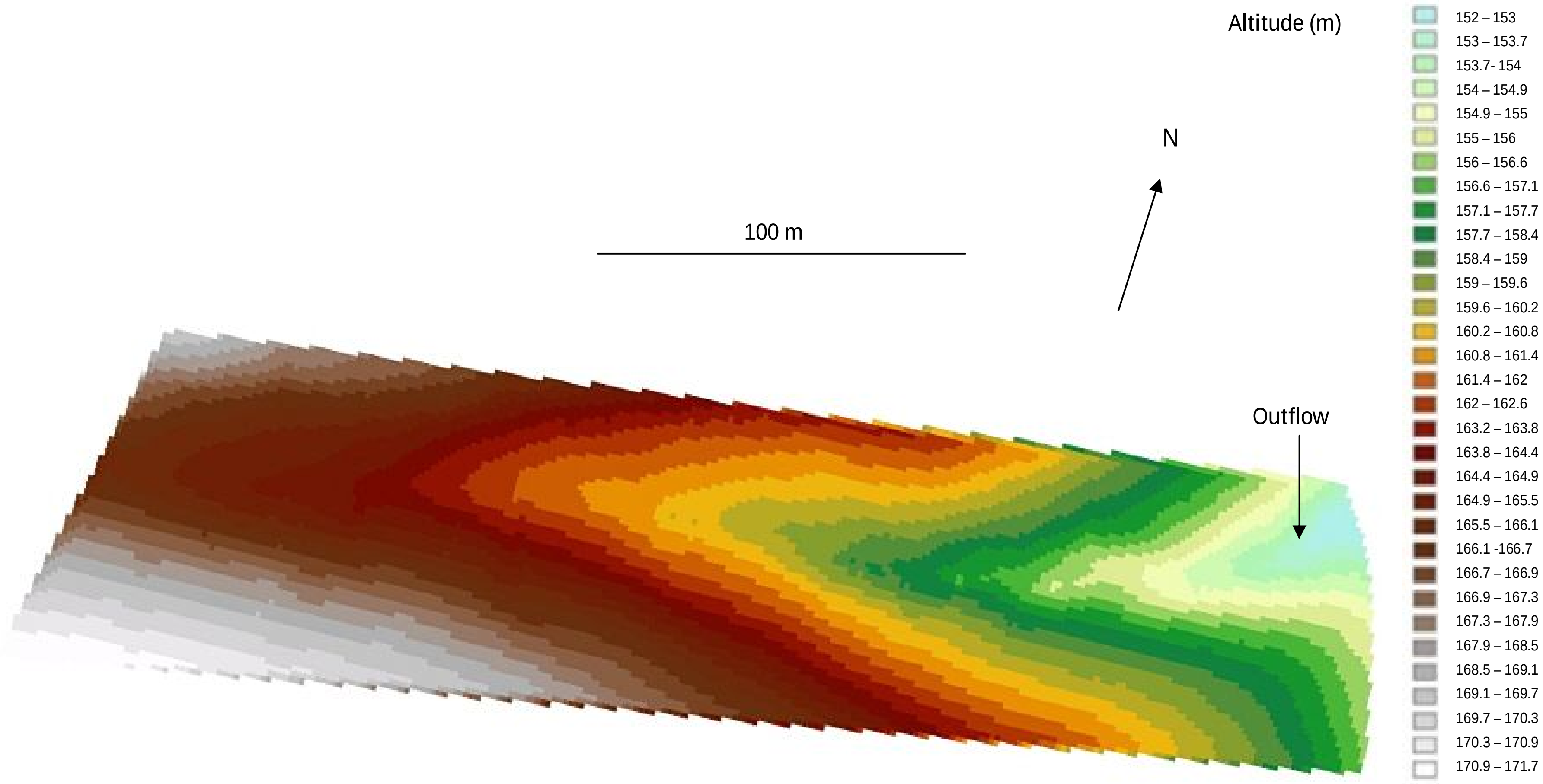


Figure 4.2: Digital elevation model of Sykeside catchment as derived from DGPS at 10 cm vertical resolution on a 1.5 m grid.

An assessment of the catchment slope was made to understand the distribution of the topography across the site (Figure 4.3). The channel has a constant angle of below 4° and is clearly identifiable. The rest of the catchment is predominantly below 15°. The nature of the northern slope changes downstream. At the head of the catchment the northern slope is concave.

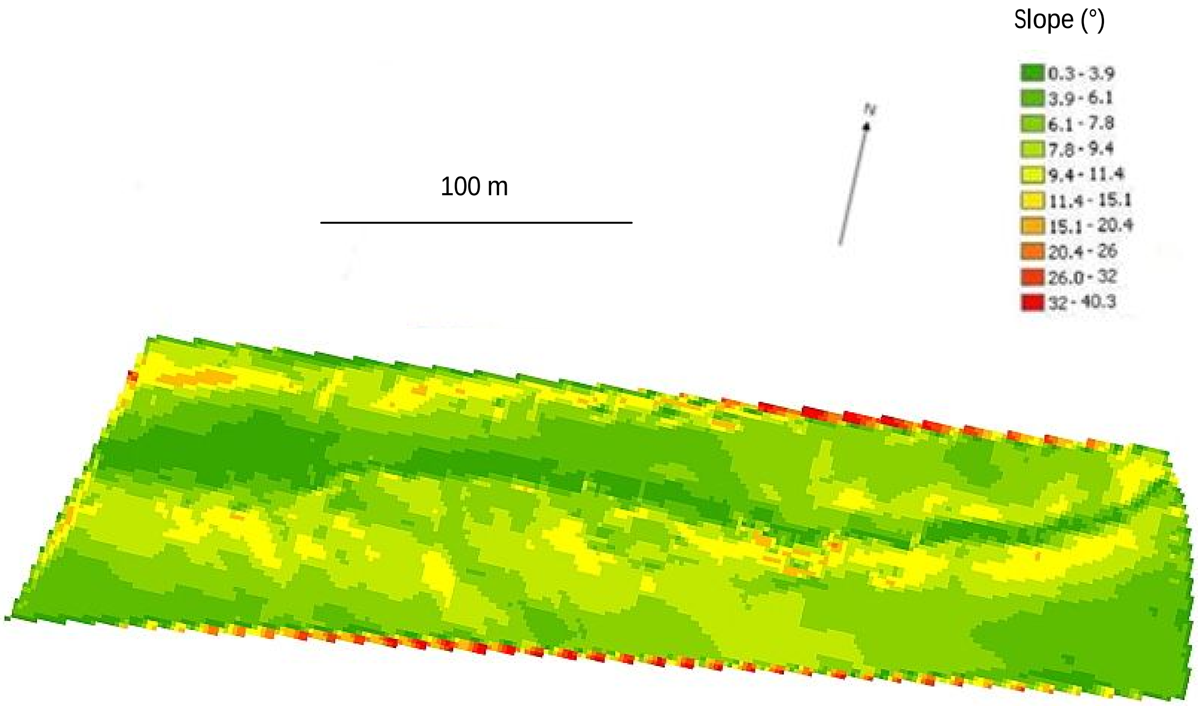


Figure 4.3: Raster of catchment slope generated from DGPS DEM using spatial statistics.

The catchment is largely defined by low slope angles and gently undulating topography with the potential for surface organisation in the west of the catchment that narrows to a more severe containment of the channel in the east. The northern slope gently grades towards the low slope angles of the channel itself. However there is a transition downstream where the channel constricts as both the north and south slopes steepen near the channel to form a much narrower valley. The southern slope does not convey the same transition or the same organisation as the northern slope but exhibits a relatively flat plateau at the higher elevations. It shows a more organised downwards slope with the indication of gullies and ridges across its surface, particularly in the west. The southern slope displays similar behaviour to the northern slope in the east of the catchment. The narrowing of the valley results in the greatest slope angels in the catchment with values as high as 40°. The slope is more consistently high compared to the northern slope. There is a clear ridge perpendicular to the channel denoted by light green colour in the centre of this section of the southern slope. The highest slope angles are specific to one main gully which is also where the most complicated slope signal is recorded. Despite the localised high slope angles seen in this gully the slopes of the catchment do not clearly identify other examples of topographic features. Although there is suggestion that there is some organisation on the southern slope this is not conclusive.

Further analysis was required to ascertain the nature of the potential surface organisation in the west of the catchment. As a result the slope aspect was derived from the DEM (Figure 4.4). The potential for gullies and surface organisation on the southern bank proves to be spurious with the majority of the southern slope being wholly orientated northwards. Thus the variation seen in the slope angles was not a valid indicator for channelization on the slopes. The northern slope also shows no significant organisation. There is variability but this is orientated southwards and south-westwards. The absence of any values orientated towards the west shows that there is no channelling on the slopes. The south-eastern corner of the catchment is orientated away from the channel suggesting this area does not contribute to the outflow. As the channel curves northwards close to the outflow the valley slopes reorientate towards it. The greatest variation occurs close to the channel itself. Much of this is the manifestation of the channel itself indicated by a varying band orientated eastwards. However the area previously identified with high slope angles does show a significant aspect change to the rest of the southern slope. This indicates there is some small channelling, however it does not appear as though it is one structured gully. Two small gullies close to the channel are present, located where the topography was steepest.

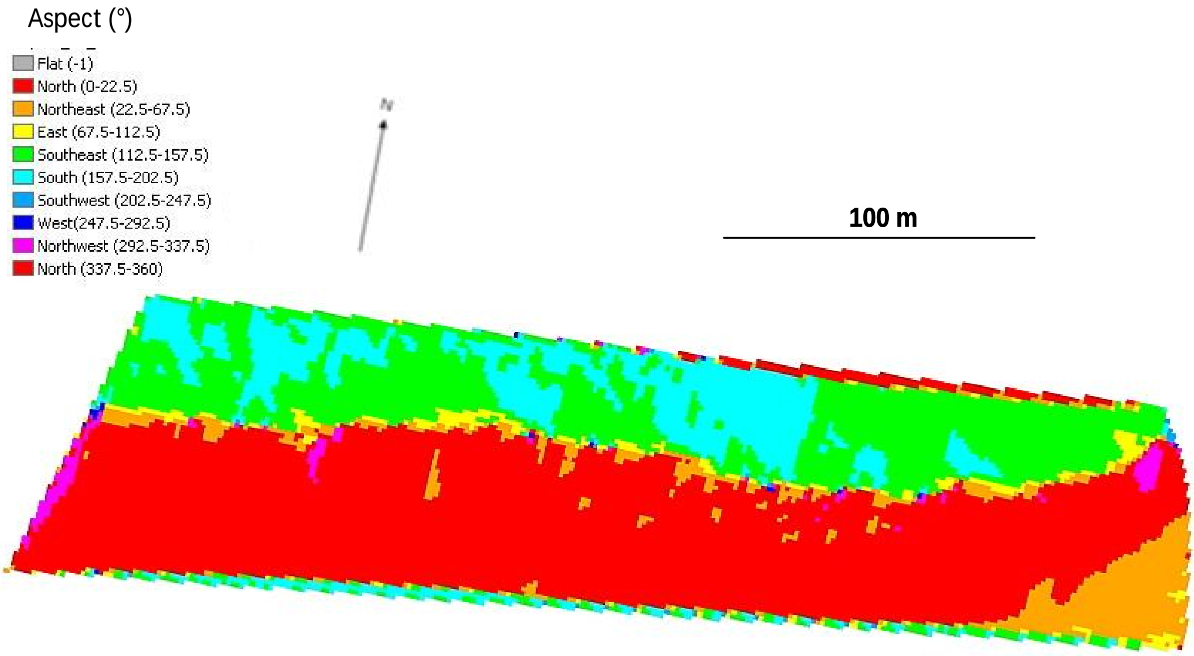


Figure 4.4: Raster of slope aspect generated from DGPS DEM.

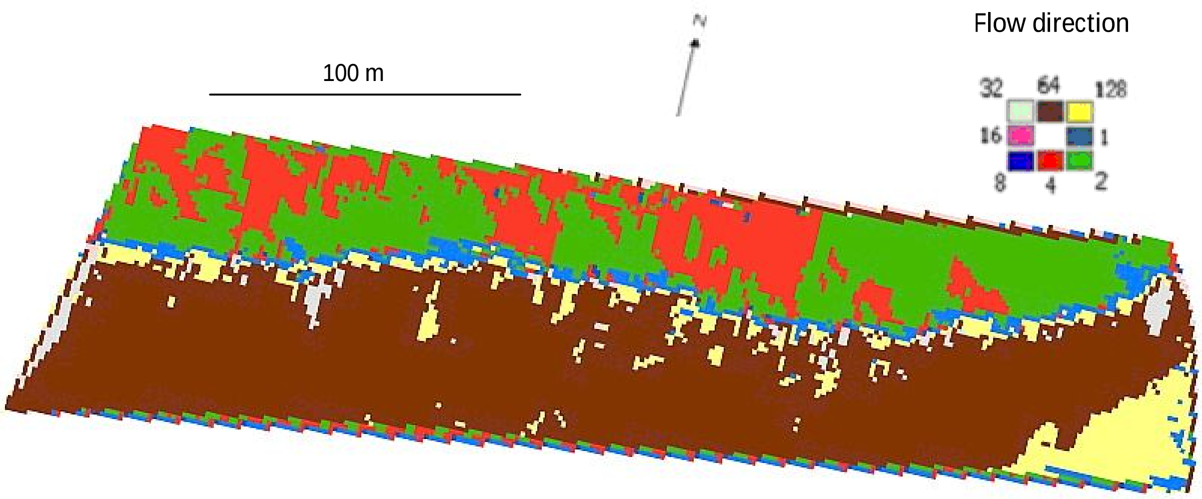


Figure 4.5: Raster of flow direction generated from DGPS DEM.

To identify the impact this slope aspect would have on surface flow, the flow direction was also estimated from the DEM (Figure 4.6) (O'Callagan and Mark, 1984). This suggests similar interpretations as for Figure 4.4. The introduction of flow direction is integral to generating an estimation of gross flow accumulation. Figure 4.6 presents the flow accumulation on the topographic surface of the catchment with zero infiltration. This analysis reflects the previous analysis displaying a number of short low value channels. The majority of the catchment surface is represented by very low accumulated values. This pattern is disrupted more on the northern slope with a complicated sequence of ridges particularly in the west. The southern slope is more contiguous with the main disruption separating the south-eastern corner which has been identified at being orientated away from the catchment outflow. The lateral flow pathways are short and consistently low in value. These are consistent between both the north and the south slopes. The accumulation in the channel is of particular interest. It was highlighted on the DEM that there are locations of erosion due to a broken subsurface drainage pipe. The impact of these holes is evident from Figure 4.6. The location of washout holes creates breaks in the channel that causes a series of flow accumulation sequences along the channel of varying lengths. The best example of this is a third of the way down the catchment where the high accumulation values above 1500 give way to low accumulation below 1000. Seven distinct sections of channel are identifiable. Areas where this accumulation breaks down in reality represents connection to the outflow via the subsurface drainage. The flow accumulation reveals a relatively unorganised planar surface with limited accumulation into lateral gullies to the main channel. The main ephemeral channel generated an intricate pattern highlighting the breaks in the continuity of the channel.

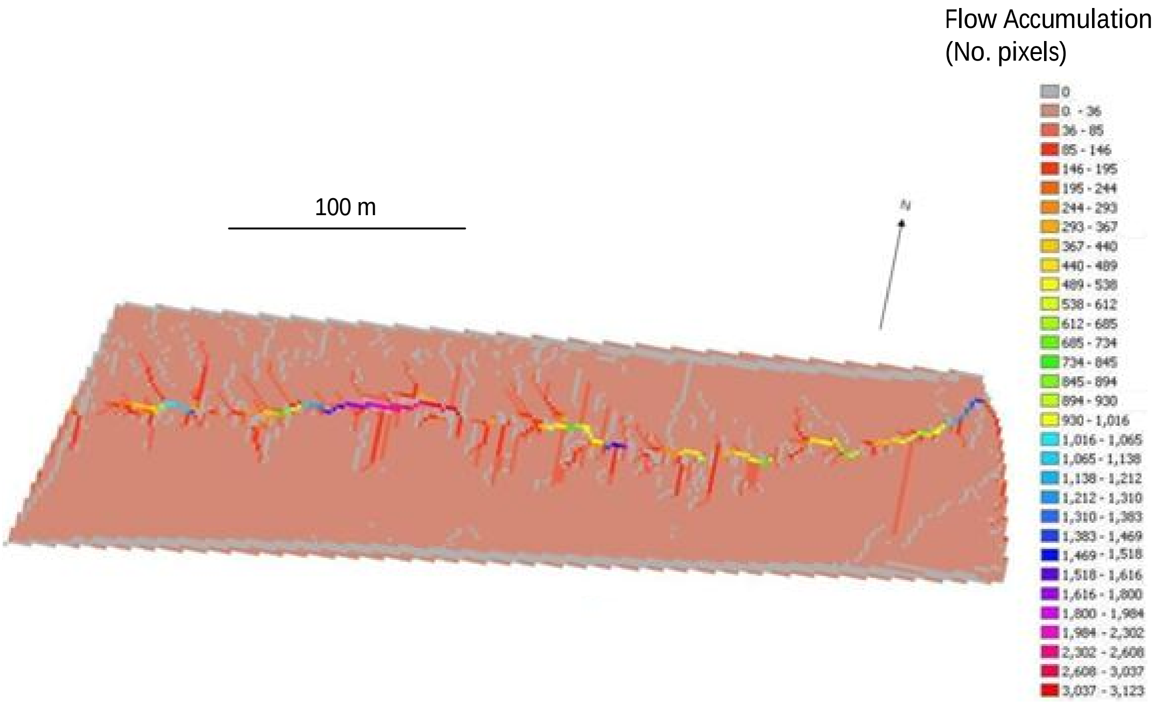


Figure 4.6: Raster of flow accumulation generated from flow direction raster.

4.2 Antecedent conditions – Rainfall events

The importance of rainfall is considered to better understand the soil moisture distributions. The Sykeside catchment has a six year long rainfall record. As a result the conditions of the survey period can be compared to give an impression of how typical the rainfall record is. Firstly a total for each year was calculated for the period at which the study took place (8^{th} February – 5^{th} May). Figure 4.7 shows this relationship highlighting the low volume of rainfall measured for this catchment by comparison to recent years. Despite year to year variability 2010 is notably drier than the previous 5 years receiving 80 mm lower than average over the spring period. As a result it can be expected that Spring 2010 produced the lowest discharge compared to the last 5 years.

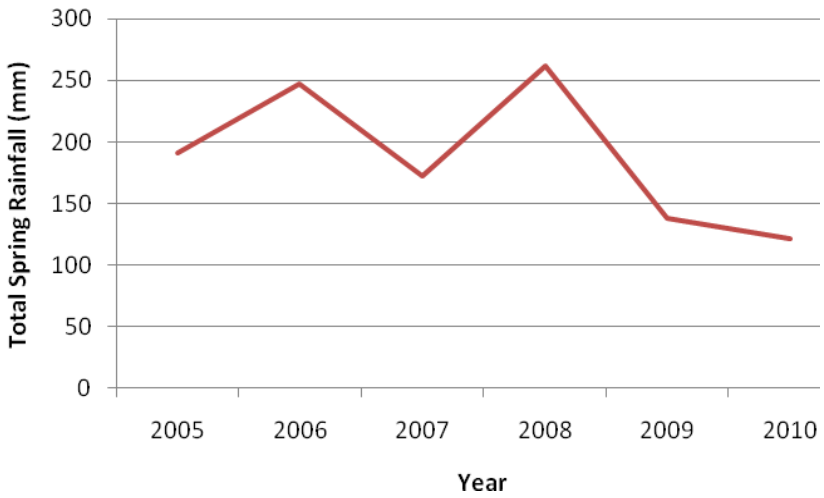


Figure 4.7: Spring rainfall totals for Sykeside farm March - May 2005-2010.

The distribution of rainfall intensity was also generated to ascertain whether the rainfall in spring 2010 was representative by comparison to the rainfall record (Figure 4.8). The intensity was maintained in hours rather than being displayed as a percentage in order to develop the pattern seen in Figure 4.7. Figure 4.8 emphasises the variation between years with 2010 clearly having the lowest rainfall. Previous years (2005, 2007 and 2009) appear to have a similar number of total rainfall hours however the distribution towards the lower intensities suggest that 2007 and 2009 had more extended periods of low intensity rainfall in comparison to 2005 which shows a smoother transition to higher rainfall intensities. There is a similar discrepancy between the high rainfall years with 2008 showing a more stepwise increase in rainfalls below 1 mm. In contrast 2010 had far fewer hours of rainfall with a very large proportion falling at the lowest intensity recorded. It is clear that consideration has to be taken when drawing conclusions from this study given the relatively low rainfall. However the distribution of the rainfall correlates well with the historical rainfall record (Figure 4.9). Indeed, the 2010 record has a very similar distribution to the highest rainfall year in this record (2008). This suggests that despite the low number of rainfall hours the distribution is consistent with the historic record.

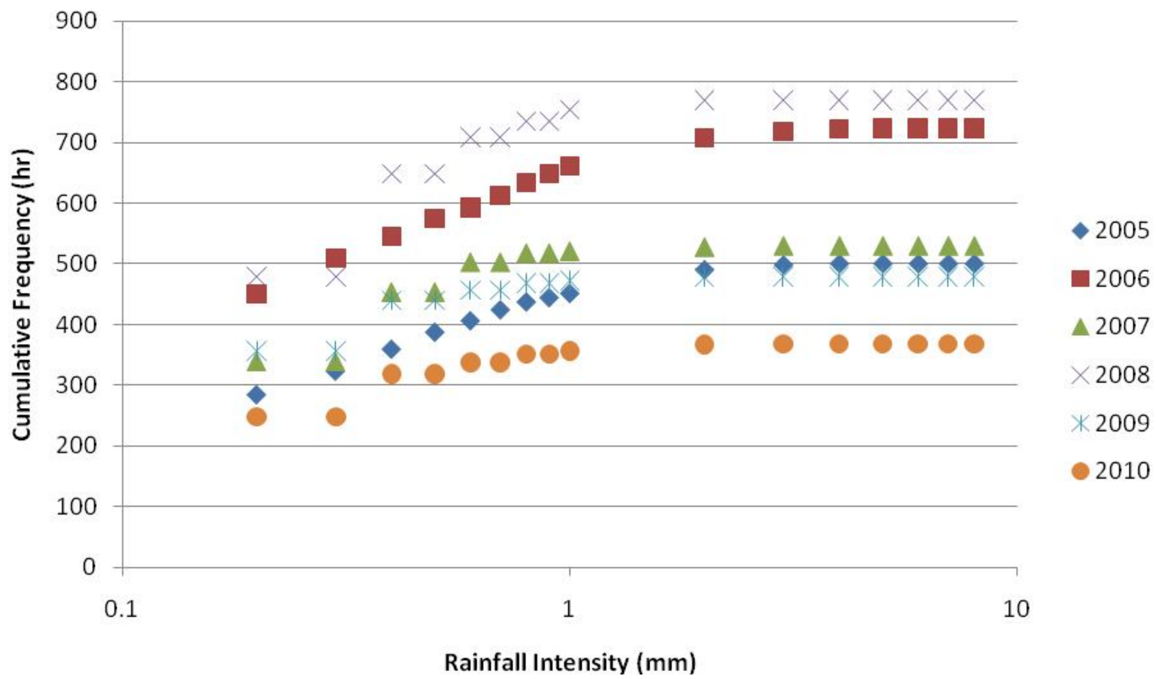


Figure 4.8: Cumulative frequency graph of rainfall hours for the period of study 8th February – 5th May.

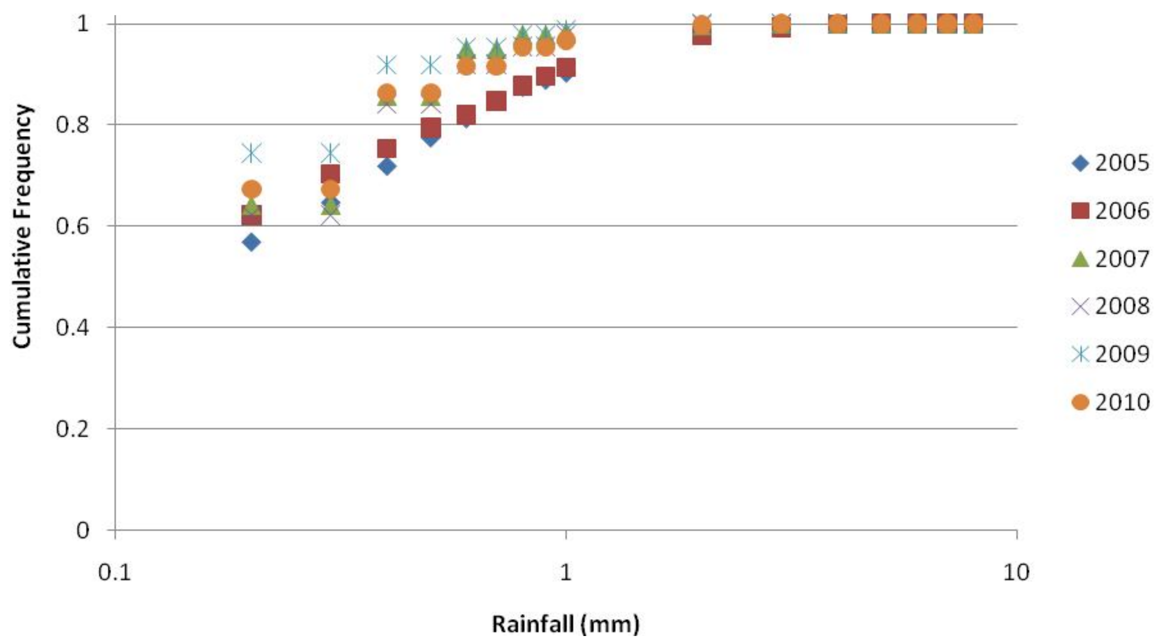


Figure 4.9: Cumulative frequency graph showing the distribution of rainfall for the period of study 8th February – 5th May 2005-2010 in percentage.

This distribution is further explored through analysis of rainfall spell (a spell was a period of time where there was at least 0.1 mm of rainfall in 24 hours). Contiguous rainfall periods separated by 24 hours were identified. Table 4.1 shows a summary of this spell analysis. Interestingly the mean intensity suggests that the rainfall distribution is more complicated than Figure 4.8 initially showed. The number of spells has considerable variation. There is some continuity between the maximum spell rainfall and the total rainfall, except for 2010 whose maximum spell rainfall total is higher than would be expected. Maximum rainfall intensity is very similar across the record. However the maximum duration shows that 2006 has the longest spell by nearly 200 hours. The combination of these factors gives a mean intensity which is counterintuitive. 2007 has a very high mean intensity. This high intensity combined with the relatively low rainfall total suggests that 2007's rainfall is characterised by a small number of high rainfall events. 2010 has the second highest average rainfall intensity. Given the very low total rainfall this suggests a similar pattern to 2007. 2010 also has the shortest average spell duration which suggests a short period of high intensity rainfall combined with low rainfall events. This pattern is common between 2007-2010. 2006, by contrast, has large volumes of low rainfall intensities over a long period of time. 2005 also shows this form of rainfall. These results indicate that the specific manner of rainfall varies a great deal across the years. Given that the maximum intensity is relatively consistent it becomes clear that it is the duration of high intensity rainfall that distinguishes the years. This is identified by the mean spell duration which matches the pattern seen in the total rainfall. There is a clear distinction between the high rainfall years of 2006 and 2008. 2006 has long periods of low intensity rainfall which is in contrast to 2008 which shows short duration higher intensity rainfall. Figure 4.10 highlights this difference. There is a completely different pattern between mean rainfall intensity and the mean rainfall per spell. This shows that rainfall intensity is not as important as the total rainfall in a spell demonstrating the contribution made by low rainfall to the total. The combination of these factors in addition to the frequency of the rainfall spells defines rainfall distribution.

	Number of spells	**Maximum spell rainfall (mm)**	**maximum duration (hr)**	**mean duration (hr)**	**maximum intensity (mm hr^{-1})**	**mean intensity (mm hr^{-1})**
2005	10	36.52	268.00	143.60	3.68	0.13
2006	12	44.19	458.00	103.83	4.17	0.18
2007	13	36.23	150.00	51.08	4.80	0.64
2008	20	55.25	160.00	49.55	4.40	0.23
2009	13	25.62	185.00	61.15	3.80	0.22
2010	20	47.61	184.00	26.4	4.40	0.27

Table 4.1: Summary of spell analysis for spring rainfall (February-May) for 2005-2010.

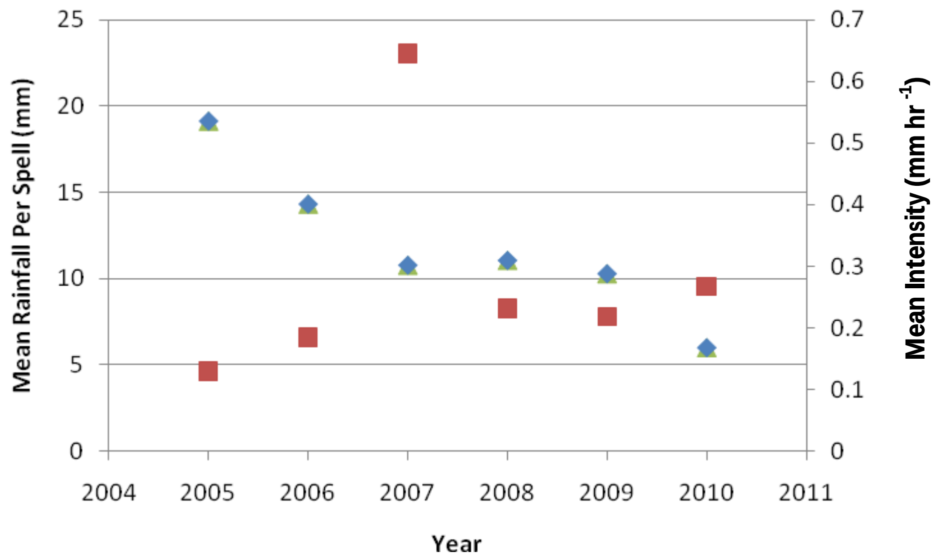


Figure 4.10: Scatter plot of mean spell rainfall intensity (red) and mean rainfall per spell (blue).

4.3 Antecedent conditions – Stage

The rainfall record indicates that the rainfall for the period of the study is the lowest in five years. With this in mind the stage record for the winter period (November 2009 – May 2010) and the study period (February – May 2010) were analysed (Figure 4.11 and Figure 4.12). The stage record for the winter of 2010 has a bimodal distribution. The two peaks are centred around 26 cm and 43 cm. These two peaks suggest a peak of unconnected base flow as well as a connected rainfall peak flow as a result of rain storm events. The cumulative frequency shows that the initial peak represents approximately 25% of the total stage with the higher peak representing 30%. There is a longer tail of very high stage levels compared to the low stage levels. This indicates that the lower stage peak represents lower rainfall scenarios. The bimodality suggests a threshold system of high and low flow. By comparison to the study period the low stage peak remains however the high flow peak becomes absent. Having identified 2010 as a dry year the spring period represents the lower flow conditions. The smaller peak in stage is important regarding the development of soil moisture over the study period. Clearly the majority of the significant rainfall occurs earlier in the winter. The rainfall analysis highlighted that the rainfall is limited to short term events of relatively high intensity. Thus the wetting up before the study period was subject to the majority of the rainfall suggesting a consistent drying out with short rainfall events.

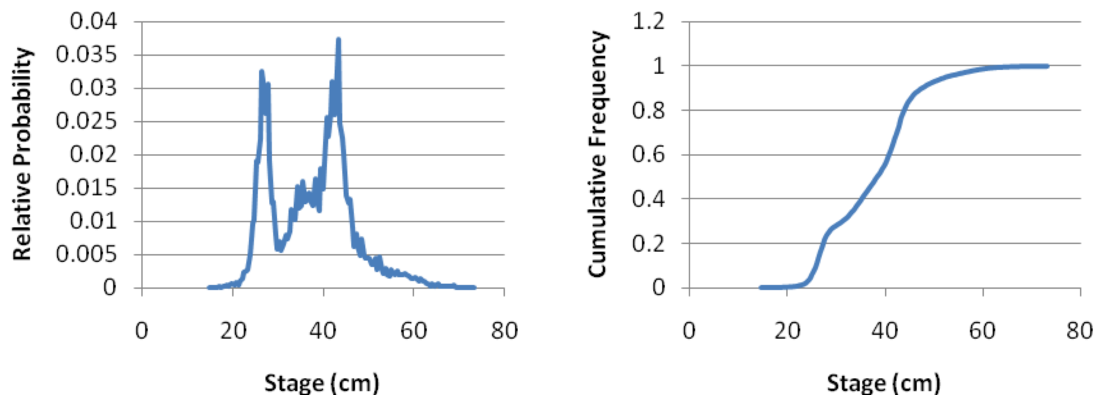


Figure 4.11: Relative probability and cumulative frequency of stage for the Winter and Spring period (November 2009 – May 2010).

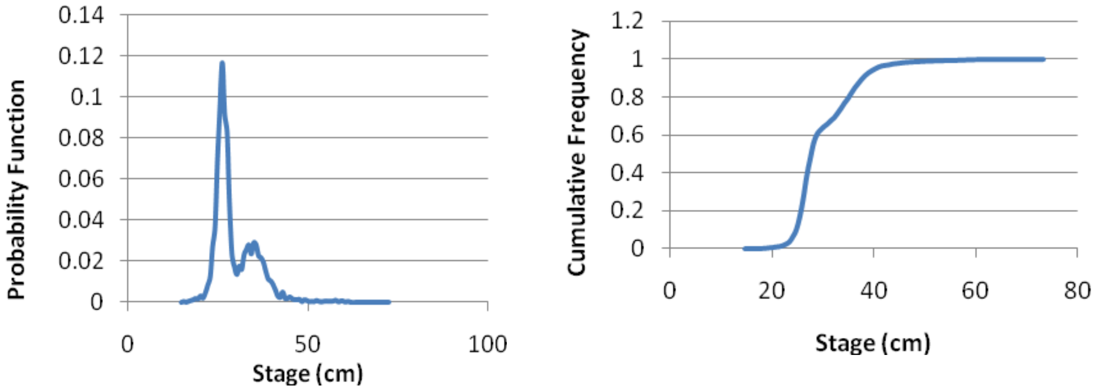


Figure 4.12: Relative probability and cumulative frequency of stage for the study period (February – May 2010).

Figure 4.13 shows the total stage record for the Sykeside catchment which extends between November 2009 to May 2010. The rainfall record is also displayed. This graph confirms that the majority of the rainfall events and rainfall volume occur before the study period, particularly in November. December and January exhibit fewer high intensity rainfall events which results in fewer sharp peaks in stage. However over these two months the volume of rainfall is sufficient to maintain the stage above 40 cm for the majority of the period. The continued low level of rainfall, particularly the lack of high intensity events, result in a decline in the stage. This is highly variable as a result of small rainfall events which have an increased impact as the stage falls. The study period is dominated by one short period of high intensity rainfall followed by a long period of no rainfall. This gives a good combination of conditions for soil moisture variability, however, the highest level of saturation is likely to be less than would have been seen in November. Figure 4.14 shows in more detail the individual rainfall and stage record for the study period. There are two large peaks of rainfall that follow one another with a subsequent 22 day period with no rainfall at all. The polarity of the rainfall study has a strong hydrological impact on the stage and the soil moisture distributions with three surveys conducted before it and three after. However despite this long period of dry conditions the stage record is variable. Although this is expected during periods of rainfall it shows that antecedent conditions many days earlier impact on the stage outflow, yet intense rainfall create rapidly rising and receding peaks in the stage data. The highly reactive nature of the catchment to rainfall highlights its importance to catchment response and the likely impact on soil moisture.

In order to better understand the relationship between the stage and rainfall data each rainstorm event with an intensity of 1 mm hr^{-1} or greater was analysed. Rainstorm events during the study period were limited with only four that exceeded the 1 mm hr^{-1} threshold. This was not a sufficient number to generate meaningful relationships. As a result rainstorm events were included from the whole winter record. The first consideration was the relationship that the rainfall has with respect to time and how the four events during the study period compared to the winter as a whole. Figure 4.15 shows this relationship which displays a positive correlation. The distribution of rainfall events show that the majority of rainstorms are below 10 hours in duration and below 10 mm in total. Despite the study period only exhibiting four storms their magnitude and duration number amongst the largest of the winter. This suggests that despite the dry winter the study period has some significant rainfall events. There are two outliers showing the extent of the magnitude and duration of rainfall events. It should be noted that these are all considerably shorter in duration than those reported in the spell analysis.

The impact of storm events on stage was then assessed (Figure 4.16) by correlating the magnitude of each hydrograph's rising limb with total storm rainfall. The distribution is positive with an increased stage response reflecting an increased total rainfall. The results are more evenly distributed displaying a curved pattern indicating a limit to stage response. Again the study period events display some of the highest responses. The magnitude of stage increase is important because the variation in antecedent conditions result in no trend from the maximum stage with rainfall volume or intensity (Figure 4.17). The trend from Figure 4.16, however, shows the impact of rainfall while removing the effect of antecedent stage conditions. Alternatively the combination of high uniformity in the maximum stage and a trend between catchment response and total rainfall suggest limited infiltration resulting in a consistent runoff response from the catchment. High rainfall seems to result in similar maximum stage responses whist creating a trend of increase in stage.

The time taken for this catchment response was subsequently assessed. It was found that there was no real relationship between the lag time of the storm hydrograph and the total rainfall (Figure 4.18). There was a complete range of catchment responses across the total rainfall distribution. However when lag time was correlated against mean storm intensity a distinct threshold emerged. The volume of rainfall is not the key factor in eliciting a rapid rainfall response. By contrast high rainfall intensities cause a divergence in this distribution. Below an average intensity of 1.5 mm hr^{-1} there is a significant range of lag times. This is likely to be as a result of varying degrees of catchment saturation. Above this threshold the majority of catchment responses are an hour or less. This rainfall intensity appears to represent the level of rainfall required to ensure rapid runoff from the catchment.

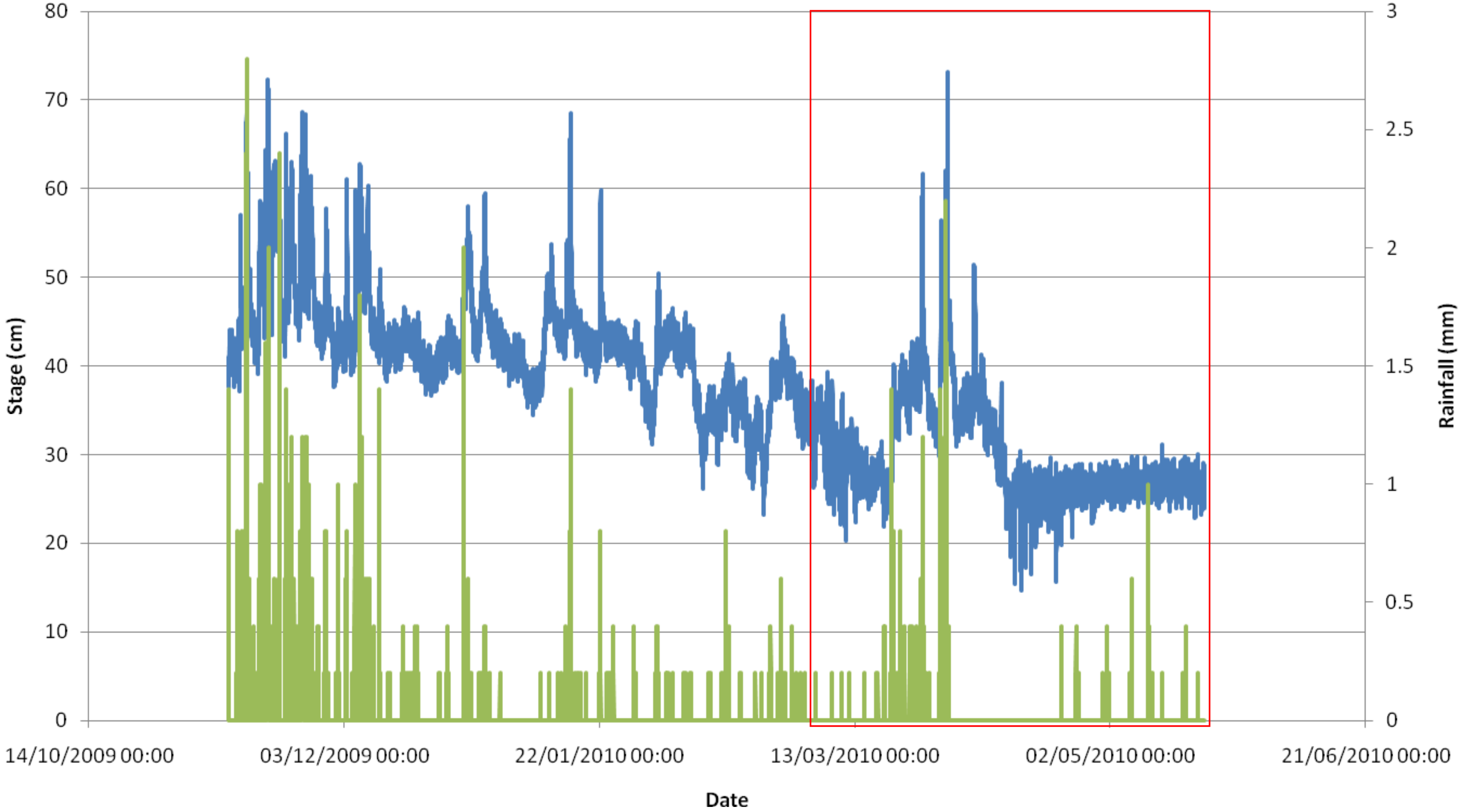


Figure 4.13: Rainfall and stage data for the Winter period (November 2009 – May 2010) Highlighted area in the red box shows study period in more detail in Figure 4.14.

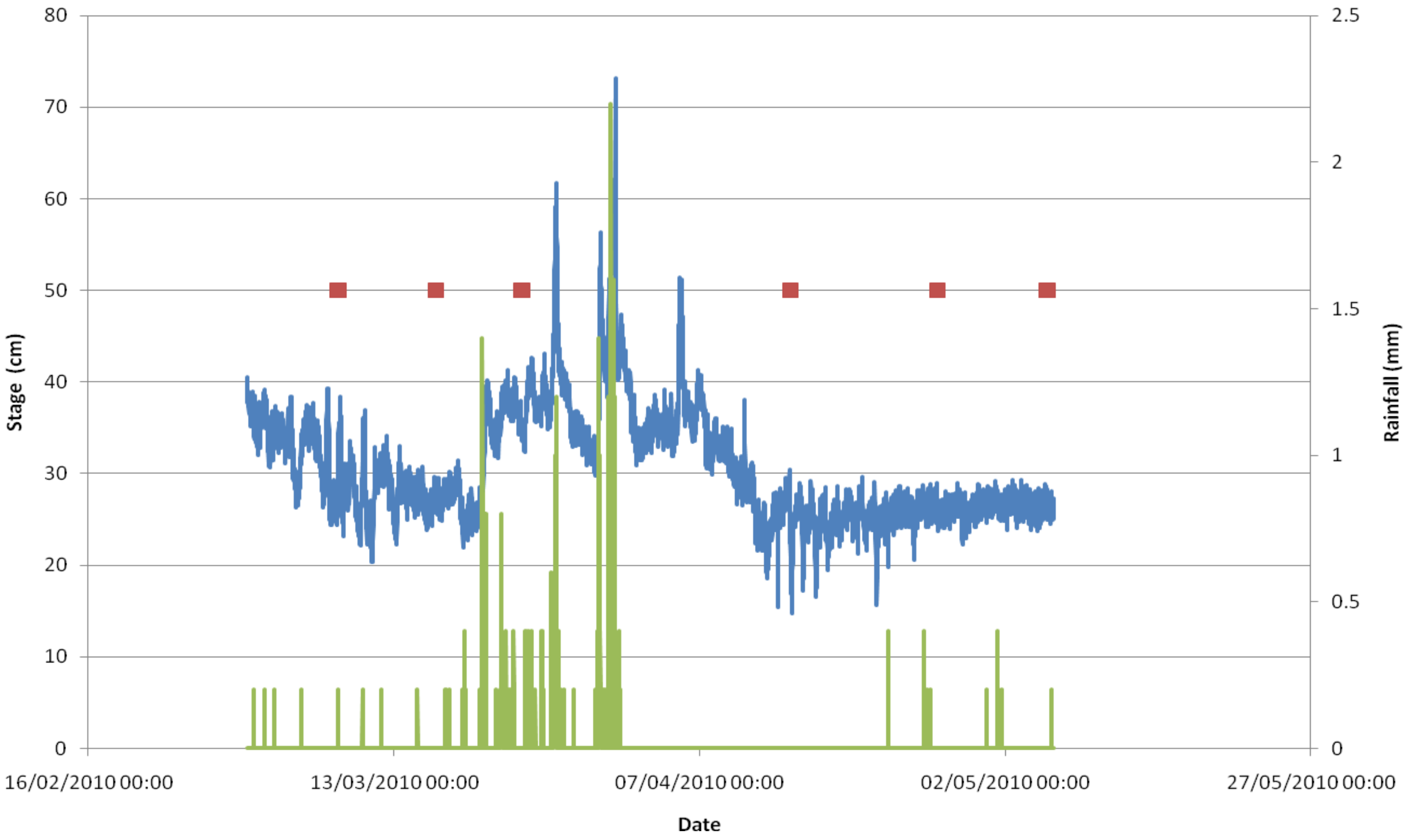


Figure 4.14: Graph of stage and rainfall data for the period 1st March – 5th May 2010. Red markers denote the day when soil moisture distribution was measured.

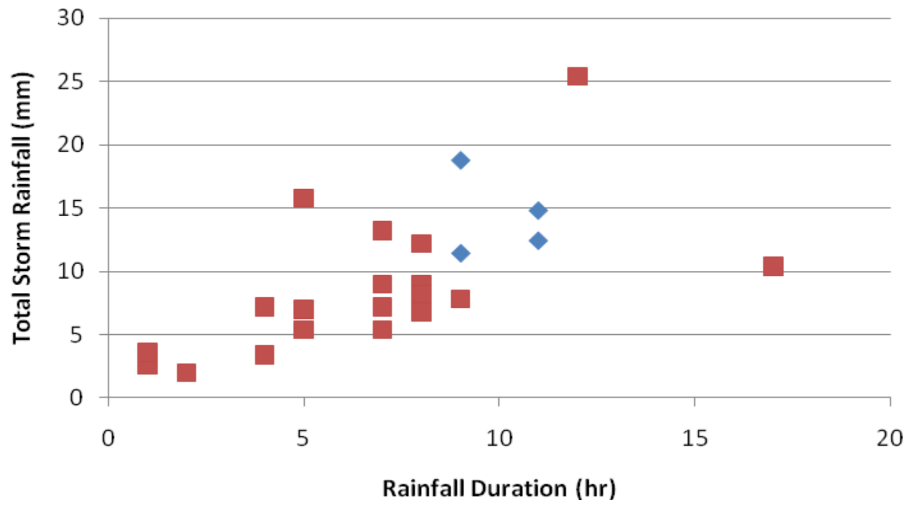


Figure 4.15: Scatter plot of duration of rainstorms against total rainstorm rainfall. Blue markers represent events during the study period.

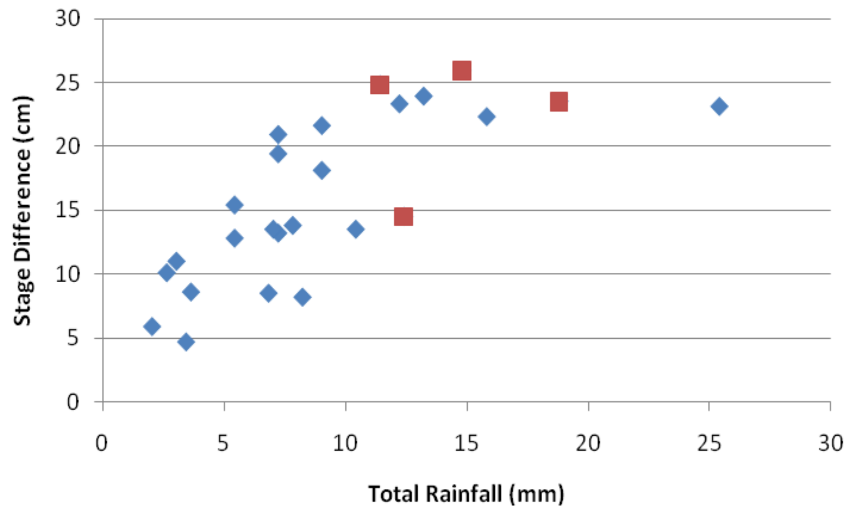


Figure 4.16: Scatter plot of total rainfall against the difference between initial and peak stage. Red markers represent events during the study period.

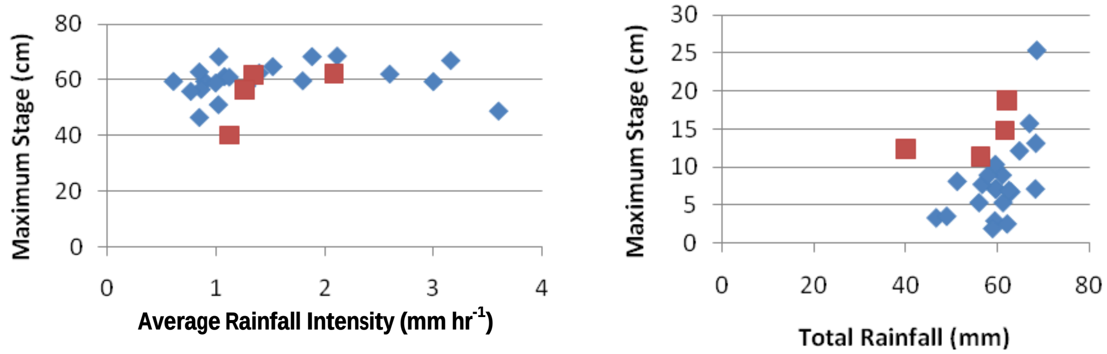


Figure 4.17: Scatter plots of maximum stage against rainfall intensity and total rainfall. Red markers represent events during the study period.

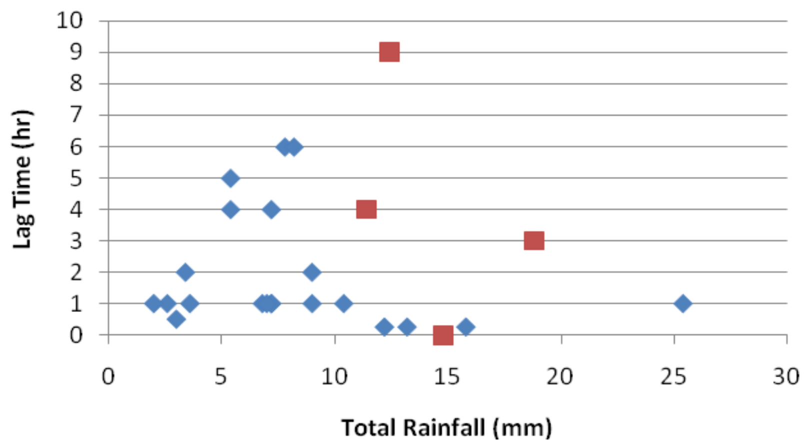


Figure 4.18: A scatter plot of total rainfall against hydrograph lag time. Red markers represent events during the study period.

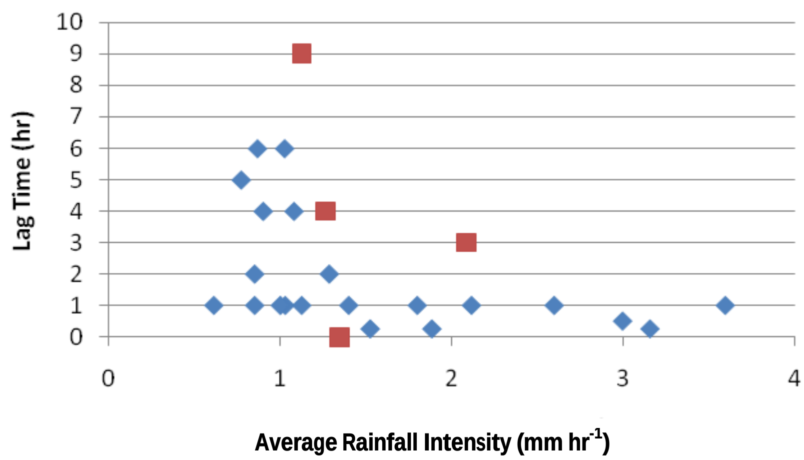
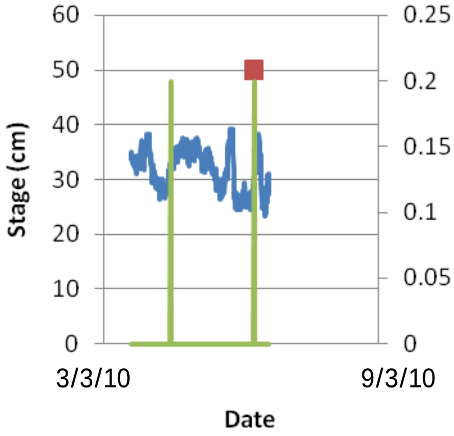


Figure 4.19: A scatter plot of mean storm intensity against hydrograph lag time. Blue markers represent events during the study period. Red markers represent events during the study period. Red markers represent events during the study period.

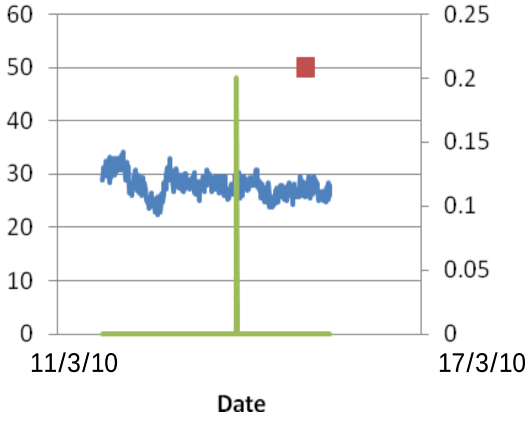
Figure 4.20 shows individual 3 day antecedent conditions for each survey. What is immediately apparent is the variability in the stage data irrespective of rainfall input. This is likely to be due to weather conditions and equipment accuracy. However there is a clear range for low rainfall conditions and this can be confidently averaged. The largest antecedent stage was identified as 40.2 cm for the third survey. The wet surveys (1 and 2) show a variable stage record that suggests a decline over time indicating earlier rainfall seen on the 26th February. There is very limited rainfall for the periods shown. Again the conditions are important in order to understand the pattern that this displays. Falling stage in surveys 1 and 2 suggest earlier rainfall and explains the high soil moisture as well as the low potential for evapotranspiration at that time of year. Survey 3 shows the wettest antecedent conditions and this is reflected in the stage response and the high level of soil moisture recorded. Survey 4 is at the end of the 22 day period of no rainfall and that results in a gradual drying out of the catchment and reduction in stage. Survey 5 and 6 show small volumes of rainfall which have a limited impact due to the increased potential for evapotranspiration at this time. Antecedent conditions are very important in understanding soil moisture patterns and the potential for estimation of hydrological connectivity. Subsequently antecedent conditions that were identified by Ali and Roy (2010) were also calculated for this study in order to compare with soil moisture metrics. These conditions are shown in Table 4.2.

Survey	AP1 (mm)	AP2 (mm)	AP5 (mm)	AP7 (mm)	AP12 (mm)	AP14 (mm)	PD_stage (cm)	SD_stage (cm)	DA_1 (cm)
1	0	0	0.4	0.8	13.2	13.4	30.14	28.97	29.21
2	0	0.2	0.6	0.8	1.2	1.6	27.19	27.44	27.94
3	4	7.8	22.8	23.4	24	24.2	38.26	37.29	38.53
4	0	0	0	0	0	9.4	29.30	24.74	24.67
5	0	0	0.4	0.4	0.4	0.4	26.55	26.17	26.25
6	0	0	1.2	1.2	3.2	3.2	25.91	26.85	27.12

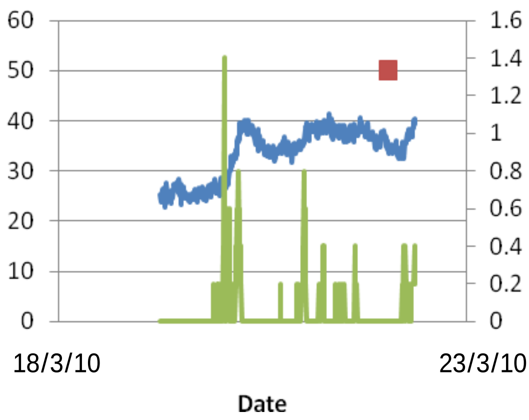
Table 4.2: Table of antecedent conditions including cumulative precipitation from one day before to 14 days before (AP1-AP14) and stage on the day of survey (SD_stage), the day preceding (PD_stage) and the day after (DA_1).



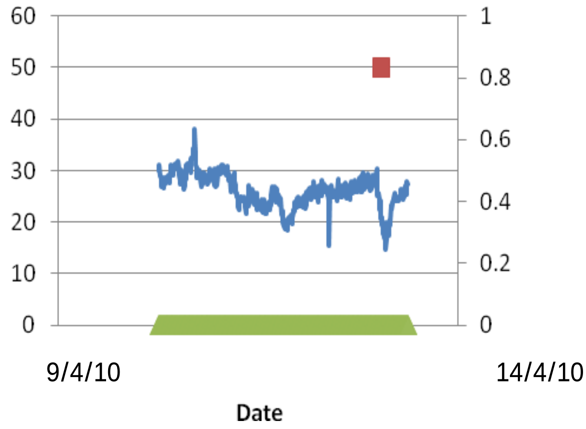
Survey 1



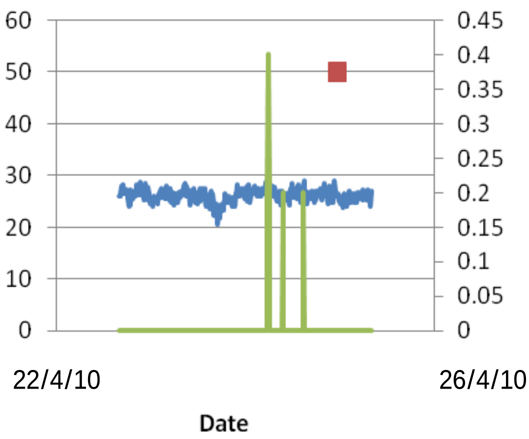
Survey 2



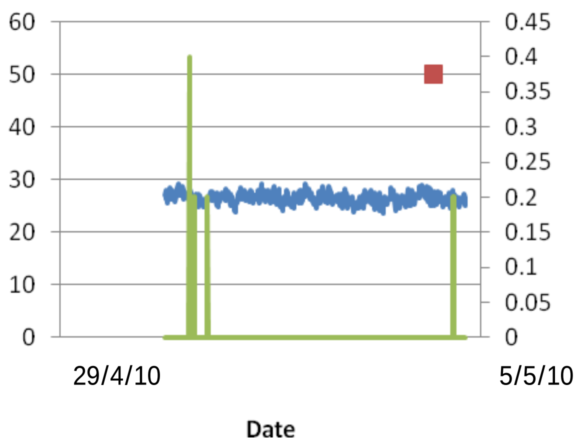
Survey 3



Survey 4



Survey 5



Survey 6

Figure 4.20: Rainfall and stage graphs showing antecedent conditions (previous three days) for each soil moisture survey.

4.4 Soil Moisture Distribution

Figure 4.21 depicts rasters of the soil moisture surveys taken between 8th March and 5th May 2010. Results from rainfall and stage analysis (Figure 4.13) show that there is a trend towards decreasing moisture. Soil moisture corroborates this, decreasing over this time period. Despite this general declining trend there is some variation particularly between the three surveys in March. The site is recovering from moderate intensity rainfall events on 26th February showing clear active areas (Figure 4.22). The limited rainfall between survey 1 and survey 2 shows a decline in soil moisture. Although the decline in stage is below approximately 5 cm the drying out of the catchment results in an absolute difference of 5 % in mean soil moisture (Figure 4.23). This shows the reactive nature of the catchment even to relatively small rainfall events.

The third survey measured on the 23rd March is the wettest survey. This survey was taken three days after one of the 4 significant storm events to occur during the study period (Figure 4.21). In spite of the subsequent 7 days exhibiting the other significant rainfall events the stage record suggest that the level of saturation seen for survey 3 is highest level of stage runoff without a significant rainfall event. The stage at this survey is representative of the wetter winter period (Figure 4.13) and, thus, can be seen to be a reasonable end member for the representation of soil moisture. The extent of soil moisture above 0.5 m^3m^{-3} corroborates this. Survey 1 and 2 can be seen to represent the transition that is not measured after the large rainfall events at the end of March. The stage record is at a similar level for survey 1 as the intervening catchment recovery between survey 3 and 4 and survey 2 shows a stage condition that is just above that of the final 3 surveys. There are a number of differences between these three surveys. Three areas of high saturation can be identified (Figure 4.22) in survey 1 that persist in survey 2 and in the other drier surveys. In wet conditions these high moisture areas result in similar measurements. However survey 3 shows a more extended distribution of potential source areas. The three saturated areas seen in Figure 4.22 are all found on the southern slope. Survey 3 highlights the potential for source areas on the northern slope in four locations. They are present in the drier surveys however they become disconnected and dry out more quickly. Also despite their presence they are not seen to be as wet as areas A, B and C after survey 4.

The connectivity of these wet areas varies. Connectivity is hard to visually assess due to the relatively dry nature of the channel itself. Areas A, B and C remain connected until survey 4. Beyond this the catchment dries out to the extent that even these wet areas are no longer connected to the channel. The wet areas on the northern slope show a more interesting development. These source areas are further away from the channel resulting in a more easily identifiable flow pathway. These pathways are clearly connected in survey 3 and survey 1. Survey 2 appears to be approaching the threshold for disconnection. Despite still being connected to the channel by pixels with elevate soil moisture it is in some cases limited to a single pixel. The dry areas are becoming increasingly distinct particularly the large contiguous southwestern section and the ridges between the source areas. By survey 4 the source areas on the northern slope are disconnected by dry soil moisture pixels. A number of areas of rapid draining dry areas are also observable. These can be seen even in survey 3 but become more apparent as the catchment dries. The wet areas are separated by rapidly draining sections. There are also two large patches in the northeast and the southwest that are more uniformly dry. These are apparent even for survey 3. These dry regions expand around and into the source areas over time to become indistinct as the catchment dries.

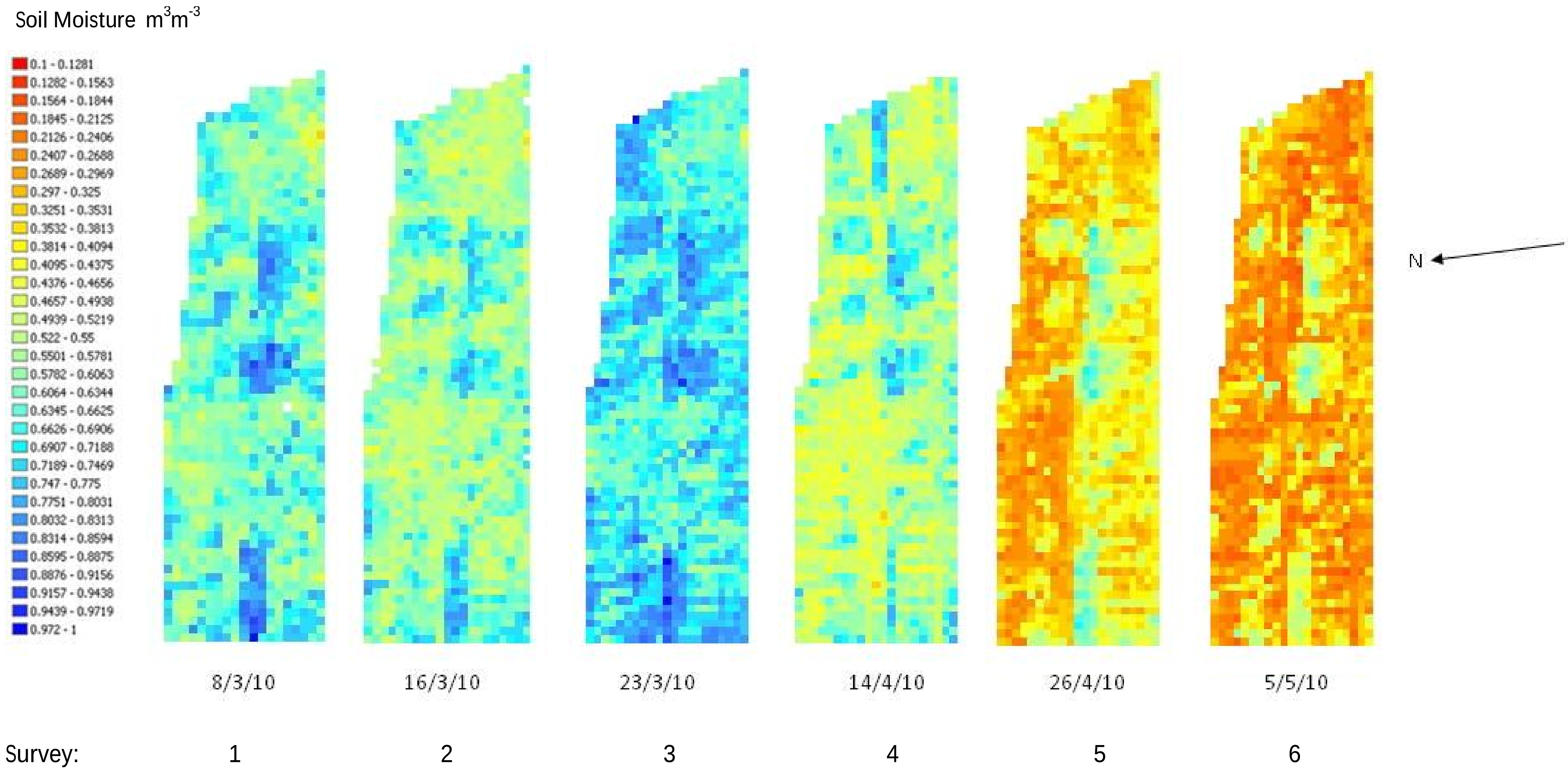


Figure 4.21: 6 shallow surface (5 cm) soil moisture distributions taken between March – May 2010 at a 5m resolution.

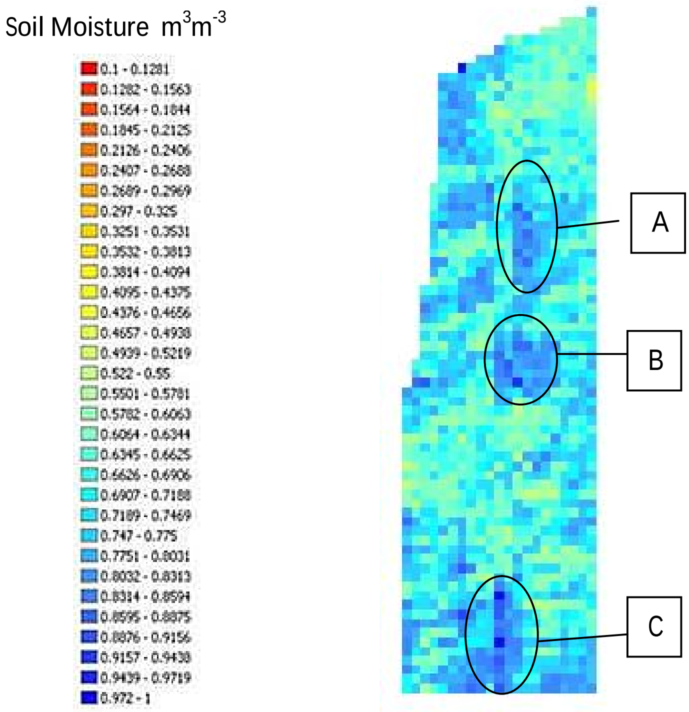


Figure 4.22: Soil moisture survey from 23/3/10 with three areas of high soil moisture concentration identified.

Survey 4 represents the transition between dry and wet conditions. This survey was taken 14 days after any rainfall and the catchment stage has fallen to a constant level of disconnected base flow. Over the subsequent 3 weeks rainfall is isolated and very limited in volume. The transition from survey 4 to 6 is an intensification of the process seen between surveys 3 and 1. However the organisation in soil moisture seen in the initial three surveys is absent. Survey 4 shows disconnection of the northern source areas. Remnants of the flowpaths remain, however the average soil moisture has fallen to 0.55 m^3m^{-3}. The continued lack of rainfall provides an opportunity to observe the transition of the catchment to dry conditions. The continuity in the stage record suggests these are low flow conditions. The wet source areas sequentially shrink with the northern slope rapidly drying out leaving only very small scale indication of the wet source areas. As time progresses the soil moisture also becomes more seemingly randomly distributed. The northern slope dries out faster than the southern slope. By survey 6 the majority of the catchment is randomly distributed. Only the source area B maintains a sizable area of high soil moisture with areas A and C being reduced to very small scale poorly defined wet areas.

The most surprising outcome of the soil moisture surveys is the condition of the ephemeral channel which is consistently dry. Even in the very wet conditions of survey 3 it is drier than the three wet areas of the catchment throughout the study period. This is not what would be expected given the flow accumulation identified in Figure 4.6. Given the site has a short flow distance to the channel the focus of the soil moisture from the site is centred in the channel very rapidly. Despite the increased drainage afforded to the channel through the subsurface drainage present it is surprising to find that the whole channel is so uniformly dry. Evidence of channel sectioning from flow accumulation (Figure 4.6) is not manifested in the soil moisture signal with no clear variability evident along the channel course. This means that even in sections of the channel between the drainage outlets there is no clear increase in soil moisture.

Figure 4.23 is a time series plot of mean soil moisture. This graph shows the mean trend of soil moisture fall between the surveys over time. The graph represents the wide range of soil moisture conditions that were observed by the series of soil moisture surveys. The range seen over the two month period presents a clear drying transition from winter to spring, yet indicates the potential for short term variability through the increase in soil moisture seen on the 23rd March (survey 3). The range of soil moisture over the two month study period is high from complete saturation to under 0.2 m^3m^{-3} representing a variation of over 80%, a feature that is typical to temperate rangeland (Western et al., 2001). To further assess the distribution a cumulative frequency graph was generated for each soil moisture distribution (Figure 4.24). The distributions of most of the surveys are contained within the range between 0.4 m^3m^{-3} and 0.6 m^3m^{-3}. Surveys 5 and 6 show a much drier distribution. The cumulative frequency shows that the moisture surveys were reaching the limits of the range of soil moistures that the catchment could produce. The steep nature of the distribution for survey 3 indicates that the site was reaching its maximum saturation. Likewise survey 6 shows a steepening distribution with the low values indicating the approach of the driest conditions. The impact of antecedent conditions is already apparent given the difference between the first three surveys. The variation in the distribution and extent of soil moisture over this period shows the potential for the catchment to respond over a short period of time. This change is also indicated through the mean soil moisture content time series graph (Figure 4.23) which indicates a range of 10% over the three week period between survey 1 and 3.

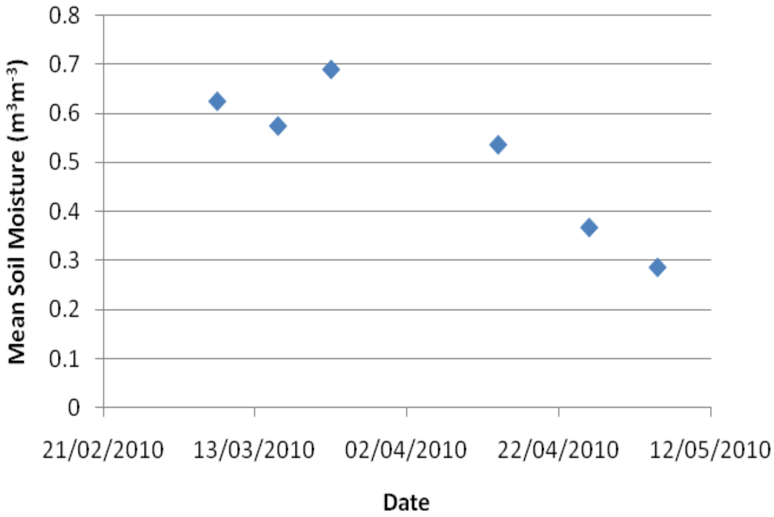


Figure 4.23: Time series graph showing mean soil moisture content.

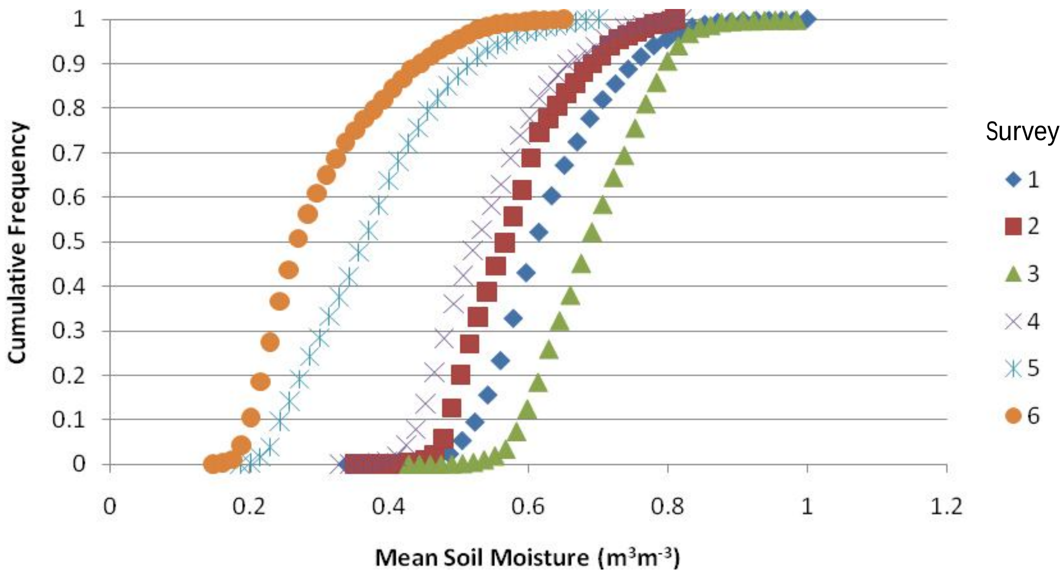


Figure 4.24: Cumulative frequency distribution of each soil moisture surveys.

A scatter graph of standard deviation was produced to estimate the change in the range of the distributions (Figure 4.25). The graph shows a negative correlation between standard deviation and soil moisture. Although this appears to be relatively slight, with a difference of only 0.02 across the complete distribution of soil moistures, it shows that the distribution of the catchment's soil moisture increased as the catchment dried. This lends weight to the argument of decreased organisation in catchment connection as visually identified for the soil moisture rasters. However it also suggests that despite survey 3 indicating a steepening of its cumulative frequency profile the same cannot be said for survey 6. Even though it appears that the cumulative frequency for survey 6 has a high concentration of low soil moisture values the catchment is still in transition and as a result still has a considerable range of soil moistures. This is likely to be due to the persistence of saturated areas that were identified from the soil moisture distributions (Figure 4.21).

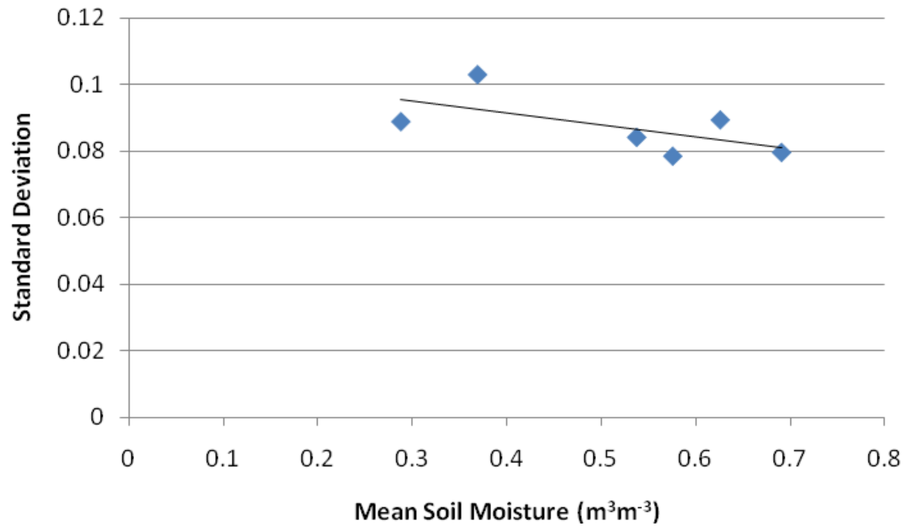


Figure 4.25: Scatter graph showing the relationship between the mean soil moisture content and the standard deviation of each distribution.

Summary

This chapter presented the topographic structure of the catchment developing understanding into physical characteristics of slope aspect and flow accumulation. This exhibited a detailed understanding of the way that the morphology of the catchment might affect hydrological connectivity. In addition to this rainfall and stage data were presented including both historic and for the study period. These results highlight the relatively dry nature of the catchment by comparison to the historical record and the distribution of the stage and rainfall with reference to each soil moisture survey. This framed the conditions under which the soil moisture surveys themselves were undertaken, identifying a wide range of soil moisture scenarios. This chapter identified the conditions under which the connectivity metrics and models were tested. The next chapter presents the results of this analysis.

5.0 Analysis of metrics of hydrological connectivity

Progressing on from the hydrological conditions represented during the study period for this catchment the different methods of hydrological connectivity were carried out. Their performances were assessed with reference to temporal, hydrological and meteorological drivers to ascertain those metrics that best represent the hydrological connectivity variability. This was developed to include the Cumulative Probability Network Index to further progress the potential of the index approach to connectivity.

5.1 Connectivity Thresholds and Metrics

Thresholds of soil moisture and connectivity metrics are investigated in order to ascertain their applicability for estimating hydrological connectivity. The thresholds used in this study are the same that were used by Ali and Roy (2010). The thresholds dp10, dp35, dp50, dp75 and dp90 represent percentiles of the overall spatial soil moisture distribution while sm values were defined using constant moisture contents (20%, 30%, 40%, 50%, 60% and 70%). The sm values were translated upwards by comparison with Ali and Roy (2010) to better represent the higher soil moisture values seen in this catchment. Ali and Roy (2010) also included a third metric of percentiles derived from depth oriented soil moisture distributions. However due to the univariate nature of the depth measurement used in this study these thresholds were not available.

Figure 5.1 and Figure 5.2 show the distributions of soil moisture at each threshold. For the dp threshold the distribution is relatively consistent throughout. This shows continuity in the threshold pattern throughout the period of study. The three areas of high saturation seen in Figure 5.24 are consistently identifiable at the 90th percentile threshold. The channel is also conspicuously absent at the high thresholds. However there is a shift in the orientation of the soil moisture over the period. This is particularly apparent at the 25th and 50th percentile. There is a clear transition from a balanced distribution above the threshold in the earlier wetter surveys towards a polarity between the northern and southern slope. It is clear that by survey 5 (26/4/10) the northern slope is much drier than the southern slope. This distinction then breaks down as the catchment continues to dry out. The disconnected south-eastern section of hillslope can also be identified as having a consistently lower than average soil moisture.

The consistency seen in the percentile thresholds is very different to the soil moisture constant thresholds (Figure 5.2). The percentile distributions depict the continuity in the distribution of wet and dry areas in relation to the mean. Soil moisture constants show the transition in soil moisture saturation over time. Thus there is a transition from the distributions with high soil moisture content with complete connection at low thresholds to distributions with low soil moistures with no connection at high thresholds. This transition identifies not only the extent of soil moisture but also its spatial dispersal. Figure 5.2 shows that over this time period the soil moisture varied greatly. It also shows continuity in how the catchment wets up and dries out. For example sm60 shows a consistent pattern before and after the high saturations of survey 3 (23/3/10) suggesting that the catchment has a consistent pattern of organisation. This consistency emphasises the importance of hydrological connectivity in this catchment. This figure also suggests that areas that wet up the most are the last to dry out. This pattern is suggested by the similarity between the distribution of moisture at the highest moisture threshold (sm70) for the third survey (23/3/10) and the distribution at sm30 for the last survey (5/5/10). This shows that the wet areas are consistent and that the drying out of the catchment is sequential.

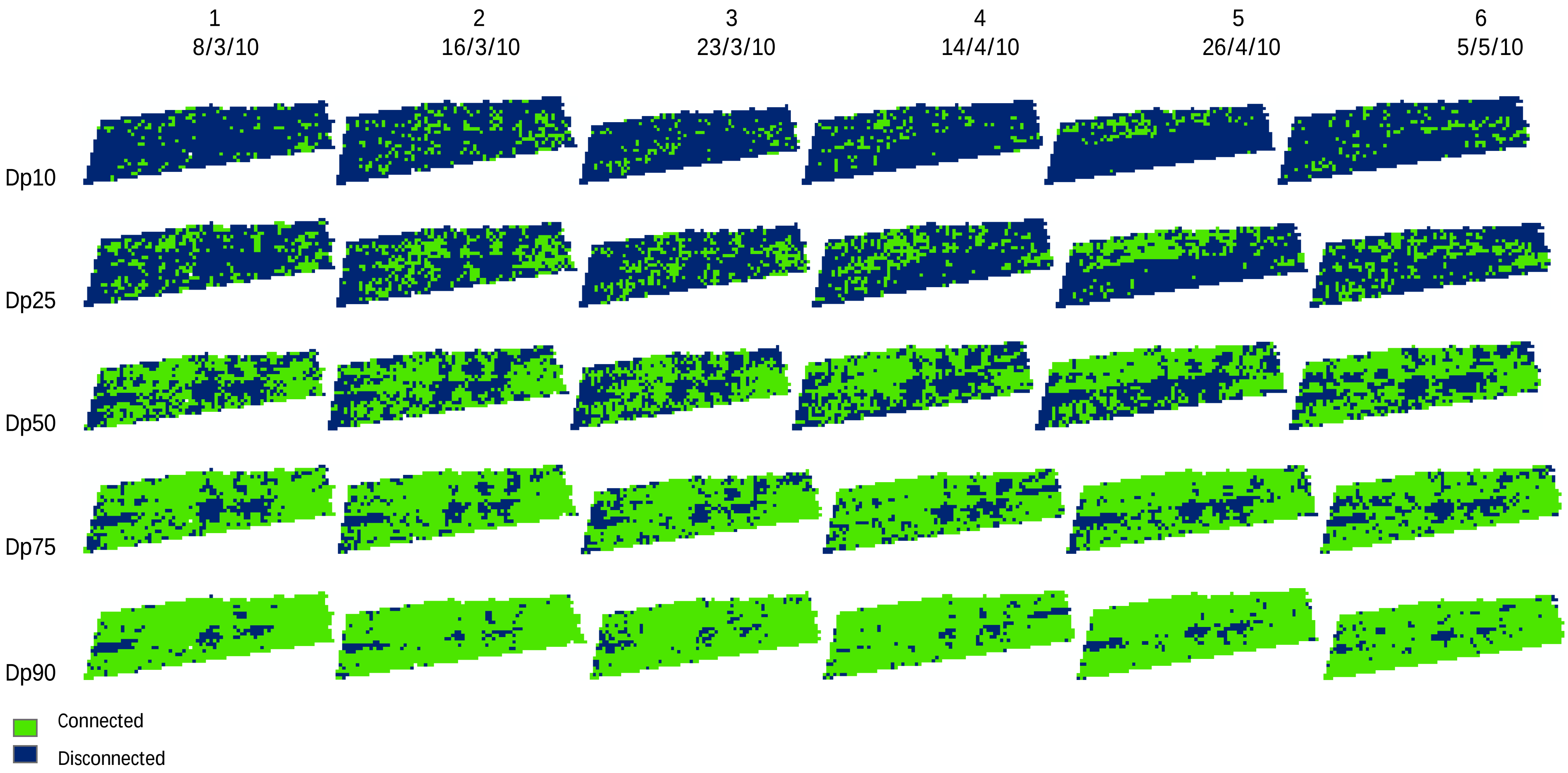


Figure 5.1: Soil moisture thresholds at 10th, 25th, 50th, 75th and 90th percentile of each survey distribution.

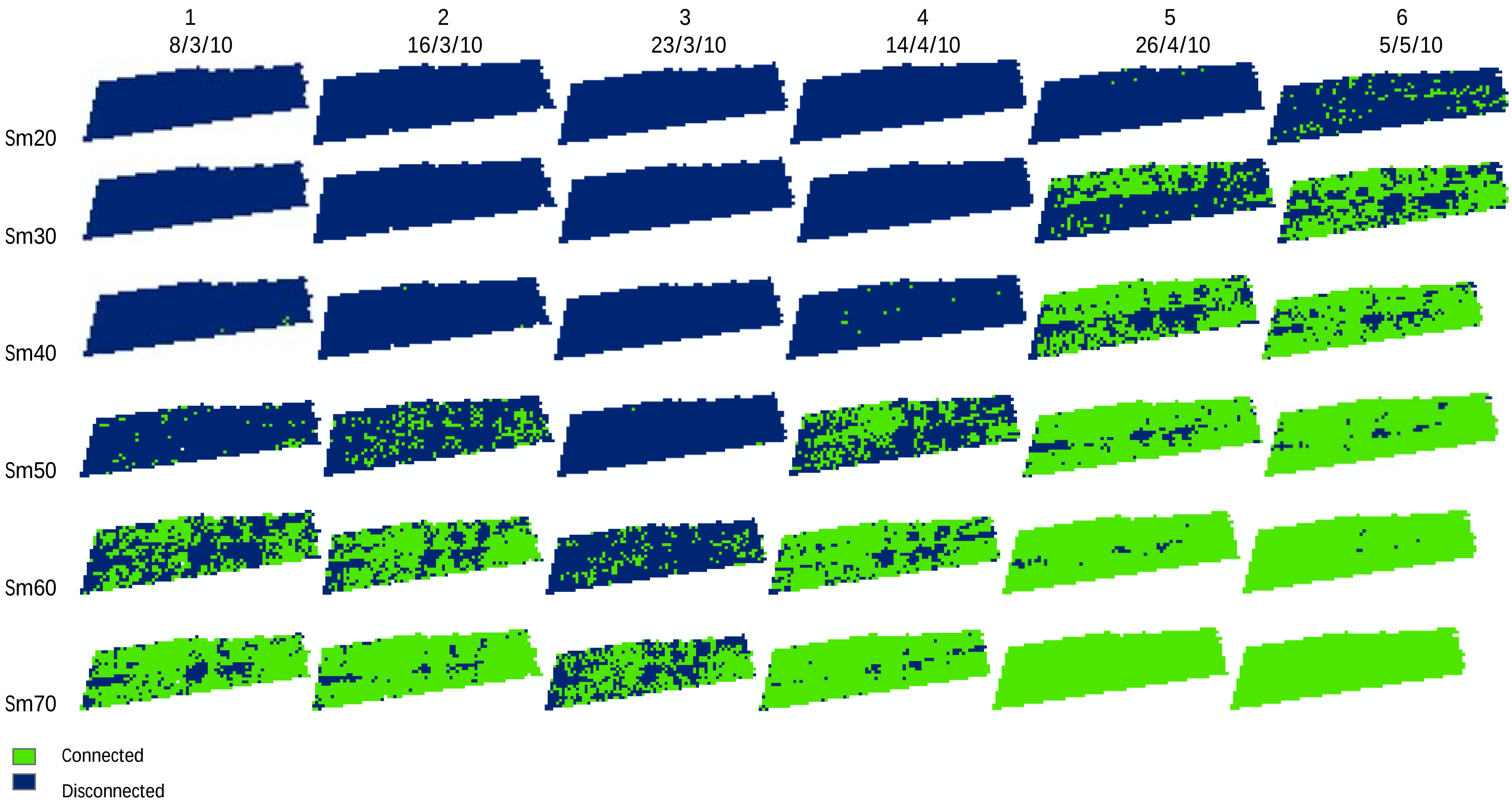


Figure 5.2: Soil moisture thresholds at 20%, 30%, 40%, 50%, 60% and 70% moisture content for each soil moisture distribution.

5.2 Soil moisture and Metric Analysis Variables

The relationship between mean soil moisture content (MSMC) and antecedent rainfall, and MSMC and catchment stage need initially to be addressed in order to ascertain the efficacy of these relationships as a basis for testing the metrics performance. MSMC displayed a positive correlation with stage on the day of the survey (CD_Stage) ($r_{spearman}$ = 0.77, p = 2.68 E^{-7}). This relationship suggests that the MSMC reacts in a similar manner to CD_Stage and supports the use of stage as a method of analysis for the connectivity metrics. The relationship between MSMC and stage indicates a threshold response (Table 5.1). There is a limited response from the stage data until soil moisture reaches 60% saturation. At this point the catchment appears to elicit a significant response. The relationship with antecedent precipitation (AP) was more complicated. Due to the relatively low volume of rainfall that fell over the rainfall period (Table 5.1) the shorter time period of antecedent rainfall did not have sufficient data to differentiate the surveys. This is the case for AP1, AP2, AP5, AP7 and AP12 all of which have a $r_{spearman}$ of equal to or less than 0.6. However due to the lack of rainfall and the presumed low consistent nature of evapotranspiration it is likely that longer term rainfall would have an impact. As a result AP 14 was found to give a much better relationship ($r_{spearman}$ = 0.71, p = 7.94E^{-9}). The nature of the distribution of the rainfall in this regard as well as the relatively high density of surveys in a short 9 week period also results in a poor relationship between MSMC against days since rainfall (SINCE) ($r_{spearman}$ =-0.23). Consequently the relationship between stage and antecedent precipitation is relatively strong particularly between AP14 and CD_Stage. Figure 5.4 shows the relationship between the two factors. Although there is some fluctuation the threshold nature seen for both is subsequently ameliorated to generate a linear relationship. However it is also important to note that this threshold is highly dependant on the final, highest soil moisture condition and that without this the relationship breaks down.

	Survey	MSMC (mm)	SINCE (d)	AP1 (mm)	AP2 (mm)	AP5 (mm)	AP7 (mm)	AP12 (mm)	AP14 (mm)	PD_Stage (cm)	CD_Stage (cm)	DA1_Stage (cm)
8th and 9th March	**1**	**0.63**	**2**	**0**	**0.4**	**0.8**	**13.2**	**13.4**	**13.4**	**30.14**	**28.97**	**29.22**
16th and 17th March	**2**	**0.58**	**2**	**0.2**	**0.6**	**0.8**	**1.2**	**1.6**	**1.6**	**27.19**	**27.44**	**27.94**
23rd and 24th March	**3**	**0.69**	**1**	**7.8**	**22.8**	**23.4**	**24**	**24.2**	**24.2**	**38.26**	**37.29**	**38.54**
14th and 15th April	**4**	**0.54**	**14**	**0**	**0**	**0**	**0**	**9.4**	**9.4**	**29.30**	**24.74**	**24.68**
26th and 30th April	**5**	**0.37**	**1**	**0**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**26.55**	**26.18**	**26.26**
5th and 6th May	**6**	**0.29**	**4**	**0**	**1.2**	**1.2**	**3.2**	**3.2**	**3.2**	**25.91**	**26.85**	**27.12**

Table 5.1: Hydrometeorological conditions for each soil moisture survey.

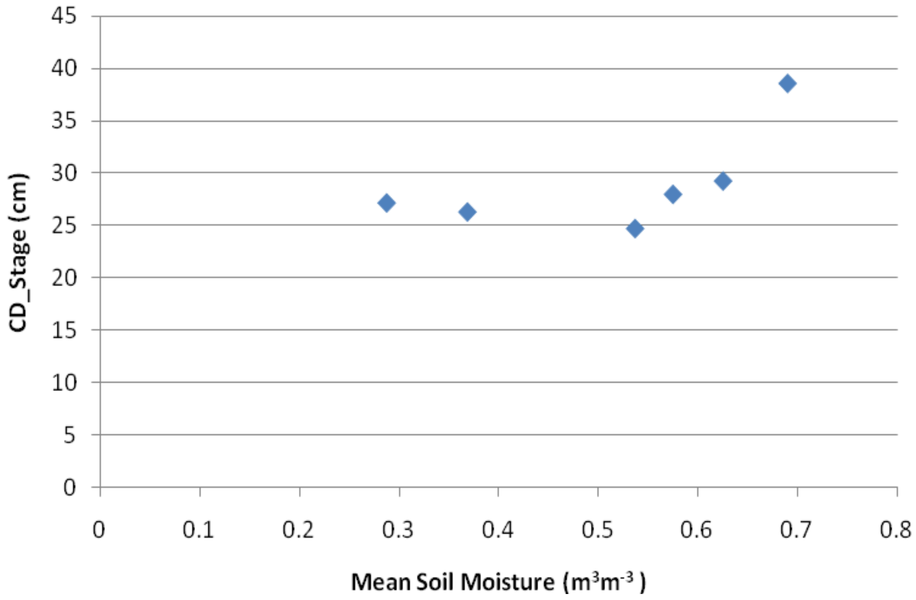


Figure 5.3: Relationship between mean soil moisture and stage on the day of survey (CD_Stage).

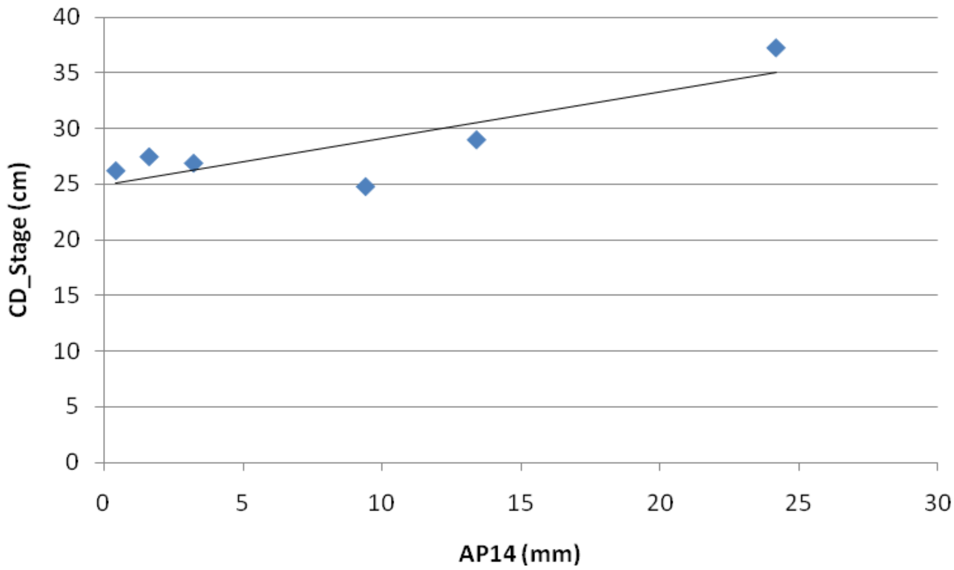
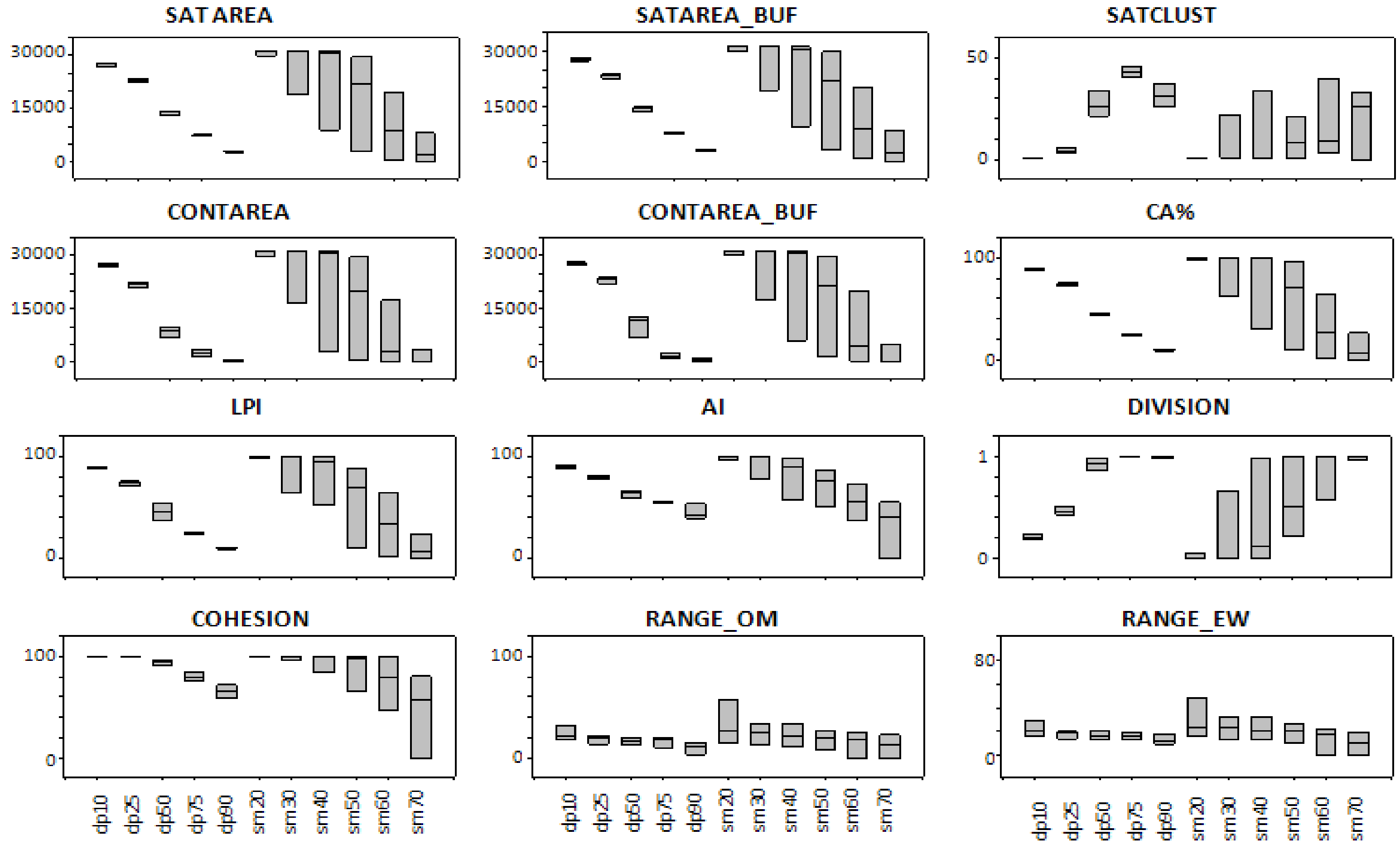


Figure 5.4: Graph of 14 day antecedent precipitation with stage on the day of survey (CD_Stage). Best fit line has an R^2 of 0.7.

5.3 Connectivity Metrics

The connectivity metrics provide a range of responses generating insights into the catchment, the thresholds and the metrics themselves (Figure 5.5). This range of responses is highlighted by figure 5.5, which depicts the range and median for each of the thresholds and metrics. The saturated area (SATAREA) and the contributing area (CONTAREA) showed meaningful differences between them. Yet this difference varied depending on the threshold that is being presented and the presence of a buffering factor. The box plots (Figure 5.5) suggested that the SATAREA was relatively constant across the dp threshold classes. This was consistent with the buffered SATAREA (SATAREA_BUF). The dp data fell sequentially with increasing threshold value. The low range suggested that these areas were consistent despite temporal changes. By contrast the sm classes showed considerable temporal variability with consistent high mean values up to sm40 at which point the saturated area began to fall. The most active range was sm60 which exhibited almost the full spatial range across the period of study. The buffering of SATAREA had little effect on saturated area. However this was not the case for CONTAREA. CONTAREA broadly showed a similar pattern and range to SATAREA. However the mean ranges particularly for the higher thresholds were reduced. This was particularly evident for dp50, sm60 and sm70. CONTAREA showed greater range in the dp thresholds showing the potential for disconnected cells. This is most pronounced for dp50 which was noticeably lower. The impact of buffering could be seen on this threshold with the buffered dp50 showing the greatest range of area for the dp thresholds. However the buffering had a limited effect on the CONTAREA distribution due to the large range of connection areas.



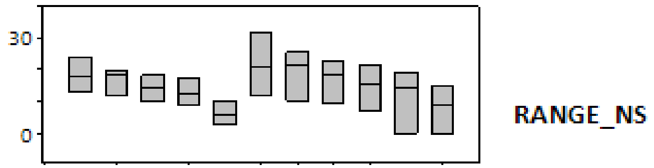


Figure 5.5: Box plots of connectivity metrics at each indicator threshold.

The number of saturated clusters (SATCLUST) showed a complex variation across the thresholds especially for dp. SATCLUST had a progressive increase to dp75 and then fell at the dp90 threshold. Given the constant value of 1 cluster at dp10 it appears that the decrease in the number of cells causes a gradual increase in the number of patches which reaches a peak number and distribution before some of these are subsequently removed at the 90th percentile. This reflects the normal distribution of this threshold method. SATCLUST showed a relatively consistent range for sm thresholds although the mean values remain at 1 until sm50. The consistency of the range and mean for sm and the distribution of dp suggest that this metric will struggle with the metric analyses due to their presumption of sequential ranking and linear distribution.

The FRAGSTATS cluster metrics showed more variability than SATAREA and CONTAREA. The first (CA%) is the rendering of SATAREA as a percentage of the total catchment. This was found to be consistent with SATAREA. Although this suggests that the potential for these two metrics are the same the expression of saturated area as a proportion aid the understanding of the extent to which the catchment is portrayed as connected for each threshold and in that way it is easier to interpret. However as a result the statistical differences are negligible. LPI showed similar variation to CA%. As a metric measuring the proportion of the largest cluster to the whole catchment this metric has little impact at the lowest thresholds where values above the threshold are more or less completely interconnected. The Largest Patch Index (LPI) resulted in a similar distribution, for dp thresholds. SATAREA however displayed a large range at dp50. This differed greatly from the other dp thresholds that show very low ranges. This is likely to be due the very low values exhibiting one complete catchment patch and high values being limited to one large specific constant saturated area. At the 50th percentile however the distribution of soil moisture appears to vary such that the proportion of the largest patch can range from 97% to 40%. The sm thresholds maintain a similar pattern to those seen for CA% with a similar range and mean across the thresholds. The Aggregate Index (AI) displayed a much narrower field of results. Again the same consistent pattern of decrease with increased threshold values was evident, however the number of adjacencies did not fall as steeply as previous metrics particularly for dp thresholds. AI showed a consistent level of cell adjacencies that was not apparent from SATAREA or LPI. This level appears consistent with sm thresholds showing a limit to the ranges by comparison to the area metrics. However this pattern is disrupted by sm70. This shows that the soil moisture above these thresholds, although rapidly reducing in area, maintains a high degree of spatial contiguity. DIVISION and COHESION approach the spatially proximal nature of the threshold cells from opposite directions and get very different results. The DIVISION metric generates very different results depending on the type of threshold. For dp thresholds the range is very narrow resulting in a consistent development of increasing division. Whereas for the sm thresholds the range is very large showing the wide potential for division particularly for sm40 that exhibits the complete range from 0 to 1. By contrast COHESION suggests that the cells that are above the threshold have a tendency to be proximal. The ranges are narrow relative to DIVISION and result in cohesion values above 50% (i.e. 50% of the cells are in a patch with at least one other cell). Again this pattern only breaks down when sm70 tends to zero.

With regards to the semivariograms there was a degree of consistency between the three metrics. They had a consistent pattern highlighting a decrease in cell continuity with increased threshold level which emphasised the shorter lengths available to RANGE_NS due to the limits of the catchment. That being said, the range of RANGE_NS is proportionally greater than that of RANGE_EW and RANGE_OM. Interestingly it is only this metric where there is a degree of continuity between dp and sm thresholds although the range is recognisable smaller for dp as it is with all of the other metrics under investigation. The semivariogram metrics reflect the COHESION results on the continuity of cells even at high thresholds.

5.4 Metric Analysis and Performance

Table **5.2** displays the combined total for the three analyses of the metrics. It is apparent from this table that the dp percentile thresholds derived from the soil moisture distributions of each soil moisture survey were very limited in distinguishing the pattern of soil moisture that were hydrologically significant. None of the metrics achieved the standard set by Ali and Roy (2010) of 8 or higher. Indeed a number of these threshold metric combinations achieved the lowest possible satisfaction score of 3. This appears to be relatively uniform across the lower thresholds (i.e. dp10 and dp25) irrespective of the metric used. The persistence of these very low scores into the higher thresholds indicates a very low representation of the conditions in terms of the catchment response over time. Despite some variation across the metrics using these thresholds they all perform comfortably below the desired standard and as a result these variations are considered to have limited significance.

By contrast the sm absolute soil moisture thresholds showed greater potential with a number of the metric threshold combinations achieving the required standard. This was found to be limited to the higher percentage thresholds with no significant thresholds being identified below sm40. Again the persistence of very low scores (4 or fewer) emerges, however these were more in line with the mean soil moisture distributions (Table 5.1) and as a result reflect the greater or lesser extent of the contiguity of the soil moisture across the catchment. Above this, however, at levels where the most variability was found in soil moisture over the study periods a number of well performing metrics began to emerge. This was particularly centred on sm70, the highest threshold. This concentration of high performance is in line with the threshold response seen in Figure 5.3. SATCLUST is notable for not having a significant score at any threshold. It is also notable that the more detailed cluster metrics did not achieve a consistently high standard with AI, DIVISION and COHESION only attaining one threshold recording 8 each. CONTAREA performed better than SATAREA however there was no significant improvement with either of the buffered alternatives. There was no clear best performing metric although the semivariograms had a consistent performance. CONTAREA exhibits the most consistently high satisfaction scores.

	dp10	dp25	dp50	dp75	dp90	sm20	sm30	sm40	sm50	sm60	sm70
SATAREA	4	4	4	6	5	3	4	5	8	8	9
CONTAREA	4	4	3	5	6	3	3	5	8	9	9
SATCLUST	3	4	3	3	3	4	5	5	6	7	6
SATAREA_BUF	4	4	4	5	4	3	4	5	8	8	8
CONTAREA_BUF	4	5	5	4	6	3	3	5	8	9	8
CA%	3	3	4	5	5	3	4	7	7	8	9
LPI	3	4	3	6	5	3	4	5	8	8	9
AI	3	3	3	3	3	3	3	4	7	7	8
DIVISION	3	4	3	3	4	5	6	6	8	7	5
COHESION	3	4	4	3	3	3	3	3	4	6	8
RANGE_OMNI	5	3	4	3	4	7	6	7	8	8	8
RANGE_EW	6	5	4	4	3	7	7	7	7	8	8
RANGE_NS	6	6	6	6	4	6	6	8	8	7	8

Table 5.2: Combined satisfaction score table for analyses of connectivity metrics

5.5 Metrics and Individual Satisfaction Criteria

The coefficient of variation (CoV) generated a far greater temporal variability for sm thresholds than for dp thresholds (Appendix A) with each of the metrics generating at least an intermediate result. The greatest temporal variability shown for a metric under the percentile threshold approach (dp) was CONTAREA_BUF displaying an intermediate level for the higher thresholds. There was no high temporal variability indentified for any of the metrics using this threshold approach. By contrast the metric that displayed the greatest temporal variability for constant soil moisture thresholds (sm) was SATCLUST. This is primarily due to the considerable range between the single cluster of complete connection seen at low moisture content thresholds by comparison to the large number of separate clusters at greater thresholds as identified in Figure 5.2. This is evident from the size of variation seen at sm30 which is due to two surveys showing a large number of clusters. The exception of the focus of high variability at high thresholds is DIVISION which actually shows its greatest variations at the lower thresholds. The nature of DIVISION, as a metric, highlights that even despite the maintained unity of the patches at low thresholds there is still a degree of separation over time. The reduction at higher thresholds indicates an asymptotic consistency at higher thresholds of the same areas being consistently present. AI and COHESION performed the poorest of all the metrics with only one threshold reaching a significant level. This suggests there is not enough variation from these methods over time irrespective of the threshold system. Ali and Roy (2010) made the suggestion that an alternative to CoV would be correlation with MSMC. It was found this was not an improvement on CoV being far more uniform in its distribution across the thresholds and metrics. As a result this was not incorporated into the analysis.

Of the two stage records the shorter term response was consistently better represented by the metrics and was adopted over the medium term response (Appendix A). There was a greater degree of satisfaction to this analysis than there was to CoV. Indeed there was a series of good responses at the dp threshold, with RANGE_NS achieving a score of 3 for each of dp10, dp25, dp50 and dp75. This meant that RANGE_NS was the highest performing metric for this analysis with only two thresholds not scoring 3. However dp thresholds still perform less well than sm. There was a great deal of consistency at the high sm thresholds, with the majority of metrics achieving high Spearman's Rank coefficients with stage (Table 3.1). However the notable metrics that did not perform well under CoV also struggled in places here with COHESION and DIVISION scoring two insignificant thresholds above sm50. The consistency of the semivariograms is borne through the similar pattern seen between the two types of threshold (Figure 5.5). CA% showed persistence into sm40 that is not seen in the cluster analyses indicating that there is some difference between proportion and SATAREA.

By contrast the antecedent precipitation thresholds showed a different pattern. Here there was more persistence of satisfaction of the criteria than with the other two thresholds (Appendix A). It is to be expected that metrics perform better here than against Ali and Roy (2010) as only one meteorological variable is considered. The dp thresholds perform best for this analysis particularly for SATAREA and CONTAREA and their buffered alternatives. Interestingly there is a clear difference between the semivariogram ranges that was not present for the other methods of analysis. Again for the sm thresholds there is a consistent high satisfaction of the analysis at and above sm50. However there is a gradation from low thresholds with intermediate thresholds showing intermediate results. This feature is also not apparent for either of the other two thresholds. Again SATCLUST is the poorest performing metric with no high level scores. COHESION is another notable exception with limited correlation with AP14 by comparison to the other metrics. RANGE_NS again has the best relationship with AP14 with the majority of sm thresholds being scored 3.

5.6 High Performing Metrics

There were six metrics that scored an objectivity function of nine, the maximum possible. There were a further 22 that scored eight, a maximum in two categories and an intermediate score. These are presented in Table 5.3. Due to the large number of metrics that scored 8 their analysis was not taken any further. The 6 metrics that scored 9 were correlated against the 2 day stage record and AP14 in order to visualise the relationships that had been identified by the objectivity function. Figure 5.6 and Figure 5.7 display these relationships. The metrics all showed a strong linear relationship with the AP14 data. However there is an indication that a critical volume is required to generate large areas of soil moisture. The values of the metrics seen below 10 mm are limited to approximately 5000 m^2 with the contributing patches representing only 10% of the catchment. Above this level there is a strong increase from all of the metrics with large magnitude responses increasing between 13 mm and 24 mm (Figure 5.6). There is a significant difference in the extent to which they increase however particularly between CONTAREA at sm70 (CONT70) and CONTAREA_BUF at sm60 (C_BUF60) the buffering effect combined with CONT70 being a high threshold might explain the discrepancy in area. Similarly there is a difference of nearly 10% between CA% at the sm 70 threshold (CA%70) and LPI at the sm70 threshold (LPI70). The difference between these two is the area of the catchment that is not part of the largest patch.

The relationship between the metrics and the 2 day stage record give strong support to the potential presence of a threshold (Figure 5.7). Here the data is clustered around 25 cm with very low values. There is then a very rapid response between 27 cm and 28 cm, which continues to the peak of the data recorded at 38 cm. it is apparent that there is some small scale fluctuation in the metrics below 27 cm with a range of metric results not correlated to the stage level. This is the base level measured over the study period with small scale fluctuations in soil moisture not generating connection to the outlet and increasing flow. Subsequent larger soil moisture reflects the increase in connectivity and result in higher stage levels. There is some variation but this is again due to different threshold and metric methods.

Connectivity Metric	Threshold
SATAREA	Sm50
	Sm60
	Sm70
CONTAREA	Sm50
	Sm60
	Sm70
SATAREA_BUF	Sm50
	Sm60
	Sm70
CONTAREA_BUF	Sm50
	Sm60
	Sm70
CA%	Sm60
	Sm70
LPI	Sm50
	Sm60
	Sm70
AI	Sm70
DIVISION	Sm50
COHESION	Sm70
RANGE_OMNI	Sm50
	Sm60
	Sm70
RANGE_EW	Sm60
	Sm70
RANGE_NS	Sm40
	Sm50
	Sm70

Table 5.3: Table of metrics and threshold combinations that scored 8 or over. Those metric and threshold combinations that achieved a maximum score of 9 are highlighted in purple.

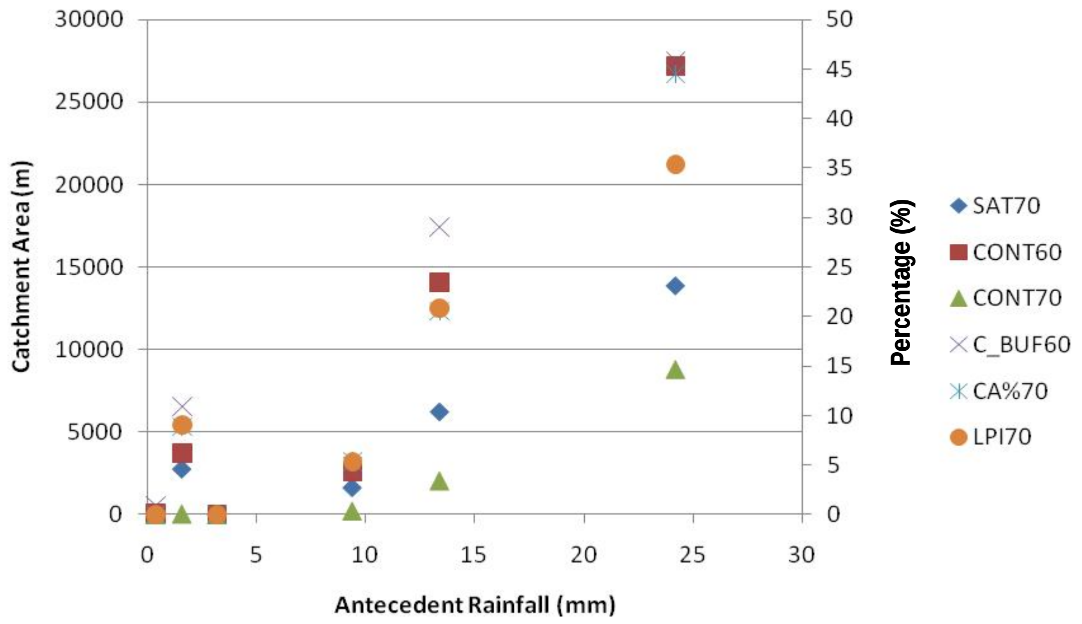


Figure 5.6: Graph showing the relationship between 14 day cumulative antecedent precipitation (AP14) and the high standard metrics. LPI70 and CA%70 were plotted on the secondary right-hand axis as they are recorded in percent.

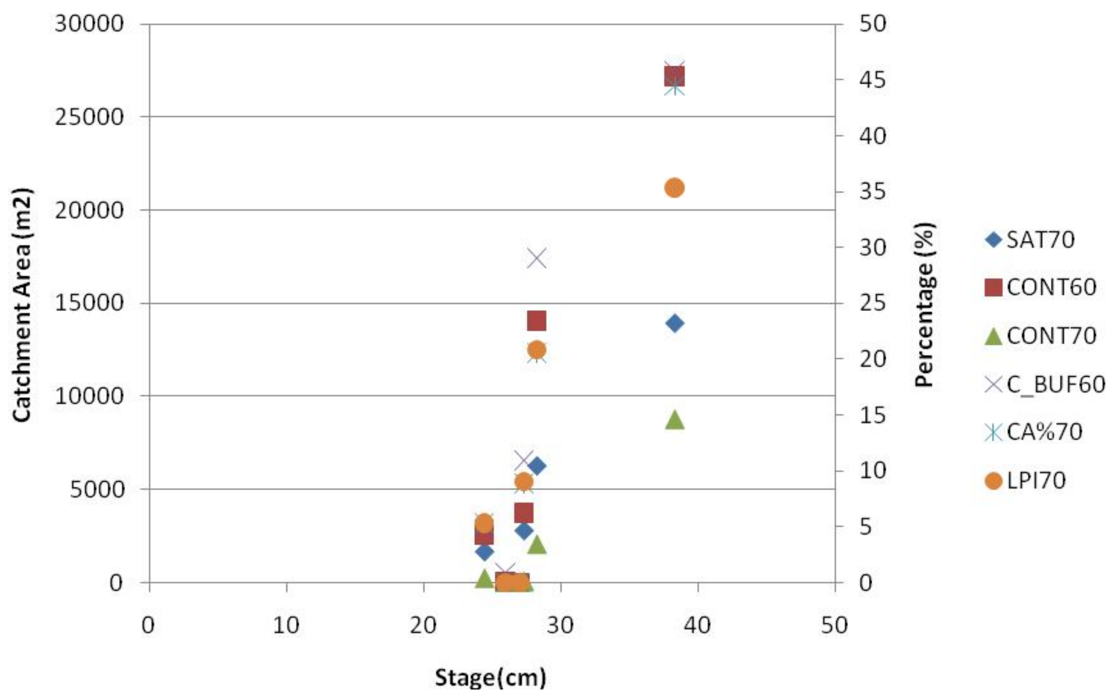


Figure 5.7: Graph showing the relationship between 2 day stage data and the high standard metrics. LPI70 and CA%70 were plotted on the secondary right-hand axis as they are recorded in percent.

5.7 Network Index and CPNI

By contrast to the complex responses derived from the connectivity metrics, the Network Index was able to generate spatially meaningful probability predictions as a result of the different soil moisture conditions (Figure 5.8). Here the persistent soil moisture areas identified in Figure 4.22 were clearly highlighted particularly area A. B was evident in wetter antecedent conditions however the Network Index did not show strong evidence of connection of C even during very high levels of saturation. The persistence of flow pathways varied greatly over time. However there was a degree of spatial connection identified for all of the scenarios. The lateral connection and the upstream persistence of the channel changed markedly over this period.

The transition between survey 1 and 2 showed the reduction in organised flow towards a uniform band of relatively low likelihood. Survey 3 showed very high potential for connectivity with strong connection laterally persisting more than half way up the catchment. This was not just limited to the active areas identified in Figure 4.22 as secondary areas became active to register as high connectivity prospects. The difference between survey 2 and 4 is interesting as it showed 4 is more extensively connected within the channel itself but that 2 has a more uniformly high chance of connection up the channel. This is despite survey 4 being drier than survey 2 (Table 5.1). The uniformity of the upstream part of survey 2 suggested that it was wetter than survey 4 but that it is disconnected. Survey 4 showed a distribution that had soil moisture drier on the whole but was wet enough in certain places to result in a greater extent to its spatial connection. The difference in their soil moisture average is very small (4%). This showed the difference than can exist as a result of the spatial organisation of soil moisture rather than simply the overall average. The surveys 5 and 6 are the driest and show very low values for the likelihood of connection. Here the majority of the catchment is estimated at zero. For survey 5 there is a low likelihood of connection with only active area A and to a lesser extent B influencing that probability upstream. Survey 6 shows minimal activity with the vast majority of the catchment displaying zero chance of connection. The area that is present had very low values. The value in this method is that it shows temporally those flow pathways that are active. This distribution changes with the soil moisture variation spatially rather than as an average.

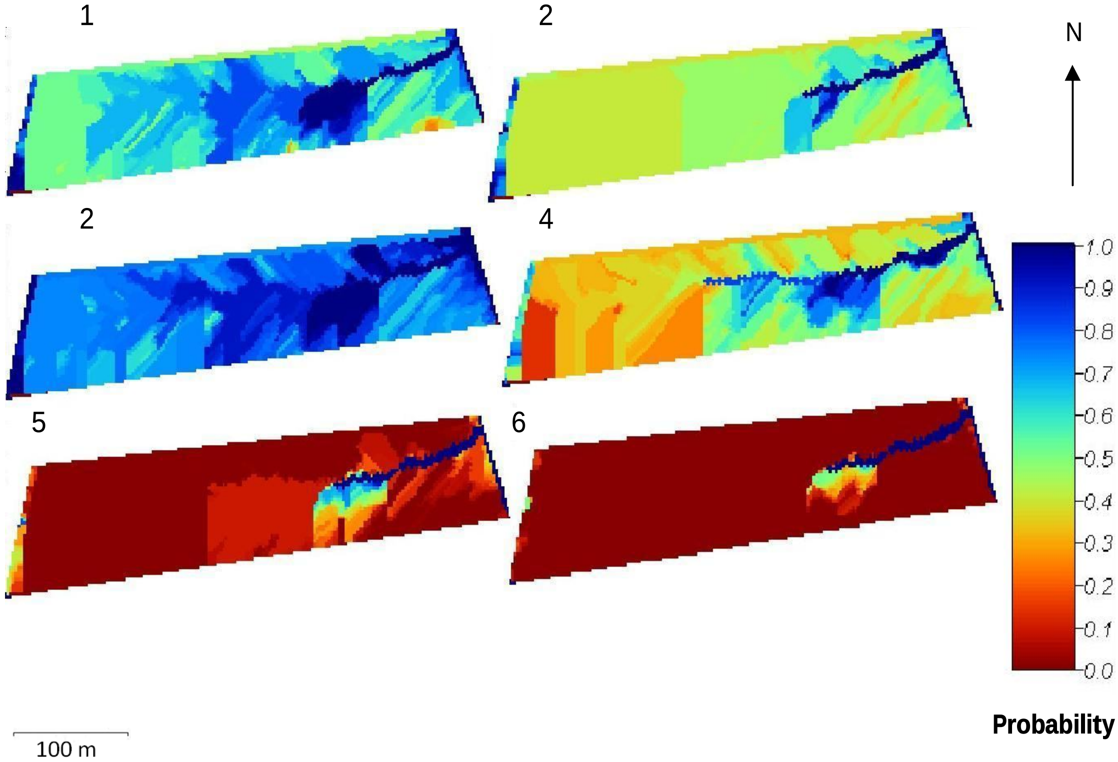


Figure 5.8: Network Index for connection probability values for each of the 6 soil moisture surveys.

Developing from the Network Index, the Cumulative Probability Network Index (CPNI) accumulates the probability of connectivity as a function of soil moisture using topographic flow pathways. There is a significant difference between the Network Index and the CPNI. Due to the accumulation of probability the extent of the flow paths were reduced resulting in a likelihood of connection as a function of soil moisture. This produced some interesting results. The core active areas were identified with survey 1 and 3 which also showed secondary and tertiary active contributing areas. These were mainly limited to 3 areas on the northern slope and the linking route between the main areas of saturation on the southern slope to the channel. The difference between survey 2 and 4 remained, although the persistence of connection upstream was greater for survey 2 than for the Network Index. Although the spatial extent of predicted connection was still greater for survey 4 the cumulative probability for connection was higher for survey 2. This shows a complication of the Network Index. The Network Index identified pathways as a function of the minimum soil moisture value for a route way. This gave a good indication of pathways that are likely to be persistent however it does not account for the potential for that minimum value to be superseded by high soil moisture values along its contributing flow path. The CPNI does this and shows that the potential for areas identified by the Network Index are more likely for survey two than those wider spatial areas seen for survey 4. Surveys 5 and 6 showed little potential for connection as the accumulated likelihood from such low soil moisture results in spatially small areas with low probability of connection.

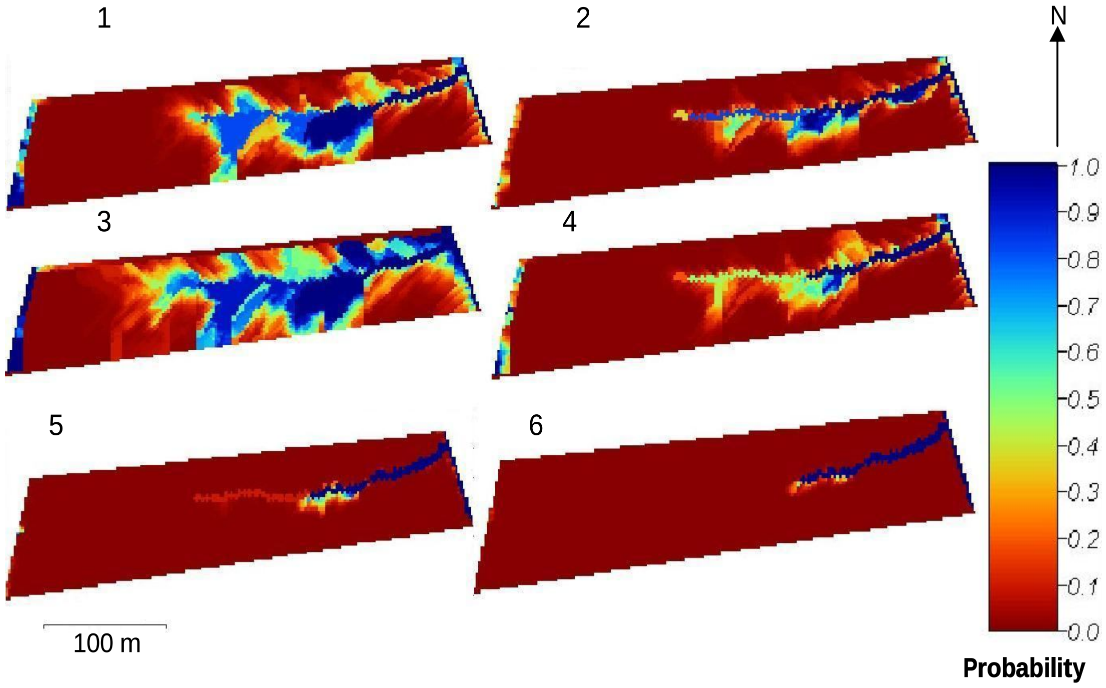


Figure 5.9: Cumulative Probability Network Index for connection probability values for each of the 6 soil moisture surveys.

The CPNI also permits the identification of areas of persistent disconnection. This is particularly the case in the south-eastern corner of the site which remained disconnected throughout the study period. The Network Index indicates that this is due to flow pathway orientated eastwards and is corroborated by slope aspect evidence (Figure 4.4). In addition to this clear ridges of disconnection emerged between the active contributing areas present both on the northern and southern slopes of the valley. These vary in size dependant on the antecedent conditions however they persist in a number of locations at the head of the slopes. It is also notable that the third area (C, Figure 4.22) of persistent moisture was not connected for any of these soil moisture scenarios. This was disconnected by intervening dry soil moisture resulting in a curtailing of cumulative probability 100 m short of the western edge of the catchment. This disparity was also recognised for the Network Index.

Chapter Summary

This chapter has presented the results from the metric analysis and model predictions for hydrological connectivity. It was found that soil moisture was represented best as a discrete percentile as opposed to a temporal univariate distribution. Soil moisture was found to have a strong correlation with antecedent rainfall (AP14) and stage data allowing for an objectivity function to be calculated of a series of hydrological connectivity metrics. A range of these metrics performed well with SATAREA, CONTAREA, CA% and LPI achieving the maximum score of 9. Semivariograms and complex FRAGSTAS cluster analyses performed poorly by comparison. These successful metrics identified a threshold response with antecedent rainfall and stage at approximately 60 % soil saturation. In addition to this the Network Index and the Cumulative Probability Network Index developed a good spatial understanding of the catchment and a strong probabilistic representation of the catchment using both topography and soil moisture. These results will now be developed and discussed in the following chapter, drawing out conclusion about the most promising hydrological connectivity approach.

6.0 Discussion

6.1 Soil Moisture Distribution

Soil moisture has for some time been seen as a pattern generated from topographic forcing (Weileret al., 2005; Western et al., 2001; James and Roulet, 2007). Developments in the assessment of soil moisture patterns have led to the perception that they are representative of hydrological connectivity flow pathways representing active areas for potential surface and through flow (Meyles et al., 2003). Despite this being challenged by Tromp Van Meerveld and McDonnell (2005) amongst others as not acceptable across different catchments, this perception has been increasingly used across hydrology. It is important to consider the flow defining variability that can be attributed to within the soil itself when deciding the likelihood of issues arising from the distribution of soil moisture. In the Sykeside catchment the distribution of soil moisture seems difficult to attribute to topography given the drained nature of the catchment channel (Figure 4.21). The drained nature of the channel results in a much lower soil moisture content than the surrounding slopes of the valley. Yet due to the nature of the catchment the main channel, despite being dry, is clearly identifiable both visually and through slope and flow accumulation analysis (Figure 4.3 and Figure 4.6). The suggestion that the importance of topography is undermined in this catchment as a result of this drainage is however misguided. The drainage of the channel is limited to the channel itself and although this subsequently results in faster connection to the outflow it does not affect the flow pathways that water takes down the valley sides short of decreasing the flow time through the drawdown of moisture from the drier channel soil (Beven and Germann, 1982). There are recognisable core active areas in the catchment that seem to reflect topographic forcing through slope analysis (Figure 4.6) particularly where steeper slopes cause funnelling and accumulation onto flatter surfaces. These areas persist even in low antecedent rainfall conditions (Figure 4.3). Their extent however cannot be explained by topography alone. Further analysis of the catchment using the Topographic Wetness Index (TWI) as a simple method of estimating likely areas of high soil moisture was carried out to ascertain whether it could predict these important active areas (Figure 6.1).

This reflected many of the results identified from the flow accumulation estimation. However the TWI identifies the contributing area for lateral surface flow. The potential importance of the frequency of lateral channels in the northwest of the catchment is clear and an element that was not evident from flow accumulation. The shorter nature of the slope combined with the larger channel density results in a well drained slope. By comparison the southern slope has fewer flowpaths that do not penetrate as far into the slope as is the case for the northern slope. On the basis of this analysis there is a greater likelihood of higher soil moistures, on average, for the southern slope. This is in line with the soil moisture distribution that was recorded. TWI also suggests that the variability in slope angle of the southern slope will have little impact on the organisation of surface flow. Where the valley is constricted in the east, the number of flowpaths is greatly reduced. The shape of the slopes in this part of the catchment, particularly on the southern side, suggest a tendency towards disconnection, although given its relatively high slope angle flow from the planar surface is likely to be greater than in areas disconnected by lateral surface organisation further west. The area of high slope angles that was also representative of a complex aspect distribution shows relatively low connection with very short narrow flow pathways (A). This suggests that despite the potential for the best connectivity derived from slope and aspect data, this area is potentially physically disconnected suggesting relatively high soil moisture should be present here. This also seems to be the case for the area across the channel on the northern slope (B). The channel itself is consistently highlighted by the TWI, although this is a truer representation of the channel without the drainage issue. Overall the lower reaches of the southern slope are predicted to have the highest soil moistures, particularly in the west. The northern slope has more dense flow pathways suggesting it will be drier overall. The catchment is predicted to be drier in the east with the narrowing of the channel. The orientation of the south-eastern corner is shown to accumulate away from the rest of the catchment and this may indicate the potential for high soil moisture than average for the northern slope.

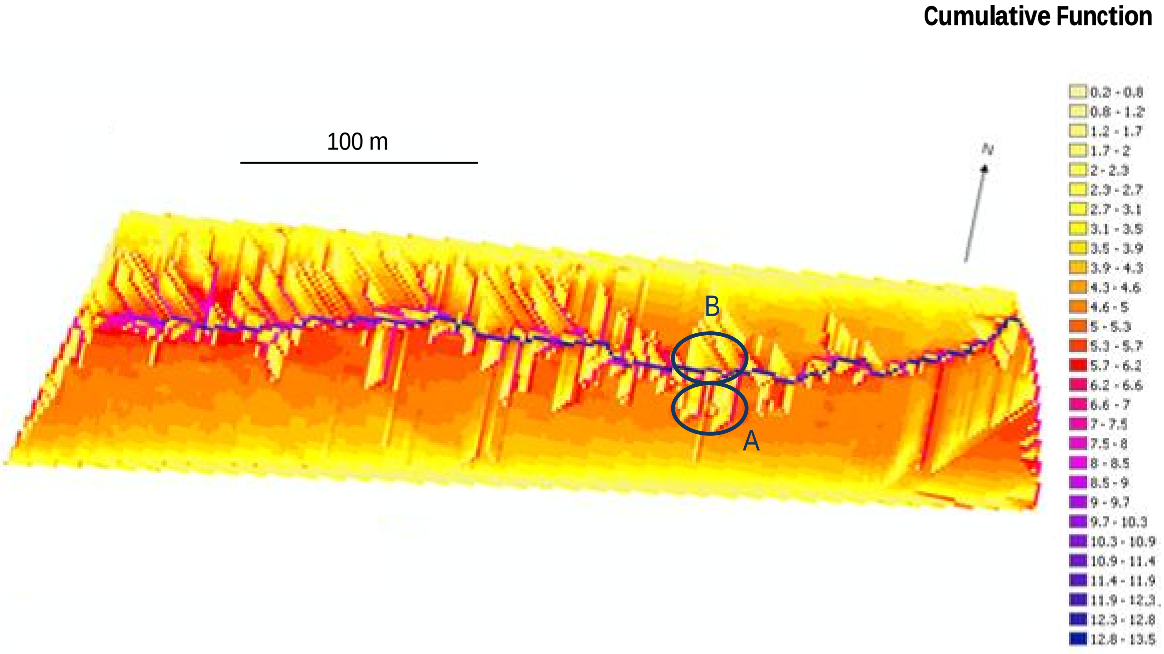


Figure 6.1: Topographic Wetness Index for Sykeside Farm generated from flow accumulation estimation. (A) represents the area of high slope angles seen in Figure 4.3. (B) identifies an area with the potential for high soil moisture.

Subsequently the difference between the soil moisture surveys and TWI were calculated to estimate whether there was significant deviation from the pattern that TWI estimated. Given that TWI does not represent a temporally variable prediction of soil moisture, the distribution of TWI instead predicts soil moisture distribution. This can be seen by the large temporal variation seen in Figure 6.2. It is clear that the range of the distribution is consistent across all the surveys when calculated as a difference of TWI. This is despite the variability in the expected development of soil moisture from connected to randomly distributed. There is also a progression in magnitude in line with soil moisture. However this is not the case for survey one which is lower than would be expected. However this representation of distribution only serves to highlight the normal distribution of the soil moisture rather than truly give an indication of the usefulness of TWI to soil moisture prediction. This discrepancy between TWI and soil moisture gives an insight into where the assumptions within TWI do not hold. Given that TWI assumes constant depth, conductivity and connectivity, continuity in soil depth and consistency at this site suggest any difference between TWI and the soil moisture can be attributed to connectivity. This indicates that the TWI is not a faultless appraisal of soil moisture distribution and that variability within the catchment that might be attributed to hydrological connectivity is present.

.

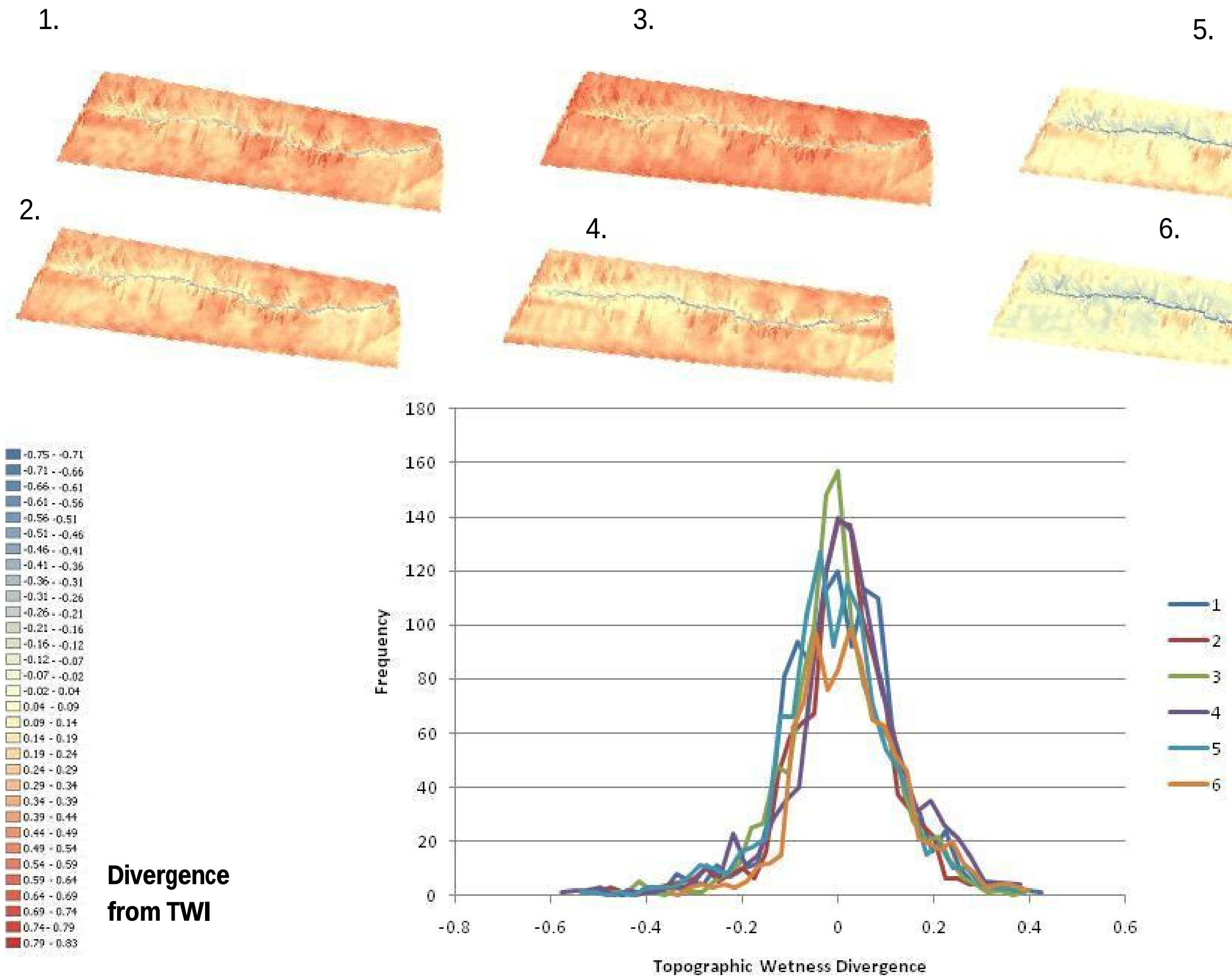


Figure 6.2: Topographic Wetness Index differences with each soil moisture survey and a graph showing the distribution of each survey divergence distribution.

This assessment of the implication of TWI on the soil moisture distribution indicates that there is certainly a limit to the efficacy of this method, even for a small catchment with a shallow active soil horizon. Despite the ease with which TWI can be integrated into physical hydrological models this study questions to what extent its predictions can be trusted. This is not a new conclusion having been highlighted by a number of previous studies (Western et al., 1999; Bobert et al., 2001; Sorensen et al., 2006), however the solution to this problem is one that has become a challenge. The impact of soil moisture particularly in humid temperate climates is significant in understanding how water flows across a catchment. It is apparent that an understanding of soil moisture distribution itself is necessary if modelling prediction methods cannot be relied upon to give a reasonable estimate.

6.2 Metrics

The statistical development of the assessment of soil moisture as a method of estimating hydrological connectivity has progressed through its advocacy by Western at al. (2001) using and perfecting initial geostatistical approaches (Allard, 1994). This development has generated an increasing cohort of papers assessing the potential for metrics in representing catchment connectivity response (Guo, et al., 2002). The performance of the metrics that were selecting by this study from this group had varied success and developed these assessments bringing together the different forms of analysis together using a similar catchment to that used by Western et al. (2001) to correlate these approaches together in order to ascertain how these methods compared.

6.2.1 Successful Metrics

The metrics that proved to be successful were limited to the higher soil moisture (sm) percentile thresholds (Table 5.2). There were four distinct metrics that achieved 9 on the objectivity function. This level wasn't not achieved by Ali and Roy (2010) when they made similar metric assessments for the Hermine catchment. There is likely to be some discrepancy between the two, however, due to different meteorological analysis approaches. In addition to this their study required a multiple depth consideration that was not applicable for the Sykeside catchment. That having been said it is important to ascertain the transferability of metrics, highlighted in the Hermine study, between forested and grassland catchments. The successful metrics identified by Ali and Roy (2010) are displayed in Table 6.1. It is immediately apparent that this table is dominated by semivariograms. The simpler areas based approaches that were used only appear on two occasions at high sm thresholds (sm50 was the highest thresholds for sm for the Ali and

Roy (2010) study). This is in stark contrast to the results this study which has a broad range of metrics that satisfy the criteria of the objectivity function. Indeed all the metrics but SATCLUST achieved a thresholds response of 8. The presence of SATCLUST in Table 6.1 is interesting given its poor performance in this study.

Depth	Connectivity Metric	Threshold
5 cm	RANGE_NS RANGE_NS	cp50 sm20
15 cm	RANGE_OM RANGE_EW RANGE_NS SATAREA SATCLUST	cp10 cp10 cp25 sm50 sm50
30 cm	RANGE_NS	cp25
45 cm	RANGE_OM RANGE_EW RANGE_EW	cp90 sm50 sm40

Table 6.1: Successful connectivity metrics for the Hermine catchment, Quebec. Metrics that are not included in this study are omitted. "cp" is a distributed multivariate threshold derived from normal distribution percentiles based on depth. This is a depth equivalent to dp that is seen in this study. Although this method is not relevant to this study those metrics that performed well for this threshold form have been included. Adapted from Ali and Roy (2010).

The best performing metrics for this study were instead orientated towards simpler area based metrics (Table 5.2) like SATAREA and CONTAREA. The metrics that were investigated clearly highlighted the threshold distinction seen in the rainfall and stage data. This is not apparent from the MSMC (mean soil moisture content) itself (Figure 4.23) which shows a good distribution of values between the recorded range of 0.7 m^3m^{-3} and 0.3 m^3m^{-3}. Therefore it was interesting that a range of the metrics, although based on soil moisture thresholds, reflected this threshold distinction.

The presence of saturated area (SATAREA) reflects very much the short nature of the surface flow pathways of this catchment. Although SATAREA is seen as one of the significant metrics tested by Ali and Roy (2010) it was not expected that SATAREA would perform as well as contributing area (CONTAREA). This is broadly the case with SATAREA given that it is not being found to have the same level of significance at the sm60 threshold, however this is a relatively small difference compared with other metrics. It is likely that this symmetry indicates that both saturated area metrics are representative of each other. It also shows that saturated area as a whole reacts rapidly with limited examples of stranded unconnected area of saturation. Had this been the case SATAREA would not have performed so well. However the fact that it was not at the same level as CONTAREA suggests that there was some discrepancy between the two. The importance of soil saturation area for hydrological connectivity has long been established (Burt et al., 1985; Stieglitz et al., 2003). In larger catchments with deep soils the distinction between saturated area and contributing area is more important with most models focussing on contributing area as a likely representative factor for hydrological connectivity (Quinn et al., 1991). However in catchments with shallower soils or with shorter flow paths this difference is much less (Ogden and Watts, 2000). The result of this metric agrees with this hypothesis given that the potential connectivity length in this catchment is not so great as to exclude saturated unconnected areas of the catchment. Instead the process is more a progressive wetting up that is similarly represented in SATAREA and CONTAREA. It might be suggested that given CONTAREA is the best performing metric, that modelling approaches like Topographic Wetness Index (TWI) can be considered as a representative method of estimating soil moisture distribution. However there is a distinct difference here between a statistical function based on a cumulative topographic area and that area which is saturated above a threshold and topographically connected to the channel. The incorporation of the soil moisture distribution itself instead indicates that the contributing area as defined by soil moisture is significant in predicting hydrological connectivity but that topographic methods of estimating this are not sufficient as suggested by Figure 6.2.

Interestingly the other two metrics were also focussed on simple area measures. These were the only metrics from the cluster analysis from FRAGSTATS to be significant for all three modes of analysis. The presence of class area, a proportion based saturated area metric (CA%) is not a surprise with it being largely a different representation of SATAREA. However CA% consistently performs less well. This indicates that the proportion does not convey as much information. The limited range that is present for many of the FRAGSTATS metrics (either as a percentage or as a function between 0 and 1) buffer the expression of threshold changes. In this way not only have many of the metrics performed less well as part of the coefficient of variance their range is not sufficient to distinguish an adequate relationship with antecedent precipitation (AP14) and stage data (Table 5.2).

The last of the four metrics was the Largest Patch Index (LPI: the largest patch as a proportion of the catchment). The fact that the largest patch showed a consistent representation of the catchment shows the degree to which the catchment changed over time. Given that the catchment was often one complete patch the representativeness of this metric at low thresholds was unlikely. However its relevance at high thresholds where LPI effectively represents the degree to which the largest patch represents catchment factors, was very high. This is not what would be expected in larger catchments where patches are hillslope specific. However if you consider a catchment as a mosaic of hillslopes the largest patch is often the most important as it represent the largest contributing flow path (Bronstert and Plate, 1997). As a result the good results for LPI show that the catchment has a temporal variation in organisation. However this patch is not necessarily connected to the channel. Although the form of this catchment suggests that that is likely this could not be assumed on other hillslope surfaces. Instead, this method represents a form of sampling whereby the largest patch becomes a proxy for saturated area as a whole. However more specifically to this catchment LPI represent the degree to which a number of persistent active areas are connected (Figure 5.2). The relationship between LPI and hydrological connectivity is complicated and it is not a metric that can be presumed to be immediately transferable to other sites even with similar flow regimes. For this catchment it is an amalgamation of the expansion and contraction of the most persistent active area under low saturation conditions with larger scale connected contiguous groups under high saturation conditions. This balance is good for this study because of the consistency of large saturated areas. Even if there was no spread between persistent areas of saturation, then the expansion and contraction of that patch would reflect the hydrological conditions. The additional inter-patch connection enhances this metric in wet conditions. The problem with translating this metric to other catchments is largely because there is not a topographic element to this metric identifying whether links between patches would have a resultant impact on hydrological connectivity. This method could however be very useful in identifying gullies from soil moisture and subsequently identifying the migration of soil moisture within the gully and into the gully itself from contributing areas as a single hydrological unit.

The metrics that satisfied the objectivity function for this study were few and limited to simple area based methods. Although these are documented in Ali and Roy (2010) there are not the metrics that are considered to have the most potential for soil moisture connectivity metrics. Thus it is interesting to develop why it is that the other more complex metrics did not meet the criteria set out to find the best metric and what implication this has for them as methods for ascertaining hydrological connectivity.

6.2.2 Non-Hydrologically Representative Metrics

Of the 11 distinct metrics five achieved a nine (out of nine) in the objectivity function (Table 5.2). Of the five that were successful, none developed in complexity beyond area measurements. The other six metrics that were not successful represented the more diverse and methodologically detailed soil moisture assessment but failed to represent temporal variability, stage and antecedent rainfall data adequately. These are broadly defined as cell adjacency cluster analyses and semivariograms. This is not to say that these performed uniformly badly as there are a range of results. It is also important to note that each of these metrics had threshold examples, notably sm70, where their performance was relatively high. However the fact that simple metrics outperformed these approaches calls into question the use of complex assessment methods to ascertain hydrological connectivity when their performance cannot match that of simple area estimates.

The cell adjacency cluster analyses of the Adjacency Index (AI), COHESION and DIVISION struggled to represent the catchment in a manner that satisfied the three objectivity function analyses. Each of these methods attempts to ascertain the uniformity of the cells above the threshold by either assessing the degree to which the cells are physically adjacent to one another (AI) or as a function of individual patch areas (DIVISION and COHESION). Temporal variation across catchment responses was a key failure of these methods generating results that did not sufficiently distinguish between different soil moisture conditions. A notable exception of this was DIVISION, which showed high variation for the low sm thresholds which unlike all of the other metrics declined in variability with increasing threshold (Appendix A). However this was because of the inverse nature of the metric. These methods were not sensitive enough to the changes across the catchment. Despite considerable temporal changes between soil moisture surveys the degree of difference resulting from these metrics was not sufficient. It is this lack of temporal distinction that causes these metrics to underperform as the results from analysis against antecedent precipitation and stage were consistent with the simple area based metrics. An explanation for these poor performances is that given these methods look to test how cohesive the patches above the threshold are, it suggests that the persistence of key active areas in the catchment, that were consistently present across the thresholds (Figure 5.2) affected the efficacy of these approaches. This is emphasised by the COHESION metric (a function of individual patch area perimeter ratio with total surface area) which showed the lowest amount of variation of all of the metrics and is supported by the variation for AI which is similarly poor. This poor variation undermines any potential significance with the two hydrology variables as the relationship is likely to be false.

Clearly the impact of soil moisture organisation, especially the potential for active areas that expand and contract as part of temporal moisture variation, can have a significant impact on metrics designed to statistically assess cluster distribution. The organisation of the threshold data was too consistent for these methods to conclusively identify difference between them. This was the case irrespective of whether area and perimeter ratios (COHESION) or cell adjacencies (AI) were used. This is of particular importance when considered in conjunction with the growing importance of the “active area” concept (Ambroise, 2004). This idea is gaining increasing importance especially regarding soil moisture. As a result the potential for using this approach to estimate at risk areas for water, nutrient and sediment transport within a catchment is growing (Newson, 2010). It is not feasible to have metrics that cannot cope with persistent organised soil moisture particularly in shallow soiled temperate catchments for which hydrological connectivity is so important. Active areas are an important feature in discerning and identifying areas of hydrological connectivity and these cluster methods sensitivity are greatly reduced by their presence, rendering them of little use as a hydrological metric.

The other notable, and perhaps more significant, metric that proved unsuccessful in this study were the semivariogram based metrics. These have proven to be something of a corner stone to the geostatistical analysis of soil moisture in recent years (Bádossy and Lehmann, 1998; Wang et al., 2001; Herbst and Diekkrüger, 2003) despite suggestions that they do not necessarily derivate between different connectivity conditions (Western et al., 1998). Although semivariograms are increasingly used as part of more developed connectivity metrics like Western et al.’s (2001) integrated connectivity scale length, the indicator semivariograms are very much a part of identifying potential connectivity variation using soil moisture and subsequently is being increasingly tested to ascertain whether they generate a significant response (James and Roulet, 2007). The semivariograms for this study reflected the results seen in earlier investigations on grassland catchments (Western et al., 2001) with continuity increasing with wetness. The omnidirectional range (RANGE_OM) was found to be very similar to that of RANGE_EW largely due to the influence of the channel. The RANGE_NS was significantly smaller due to the lower potential distance. In the context of previous studies the ranges were in line with the separation distances found by James and Roulet (2007) between 100 m and 0 m. This is relatively low by comparison to previous studies of this nature where ranges of up to 990 m have been found (Western et al., 2001). However this is likely to be a result of the catchment being relatively small and it is similar to results from Meyles et al. (2003) of 8 m to 180 m on a grass and peat dominated catchment.

There is a strong similarity between spatial (sm) and temporally distributed (dp) thresholds in terms of the shape of the distribution across the thresholds (Figure 5.5). However the range of the results between the two threshold forms is much smaller for dp and as a result shows it to be less dynamic. This is reflected by poor coefficient of variance performance (Appendix A). The performance of semivariograms is limited in this study largely due to temporal variation at high sm thresholds. The consistency of the signal distribution across the thresholds results in the best performance with the antecedent precipitation and stage data of any metric. Unusually this persists beyond lower sm thresholds that sm50. This is because there is inherent variability of soil moisture data that is above the threshold. This gives a dynamism to this metric that is not present for the other metrics as it addresses actually soil moisture values above the threshold as opposed to simply identifying binary results above or below thresholds. As a result it appears that semivariogram ranges are good at correlating with stage and antecedent responses but that these ranges are limited in their potential distribution. This results in representative ranges that do not have sufficient sensitivity to give a distinct signal. The muted nature of these relationships leads to semivariogram ranges failing to meet the criteria of the objectivity function used for this study.

This lack of temporal variation is not seen in Ali and Roy (2010) where range data (both directional and omnidirectional) were found to have threshold results that were over 100% (Figure 3.1). However they found that they performed particularly poorly when representing discharge. The efficacy seen in this study might be due to its small size resulting in flashy stage that takes a very short time to manifest rainfall. This would explain the strong correlation between stage and rainfall and could explain why problems that Ali and Roy (2010) experienced regarding representativeness with discharge are absent here. This does not undermine the conclusion however that temporal variability in this catchment was not adequate to distinguish different hydrological conditions sufficiently. This, in combination with other studies highlighting that semivariograms shows continuity rather than connection (Western et al., 1998) and problems regarding representation of hydrological response (Ali and Roy, 2010), challenge the wide ranging use of this method. That is not to say that this study conclusively proves that semivariograms cannot be use as clearly here and in Ali and Roy (2010) the difference was not so significant as to make that assertion. Yet it is clear although having potential as an initial indication of change in soil moisture distribution it is not a sufficiently rigorous metric for representing hydrological connectivity itself.

The exception from these two groups is the persistent poor performance of SATCLUST (number of saturated patches). It is an exception in that it fits neither nonhydrologically successful group and that it is the only metric tested that did not meet the intermediate criteria (a score of 8 on the objectivity function) at any threshold. This is of particular interest because Ali and Roy (2010) identified it as significant for their study. SATCLUST is fundamentally related to saturated area (SATAREA) as it uses this to calculate the number of patches. Yet the good representation of hydrological condition found using SATAREA is not present for SATCLUST. SATCLUST is arguably the simplest metric that was used yet the difference in its representativeness between this study and Ali and Roy (2010) are substantial. This is likely to be due to the manner in which the soil moisture is distributed and highlights the difficulty of identifying metrics that can be used across different hydrological conditions. Ali and Roy (2010) found that SATCLUST showed a high degree of variability irrespective of the threshold used. This was not the case to the same extent in this study with high variability only being seen for soil moisture thresholds (sm) (Appendix A) proving to be one of the most temporally variable of all the metrics. The problem with SATCLUST in this study was the propensity for the metrics itself to be normally distributed. With such a small catchment containing a large range of hydrological conditions the range tended towards 1 cluster at each end of the soil moisture spectrum. In other words the peak cluster number was not the least hydrologically connected condition. The dominance of key active areas in dry conditions provided a limit to which clusters could form. This resulted in a tendency for the data to move from a cluster number of 1 at low thresholds where the catchment is one patch through an increase of cluster number as the patches disconnect. At a critical point the number of patches would peak and then the SATCLUST value would decline. This results in a strong temporal variation but a poor response to the other methods of analysis that assume a linear response. These results bring into question the use of integer number of soil moisture patches in locations where there is the potential for a normal distribution over the range of hydrological conditions expected, especially if that is not explicitly addressed.

6.3 A way forward: Cumulative Probability Network Index

The results of the metric analysis highlight the difficulty in creating connectivity metrics that can generate results that are representative of the hydrology of a catchment or hillslope. Although metrics were identified that passed the objectivity analysis these were simple areal estimations that do not develop the understanding of the hydrological connectivity in a catchment, instead providing simple corollaries of mean soil moisture. Those metrics that provided more information about either the distribution of soil moisture clusters or continuity struggled to represent the catchment satisfactorily for the necessary range of hydrology parameters. Although further development of connectivity metrics are being developed, particularly from the connectivity scale length of Western et al. (2001) progressing from Euclidean distance towards hydrological distance through topographic flow pathways (Ali and Roy, 2010), the potential for simple computed metrics are limited in their expression of the catchment.

The potential solution that has been suggested is using topography to estimate potential flow paths through the rate determining step (i.e. the lowest value along a flow path) (Lane et al., 2004). By combining this topographic, yet temporally sensitive, approach with the identification of the need to represent hydrological connection as a probabilistic function instead of a discrete threshold (Ali and Roy, 2009), a better understanding for spatial variation can be established. This is of particular importance especially regarding connectivity metrics because the characterisation of connectivity through a single value metric greatly reduces the knowledge of spatial flow distribution itself.

The Network Index results show that, through using a soil moisture derived probabilistic connectivity distribution, spatial patterns that are otherwise lost in single threshold driven analysis re-emerge. The distribution seen identifies area where flow is curtailed and limited as a result of topographic flow pathway limitations. Thus potential flow can be identified, better disseminating, spatially, the impact of certain surface soil moisture conditions and how those impact on the likelihood of connection across the catchment. Using the Network Index definite areas of potential connection are identified. However this only shows the individual cell likelihood of connection and does not address the cumulative effect of soil moisture along flow pathways that are present and the extent to which these manifest themselves in different conditions. Due to the nature of the Network Index it provides the indicative cells from which hydrological connection can emanate.

Subsequently, the Cumulative Probability Network Index (CPNI) develops the Network Index approach by giving an indication of which areas will connect as a result of the accumulated probability of the soil moisture. Thus this method highlights those flow pathways that are likely to connect to the channel rather than the potential flow pathways. This specifies areas of potential connection from the Network Index to highlight those areas where topography and soil moisture conditions are most favourable for connection. As a result clear areas emerge as being significantly active and contributing as a function of both topography and soil moisture over time (Figure 5.9). Although these can be seen as a result of the Network Index the extent of their impact on the catchment is dependant as much on the spatial distribution of soil moisture as on topography, making the effect of antecedent conditions more readily apparent. This method combines easy to measure structural topographic data with important temporally variable functional soil moisture data to give a combined estimate of hydrological connectivity. This combination is an important step forward in providing a realistic representation of hydrological connectivity (Bracken and Croke (2007).

This CPNI method could be developed by testing this model on larger scale catchments with different land uses, to ascertain how well the model copes with longer flow pathways with a greater lag time. Through doing this the model could be more rigorously tested regarding different flow regime, particularly given that the rainfall conditions during this study were relatively dry. The effect of longer lag flow paths would be particularly interesting to see whether the model would still accurately represent temporal variation of active areas.

Chapter Summary

It is apparent that the metrics outlined in this chapter go a long way to identify the potential for hydrological connectivity via different temporal and magnitude thresholds of soil moisture. Well performing metrics were identified satisfying statistical temporal, hydrological and meteorological analyses. These results were further developed by the introduction of the Cumulative Probability Index that promoted the index form as a promising method to estimate hydrological connectivity.

7.0 Conclusions

Hydrological connectivity has the potential for wide ranging implications for hydrological study. Developments in the philosophical approach to how hydrological science is performed have opened the door for innovative concepts and theories that aim to unify hydrological knowledge. Hydrological connectivity has emerged as a unifying idea, with the potential to combine structural landscape features with variable temporal antecedent and rainfall conditions. The measurement of connectivity has proven to be challenging not least because temporal conditions are very difficult to measure. Soil moisture has emerged as a relatively simple way of hydrological connectivity estimation in shallow soiled catchments. Subsequently there has been an increase in the use of metrics to represent hydrological connectivity as a function of soil moisture.

This thesis tested a number of these metrics to ascertain their efficacy relative to temporal variability, antecedent rainfall and stage data. Each metric was subject to a range of soil moisture thresholds in order to identify connectivity thresholds and to see the effect this had on metric performance. It was found that soil moisture distribution thresholds were very poor at representing connectivity in the catchment with none of the metrics achieving high results for the metric analysis. Discrete soil moisture percentages performed much better with high soil moisture values distinguishing connectivity across a range of metrics. The simple area based metrics performed the most consistently with a high level of satisfaction being achieved by saturated and contributing area estimation. This indicated the highly representative nature of soil moisture with hydrological connectivity through strong correlations with antecedent rainfall and stage data. By contrast more complex cluster analysis methods failed to temporally differentiate the soil moisture conditions as a result of persistent active areas. This undermined their performance as a whole and highlights their fragility when there is enduring continuity in soil moisture distribution. Semivariograms also struggled to differentiate the soil moisture despite correlating strongly with stage and rainfall data. This was not sufficient evidence to undermine the assertions made by Western et al. (2001) about the usefulness of semivariograms for estimating the changes in soil moisture distribution but did cast doubt on their efficacy in different environmental condition.

The method that was found to be the most promising for estimating hydrological connectivity from soil moisture was a model derived from the topographically based Network Index. Although the Network Index was successful at identifying potential flow paths and the degree of likelihood of their connection the Cumulative Probability Network Index (CPNI) identified the accumulated probability of flow pathway connection as a function of the soil moisture. This provides a far more specific and rigorous estimation of hydrological connectivity as a direct function of soil moisture. The combination of topographic and soil moisture input data and the cumulative nature of the probability function that it creates presents an excellent combination of structural and functional connectivity information that is key to generating an authentic hydrological connectivity estimation. Through this source areas for overland flow can be identified with the development potential in the future to include through flow estimation. The CPNI provides a great deal of potential for the estimation of hydrological connectivity particularly in shallow upland catchments identifying active pathways and areas specific to antecedent moisture conditions.

8.0 References

1. Adams, R., S. M. Dunn, R. Lunn, R. Mackay, and J. R. O'Callaghan (1995), Assessing the performance of the NELUP hydrological models for river basin planning, *J. Environ. Plann. Manage., 38*, 53–76, doi:10.1080/09640569513110.

2. Ali, G. A., and A. G. Roy (2010), Shopping for Hydrologically Representative Connectivity Metrics in a Humid Temperate Forested Catchment, *Water Resour. Res., 46*, W12544, doi:10.1029/2010WR009442.

3. Allard, D. (1994), Simulating a geological lithofacies with respect to connectivity information using the truncated Gaussian model, *In* Armstrong, M., and P. A. Dowd (eds.), Geostatistical Simulations, Kluwer Academic Publishers, Dordrecht, The Netherlands, 197-211.

4. Anderson, M. G., and T. P. Burt (1990), Subsurface Runoff, 365-400, *In* Anderson, M. G., and T. P. Burt (eds.), Process studies in hillslopes hydrology, Wiley, Chichester, UK.

5. Ambroise, B. (2004), Variable active versus contributing areas or periods: a necessary distinction, *Hydrol. Processes, 18*, 1149 – 1155, doi:10.1002/hyp.5536.

6. Antoine, M., M. Javaux, and C. Bielders (2009), What indicators can capture runoff-relevant connectivity properties of the micro-topography at the plot scale?, *Adv. Water Resour., 32*, 1297–1310, doi:10.1016/j.advwatres.2009.05.006.

7. de Araujo, J. C., and J. I. G. Piedra (2009), Comparative hydrology: analysis of a semiarid and a humid tropical watershed, *Hydrol. Processes, 23*, 1169-1178, doi:10.1002/hyp.7232.

8. Aryal, S. K., R. G. Mein, and E. M. O'Loughlin (2003), The concept of effective length in hillslopes: assessing the influence of climate and topography on the contributing areas of catchments, *Hydrol. Processes, 17*, 131–151, doi:10.1002/hyp.1137.

9. Asdak, C., P. G. Jarvis, P. Van Gardingen, and A. Fraser (1998), Rainfall interception loss in unlogged and logged forest areas of Central Kalimantan, Indonesia, *J. Hydrol. Amsterdam, 206*, 237-244, doi:10.1016/S0022-1694(98)00108-5.

10. Bádossy, A., and W. Lehmann (1998), Spatial distribution of soil moisture in a small catchment. Part 1: geostatistical analysis, *J. Hydrol. Amsterdam, 206*, 1-15, doi:10.1016/S0022-1694(97)00152-2.

11. Beasley, D. B., L. F. Huggins, and E. J. Monke (1980), ANSWERS — A model for watershed planning, *Trans. Am. Soc. of Agric. Eng.*, *23*, 938– 944.

12. Bell, J. P. (1987), Neutron probe practice. 3rd edition. (IH Report No.19), Available at http://www.ceh.ac.uk/products/publications/hydrology.html (verified 22 Aug. 2010), Institute of Hydrology, Wallingford, Oxon, UK.

13. Bertoldi, G., W. E. Dietrich, N. L. Miller, and R. Rigon (2004), Role of bedrock heterogeneities and soil thickness on the saturation overland flow dynamics in headwater catchments: field observation and simulation using a distributed hydrological model, 111–113, *In* Teuling, A. J., H. Leijnse, P. A. Troch, J. Sheffield and E. F. Wood (eds.), Proceedings of the 2nd international CAHMDA workshop on: The Terrestrial Water Cycle: Modelling and Data Assimilation Across Catchment Scales, Princeton, USA.

14. Beven, K. (2000), Uniqueness of place and process representations in hydrological modelling, *Hydrol. Earth Syst. Sci., 4*, 203– 213, doi:10.5194/hess-4-203-2000.

15. Beven, K. J., and M. J. Kirkby (1979), A physically based variable contributing area model of catchment hydrology, *Hydrolog. Sci. Bull.*, *24*, 34-69.

16. Beven, K. J., and P. Germann (1982), Macropores and Water Flow in Soils, *Water Resour. Res., 18*, 1311-1325, doi:10.1029/WR018i005p01311.

17. Blackwell, M. S. A., D. V. Hogan, and E. Maltby (1999), The use of conventionally and alternatively located buffer zones for the removal of nitrate from diffuse agricultural run-off, *Water Sci. Technol.*, *39*, 157– 164, doi:10.1016/S0273-1223(99)00331-5.

18. Bobert, J., F. Schmidt, R. Gebbers, T. Selige, and U. Schmidhalter (2001), Estimating soil moisture distribution for crop management with capacitance probes, EM-38 and Digital terrain analysis, *3rd Europ. Conference Precision Agriculture, Montpellier*, 349-354.

19. Bracken, L. J., and J. C. Croke (2007), The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems, *Hydrol. Processes*, *21*, 1749– 1763, doi:10.1002/hyp.6313.

20. Brierley, G., K. Fryirs, and V. Jain (2006), Landscape connectivity: the geographic basis of geomorphic applications, *Area*, *38*, 165– 174, doi:10.1111/j.1475-4762.2006.00671.x.

21. Briggs, L. J. (1899), Electrical instruments for determining the moisture, temperature, and soluble salt content of soils, *USDA Division of Soils Bulletin, 10*, U.S. Government Print. Office, Washington, DC.

22. Bronstert, A., and A. Bárdossy (1999), The role of spatial variability of soil moisture for modelling surface runoff generation at the small catchment scale, *Hydrol. Earth Syst. Sc., 3*, 505-516.

23. Bronstert, A., and E. J. Plate (1997), Modelling of runoff generation and soil moisture dynamics for hillslopes and micro-catchments. *J. Hydro. Amsterdam, 198*, 177-195, doi:10.1016/S0022-1694(96)03306-9.

24. Bull L. J., M. J. Kirkby, J. Shannon, and H. D. Dunsford (2003), Predicting hydrologically similar surfaces (HYSS) in semi-arid environments, *Adv. Environ. Monit. and Model., 2,* 1–13.

25. Bull L. J., M. J. Kirkby, J. Shannon, and J. M. Hooke (2000), The variation in estimated discharge in relation to the location of storm cells in SE Spain. *Catena, 38,* 191–209.

26. Burke, A. R. (2009), A comparison of soil moisture and Hillslope-Stream Connectivity between Aspen and conifer-dominated hillslopes of a first order catchment in Northern Utah, MSc Thesis, Utah State University, Logan, USA.

27. Burt, T. P. and D. P. Butcher (1985), Topographic controls of soil moisture distributions, *Eur. J. Soil Sci., 36,* 1365-2389, doi:10.1111/j.1365-2389.1985.tb00351.x.

28. Buttle, J. M., and D. A. House (1997), Spatial variability of saturated hydraulic conductivity in shallow macroporous soils in a forested basin, *J. Hydrol. Amsterdam, 203*, 127-142, doi:10.1016/S0022-1694(97)00095-4.

29. Cammeraat, L. H. and A. C. Imeson (1999), The evolution and significance of soil-vegetation patterns following land abandonment and fire in Spain, *Catena, 37,* 107-127, doi:10.1016/S0341-8162(98)00072-1.

30. Chanzy, A., A. Tarussov, A. Judge, and F. Bonn (1996), Soil water content determination using a digital ground-penetrating radar, *Soil Sci. Soc. Am. J., 60,* 1318–1326.

31. Choudhury, B. J., T. J. Schmugge, A. Chang, and A. W. Newton (1979), Effect of surface roughness on the microwave emission from soils, *J. Geophys. Res.*, *84*, 5699–5706, doi:10.1029/JC084iC09p05699.

32. Clothier, B. E., I. Vogeler, S. R. Green, and D. R. Scotter (1998), Transport in unsaturated soil: Aggregates, macropores and exchange, 273–295, *In* Selim, H. M., and L. Ma (eds.), Physical Nonequilibrium in Soil: Modeling and Application, Ann Arbor Press, Ann Arbor, USA.

33. Creed, I. F., and L. E. Band (1998), Exploring functional similarity in the export of Nitrate-N from forested catchments: a mechanistic modeling approach, *Water Resour. Res., 34,* 3079–3093, doi:10.1029/98WR02102.

34. Cressie, N. A. C. (1993) Statistics for spatial data, John Wiley and Sons, New York, USA.

35. Croke, J. C., P. B. Hairsine, and P. Fogarty (1999), Runoff generation and redistribution in logged Eucalyptus forest southeastern Australia, *Hydrol. Processes, 13*, 2705 – 2720, doi:10.1016/S0022-1694(98)00288-1.

36. Croke, J. C., P. B. Hairsine, and P. Fogarty (2000), Nutrient movement due to overland flow in managed native Eucalyptus forest south-eastern Australia, *Water Air Soil Poll., 122,* 17 – 35, doi:10.1023/A:1005221723226.

37. Croke, J. C., P. B. Hairsine, and P. Fogarty (2001), Soil recovery from track construction and harvesting changes in surface infiltration, erosion and delivery rates with time, *Forest Ecol. Manag., 143,* 3-12, doi:10.1016/S0378-1127(00)00500-4.

38. Croke, J. C., S. Mockler, P. Fogarty, and I. Takken (2005), Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity, *Ecohydrology, 68,* 257-268, doi:10.1016/j.geomorph.2004.11.020.

39. Dagan, G. (1987), Theory of solute transport by groundwater, *Annu. Rev. Fluid Mech., 19,* 183–213, doi:10.1146/annurev.fl.19.010187.001151.

40. Dalton, F. N., W. N. Herkelrath, D. S Rawlins, and J. D. Rhoades (1984), Time domain reflectometry: Simultaneous measurement of soil-water content and electrical-conductivity with a single probe, *Science, 224,* 989–990, doi:10.1126/science.224.4652.989.

41. Dasberg, S., and F. N. Dalton (1985), Time domain reflectometry field-measurements of soil-water content and electrical-conductivity, *Soil Sci. Soc. Am. J., 49,* 293–297.

42. De Roo, A. P. J., and V. G. Jetten (1999), Calibrating and validating the LISEM model for two data sets from the Netherlands and South Africa, *Catena, 37*, 477– 493, doi:10.1016/S0341-8162(99)00034-X.

43. Debye, P. (1929), Polar molecules, Chemical Catalog, New York, USA.

44. Desmet, P. J. J. (1997), Effects of Interpolation Errors on the Analysis of DEMs, *Earth Surf. Processes Landforms*, *22*, 563-580, doi:10.1002/(SICI)1096-9837(199706)22:6<563::AID-ESP713>3.0.CO;2-3.

45. Deutch, C. V., and A. G. Journel, (1998), GSLIB: Geostatistical Software Library and User's Guide, Oxford University Press, Oxford, UK.

46. Devito, K. J., Hill, A. R., and N. Roulet (1996), Groundwater-surface water interactions in headwater forested wetlands of the Canadian Shield, *J. Hydrol. Amsterdam*, *181*, 127-147.

47. Dooge, J. C. I. (1986), Looking for hydrological laws, *Water Resour. Res., 22*, 46-58, doi:10.1029/WR022i09Sp0046S.

48. Fitzjohn, C., J. L. Ternan, and A. G Williams (1998), Soil moisture variability in a semi-arid gully catchment: implications for runoff and erosion control, *Catena, 32*, 55–70, doi:10.1016/S0341-8162(97)00045-3.

49. Frey, M. P., M. K. Schneider, A. Dietzel, P. Reichert, and C. Stamm (2009), Predicting critical source areas for diffuse herbicide losses to surface waters: Role of connectivity and boundary conditions, *J. Hydrol. Amsterdam, 365*, 23–36, doi:10.1016/j.jhydrol.2008.11.015.

50. Galagedara, L. W., J. D. Redman, G. W. Parkin, A. P. Annan, and A. L. Endres (2005), Numerical modeling of GPR to determine the direct ground wave sampling depth, *Vadose Zone Journal*, *4,* 1096–1106, doi:10.2136/vzj2004.0143.

51. Gardner, C. M. K., D. A. Robinson, K. Blyth, and J. D. Cooper (2001), Soil water content, 1–64, *In* Smith, K. A., and C. E. Mullins (eds.), Soil and environmental analysis: Physical methods, 2nd ed., Marcel Dekker, New York, USA.

52. Gardner, W. H. (1986), Water content, 493–544, *In* Klute, A. (ed.) Methods of soil analysis: Part 1. Physical and mineralogical properties, 2nd ed., ASA and SSSA, Madison, USA.

53. Gaskin, G. J., and J. D. Miller (1996), Measurement of soil water content using a simplified impedance measuring technique, *J. Agri. Eng. Res., 63*, 153-159, doi:10.1006/jaer.1996.0017.

54. Glover, J. K. D. (2005), Spatial assessment of groundwater recharge in the Eden Catchment – utilising a comparison between MOSES & MORECS, MSc Thesis, Newcastle University, Newcastle, UK.

55. Grayson, R. B., G. Blöschl, A. W. Western, T. A. McMahon (2002), Advances in the use of observed spatial patterns of catchment hydrological response, *Adv. Water Resour., 25,* 1313–1334, doi:10.1016/S0309-1708(02)0060-X.

56. Grayson, R. B., A. W. Western, F. H. S. Chiew, and G. Blöschl (1997), Preferred states in spatial soil moisture patterns: local and nonlocal controls, *Water Resour. Res., 33*, 2897–2908, doi:10.1029/97WR02174.

57. Grayson, R. B., G. Blöschl, and I. D. Moore (1995), Distributed parameter hydrologic modelling using vector elevation data: Thales and TAPES-C, 669-695, *In* Singh, V. P. (ed.) Computer Models of Watershed Hydrology, Water Resources Publishing, Highlands Ranch, Colorado, USA.

58. Greaves, R. J., D. P. Lesmes, J. M. Lee, and M. N. Toksoz (1996), Velocity variations and water content estimated from multi-off set, ground-penetrating radar, *Geophysics, 61,* 683–695, doi:10.1190/1.1443996.

59. Guo, D., P. Mou, R. H. Jones, and R. J. Mitchell (2002), Temporal changes in spatial patterns of soil moisture following disturbance: an experimental approach, *Journal of Ecology, 90,* 338-347, DOI: 10.1046/j.1365-2745.2001.00667.x.

60. Guo, Y., and A. Quader (2009), Derived Flow – Duration Relationships for Surface Runoff Dominated Small Urban Streams, *Journal of Hydrologic Engineering, 13,* 42-52, doi:10.1061/(ASCE)1084-0699(2009)14:1(42).

61. Hairsine, P. B., J. C. Croke, H. Matthews, P. Fogarty, and S. P. Mockler (2002), Modelling plumes of overland flow from roads and logging tracks. *Hydrol. Processes, 16*, 2311–2327, doi:10.1002/hyp.1002.

62. Hallikainen, M. T., F. T. Ulaby, M. C. Dobson, M. A. El-Rayes, and L. Wu (1985), Microwave dielectric behavior of wet soil: Part I. Empirical models and experimental observations, *IEEE Transactions on Geosciences and Remote Sensing, 23,* 25–34, doi:10.1109/TGRS.1985.289497 .

63. Harmel, R. D., R. J. Cooper, R. M. Slade, R. L. Haney and J. G. Arnold (2006), Cumulative uncertainty in measured streamflow and water quality data for small watersheds, *Transactions of the ASABE, 49*, 689-701,

64. Harvey, A. M. (1996), Holocene hillslope gully systems in the Howgill Fells, Cumbria, 247–270, *In* Anderson, M. G. and S. M. Brooks (eds.), Advances in Hillslope Processes, vol. 2, Wiley, Chichester, UK.

65. Harvey, A. M. (2001), Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, northwest England, *Catena, 42*, 225–250, doi:10.1016/S0341-8162(00)00139-9.

66. Harvey, A. M. (2007), Geomorphic instability and change-introduction: implications of temporal and spatial scales, *Geomorphology, 84*, 153–158.

67. Heathwaite, A. L. (2003), Making process-based knowledge useable at the operational level: A framework for modelling diffuse pollution from agricultural land, *Environ. Model. Software*, *18*, 753–760, doi:10.1016/S1364-8152(03)00077-X.

68. Heppell, C. M., F. Worrall, T. P. Burt, and R. J. Williams (2002), A classification of drainage and macropore flow in an agricultural catchment, *Hydrol. Processes, 16,* 27-46, doi:10.1002/hyp.282.

69. Herbst, M., and B. Diekkrüger (2003), Modelling the spatial variability of soil moisture in a micro-scale catchment and comparison with data using geostatistics, *Phys. Chem. Earth, Parts A/B/C, 28,* 239-245, doi:10.1016/S1474-7065(03)00033-0.

70. Hubbard, S., K. Grote, and Y. Rubin (2002), Mapping the soil volumetric water content of a California vineyard using high-frequency GPR ground wave data, *Leading Edge, 21,* 552–559, doi:10.1190/1.1490641.

71. Ishida, T., and T. Makino (1999), Effects of pH on dielectric relaxation of montmorillonite, allophane and imogolite suspensions, *Journal of Colloid Interface Science, 212*, 152–161, doi:10.1006/jcis.1998.6030.

72. Jackson, T. J., P. E. O'Neill, and C. T. Swift (1997), Passive microwave observation of diurnal surface soil moisture, *IEEE Trans. Geosc. Rem. Sens., 35,* 1210–1222, doi:10.1109/IGARSS.1995.520317.

73. Johnes, P.J., and A. L. Heathwaite (1997), Modelling the impact on water quality of land use change in agricultural catchments, *Hydrol. Processes*, *11*, 269– 286, doi:10.1002/(SICI)1099-1085(19970315)11:3<269::AID-HYP442>3.0.CO;2-K.

74. Journel, A. G. (1983), Nonparametric estimation of spatial distributions, *Math. Geol., 15*, 445 – 468, doi:10.1007/BF01031292.

75. Jury, W. A. (1986), Spatial Variability of Soil Properties, *In* Hern, S. C., and S. M. Melancon (eds.), Vadose Zone Modeling of Organic Pollutants, Lewis Publishers, Michigan, USA, 245-269.

76. Kirchner, J. W. (2006), Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology, *Water Resour. Res.*, *42,* W03S04, doi:10.1029/2005WR004362.

77. Kirkby, M. J., L. J. Bracken, and S. M. Reaney (2002), The influence of land use, soils and topography on the delivery of hillslope runoff to channels in SE Spain, *Earth Surf. Processes Landforms, 27*, 1459–1473, doi:10.1002/esp.441.

78. Knight, R., and A. L. Endres (2005), An introduction to rock physics principles for near-surface geophysics, 31–70, *In* D. K. Butler (ed.), Near surface geophysics. Investigations in Geophysics 13. Society of Exploration Geophysicists, Tulsa, USA.

79. Knudby, C., and J. Carrera (2005), On the relationship between indicators of geostatistical, flow and transport connectivity, *Adv. Water Resour., 28,* 405 – 412, doi:10.1016/j.advwatres.2004.09.001.

80. Lal, R. (1997), Soil degradative effects of slope length and tillage methods on alfisols in Western Nigeria. I. Runoff, erosion and crop response, *Land Degradation and Development, 8,* 201–219, doi:10.1002/(SICI)1099-145X(199709)8:3<201::AID-LDR253>3.0.CO;2-U.

81. Lane, S. N., C. J. Brookes, R. J. Hardy, J. Holden, T. D. James, M. J. Kirkby, A. T. McDonald, V. Tayefi, and D. Yu (2003), Land Management, flooding and environmental risk: new approaches to a very old question, Harrogate: CIWEM National Conference.

82. Lane, S. N., C. J. Brookes, A. L. Heathwaite, and S. M. Reaney (2006), Surveillant Science: Challenges for the Management of Rural Environments Emerging from the New Generation Pollution Models, *Journal of Agricultural Economics, 57,* 239-257, doi:10.1111/j.1477-9552.2006.00050.x.

83. Lane, S. N., C. J. Brookes, M. J. Kirkby, and J. Holden (2004), A network-index-based version of TOPMODEL for use with high-resolution digital topographic data, *Hydrol. Processes*, *18,* 191-201, doi:10.1002/hyp.5208.

84. Lane, S. N., S. M. Reaney, and A. L. Heathwaite (2009), Representation of landscape hydrological connectivity using a topographically driven surface flow index, *Water Resour. Res.*, *45,* W08423, doi:10.1029/2008WR007336.

85. Lang, P. M., and J. B. Mallett (1984), Effect of the amount of maize residue on infiltration and soil loss from a clay loam soil, *South African Journal of Plant and Soil, 1,* 97–98,

86. Leibowitz, S. G., and K. C. Vining (2003), Temporal connectivity in a prairie pothole complex. *Wetlands, 23*, 13–25, DOI: 10.1672/0277-5212(2003)023[0013:TCIAPP]2.0.CO;2.

87. Lexartza-Artza, I., and J. Wainwright (2009), Hydrological connectivity: Linking concepts with practical implications, *Catena, 79*, 146-152, doi:10.1016/j.catena.2009.07.001.

88. Liu, Q. Q., and V. P. Singh (2004), Effect of Microtopography, Slope Length and Gradient, and Vegetative Cover on Overland Flow through Simulation, *Journal of Hydrologic Engineering, 9,* 375-382, doi:10.1061/(ASCE)1084-0699(2004)9:5(375).

89. Lischied, G., C. Alwelll, J. Bittersohl, A. Gottlein, C. Jungnickel, H. Lange, B. Manderscheid, K. Moritz, B. Ostendorf, and H. Sager (1998), Investigating soil and groundwater quality at different scales in a forested catchment: the Waldstein case study, *Nutrient Cycling in Agroecosystems, 50,* 109-118, doi:10.1023/A:1009767606772.

90. Ludwig, B., J. Boiffin, J. Chaduf, and A. Auzet (1995) Hydrological structure and erosion damage caused by concentrated flow in cultivated catchments, *Catena, 25*, 227-252, doi:10.1016/0341-8162(95)00012-H.

91. Lunt, I. A., S. S. Hubbard, and Y. Rubin (2005), Soil moisture content estimation using ground penetrating radar reflection data, *J. Hydrol. Amsterdam, 307,* 254–269, doi:10.1016/j.jhydrol.2004.10.014.

92. Lyford, F. P., and H. K Qashu (1969), Infiltration rates as affected by desert vegetation., *Water Resour. Res., 5,* 1373–1376, doi:10.1029/WR005i006p01373.

93. Matrínez-Mena, M., J. Albaladejo, and V. M. Castillo (1998), Factors influencing surface runoff generation in a Mediterranean semi-arid environment: Chicamo watershed, SE Spain, *Hydrol. Processes, 12*, 741-754, doi:10.1002/(SICI)1099-1085(19980430)12:5<741::AID-HYP622>3.0.CO;2-F.

94. Marzahn, P., K. Kruger, and R. Ludwig (2007), Derivation of soil surface roughness dynamics from multi temporal and multi parametric airborne PolSAR data, *2007 International Workshop on the Analysis of Multi-temporal Remote Sensing Images*, 281-285, doi:10.1109/MULTITEMP.2007.4293082.

95. McDonnell, J. J. (2003), Where does water go when it rains? Moving beyond the variable source area concept of rainfall-runoff response, *Hydrol. Processes, 17,* 1869–1875, doi:10.1002/hyp.5132.

96. McDonnell, J. J., M. Sivapalan, K. Vaché, S. Dunn, G. Grant, R. Haggarty, C. Hinz, R. Hooper, J. Kirchner, M. L. Roderick, J. Selker, and M. Weiler (2007), Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology, *Water Resour. Res., 43*, W07301, doi:10.1029/2006WR005467.

97. McGarigal, K., and B. J Marks (1995), FRAGSTATS: spatial pattern analysis program for quantifying landscape structure, US Forest Service General Technical Report PNW 351, Portland, USA.

98. Michot, D., Y. Benderitter, A. Dorigny, B. Nicoullaud, D. King, and A. Tabbagh (2003), Spatial and temporal monitoring of soil water content with an irrigated corn crop cover using surface electrical resistivity tomography, *Water Resour. Res., 39,* 1138, doi:10.1029/2002WR001581.

99. Montgomery, D. R., W. E. Dietrich, R. Torres, S. Prestrud Anderson, J. T. Heffner, and K. Loague (1997), Hydrologic response of a steep, unchanneled valley to natural and applied rainfall, *Water Resour. Res., 33*, 91-109, doi:10.1029/96WR02985.

100. Morgan, R. P. C. (1995), Soil Erosion and Conservation, Longman, Essex, UK.

101. McGlynn, B., J. J. McDonnell, and D. Brammer, (2002), A review of the evolving perceptual model of hillslope flowpaths at the Maimai catchment, New Zealand, *J. Hydrol. Amsterdam, 257*, 1–26, doi:10.1016/S0022-1694(01)00559-5.

102. McNab, W. H. (1991), Factors affecting temporal and spatial soil moisture variation in and adjacent to group selection openings, 475-488, *In* McCormick, L. H., and K. W. Gottschalk (eds.), Proceedings, 8th Central Hardwood Forest Conference, 1991 March 4-6, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, USA.

103. Metzger, J. P., and H. Decamps (1997), The structural connectivity threshold: a hypothesis in conservation biology at the landscape scale, *Acta Oecologica, 18,* 1–12, doi:10.1016/S1146-609X(97)80075-6.

104. Meyles, E., A. Williams, L. Ternan, and J. Dowd (2003), Runoff generation in relation to soil moisture patterns in a small Dartmoor catchment, Southwest England, *Hydrol. Processes, 17*, 251-264, doi:10.1002/hyp.1122.

105. Michaelides, K., and J. Wainwright (2002), Modelling the effects of hillslope–channel coupling on catchment hydrological response, *Earth Surf. Processes Landforms, 27*, 1441–1457, doi:10.1002/esp.440.

106. Milledge, D. G., S. N. Lane, and J. Warburton (2009), The potential of digital filtering of generic topographic data for geomorphological research, *Earth Surf. Processes Landforms*, *34*, 63–74, doi:10.1002/esp.1691.

107. Morin, J., and Y. Benyamini (1977), Rainfall Infiltration Into Bare Soils, *Water Resour. Res, 13*, 813-817, doi:10.1029/WR013i005p00813.

108. Munafo, M., G. Cecchi, F. Baiocco, and L. Mancini (2005), River pollution from non-point sources: A new simplified method of assessment, *J. Environ. Manage.*, *77*, 93– 98, doi:10.1016/j.jenvman.2005.02.016.

109. Newson, M. (2010), Understanding 'hot-spot' problems in catchments: the need for scale-sensitive measures and mechanisms to secure effective solutions for river management and conservation, *Aquatic Conservation: Marine and Freshwater Ecosystems, 20*, S62–S72, doi: 10.1002/aqc.1091.

110. O'Callaghan, J. F., and D. M. Mark (1984), The extraction of drainage networks from digital elevation data, *Computer Vision, Graphics, and Image Processing, 28*, 323-344, **doi:**10.1016/S0734-189X(84)80011-0.

111. Ocampo, C. J., M. Sivapalan, and C. Oldham (2006), Hydrological connectivity of upland-riparian zones in agricultural catchments: Implications for runoff generation and nitrate transport, *J. Hydrol. Amsterdam*, *331*, 643-658, doi:10.1016/j.jhydrol.2006.06.010.

112. Ockenden, M., and N. A. Chappell (2008), The effect of topography, subsurface strata and land-use on observed distributions of soil moisture within a sub-catchment of the River Eden, Cumbria, 202–207, Sustainable Hydrology for the 21st Century, Proceedings of the 10th BHS National Hydrology Symposium, Exeter, UK.

113. O'Connell, P. E., J. Ewen, G. O'Donnell, and P. Quinn (2007), Is there a link between agricultural land-use management and flooding?, *Hydrol. Earth Syst. Sc.*, *11,* 96-107.

114. Ogden, F. l., and B. A. Watts (2000), Saturation area formation on nonconvergent hillslope topography with shallow soils: A numerical investigation, *Water Resour. Res., 36*, 1795-1804, doi:10.1029/2000WR900091.

115. Pearce, A. J., M. K. Stewart, and M. G. Sklash, (1986), Storm runoff generation in humid headwater catchments, 1. Where does the water come from?, *Water Resour. Res., 22*, 1263–1272, doi:10.1029/WR022i008p01263.

116. Pfister, L., J. J. McDonnell, S. Wrede, D. Hlúbiková, P. Matgen, F. Fenicia, L. Ector, and L. Hoffmann (2009), The rivers are alive: on the potential for diatoms as tracer of water source and hydrological connectivity, *Hydrol. Processes, 23,* 2841 – 2845, doi:10.1002/hyp.7426.

117. Pieper, G. F. (1949), The measurement of the moisture content of soil by the slowing of neutrons, Ph.D. thesis, Cornell University, Ithaca, USA.

118. Poesen, J., F. Ingelmo-Sanchez, and H. Mücher (1990), The hydrological response of soil surfaces to rainfall as affected by cover and position of rock fragments in the top layer, *Earth Surf. Processes Landforms, 15,* 653–671, doi:10.1002/esp.3290150707.

119. Pringle, C. M. (2001), Hydrological connectivity and the management of biological reserves: a global perspective, *Ecological Applications, 11*, 981–998, doi:10.1890/1051-0761(2001)011[0981:HCATMO]2.0.CO;2.

120. Pringle, C. M. (2003), What is hydrologic connectivity and why is it ecologically important, *Hydrol. Processes, 17*, 2685–2689, doi:10.1002/hyp.5145.

121. Quinn, P., K. Beven, P. Chevallier, and O. Planchon (1991), The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models, *Hydrol. Processes, 5,* 59-79, doi:10.1002/hyp.3360050106.

122. Reaney, S. M. (2008), The use of agent based modelling techniques in hydrology: determining the spatial and temporal origin of channel flow in semi-arid catchments, *Earth Surf. Processes Landforms*, *33*, 317-327, doi:10.1002/esp.1540.

123. Rhoades, J. D., F. Chanduvi, and S. Lesch (1999), The use of saline waters for irrigation, FAO Irrigation and Drainage Paper No. 48, FAO, Rome, Italy.

124. Robinson, D. A., C. S. Campbell, J. W. Hopmans, B. K. Hornbuckle, S. B. Jones, R. Knight, F. Ogden, J. Selker, and O. Wendroth (2009), Soil Moisture Measurement for Ecological and Hydrological Watershed-Scale Observatories: A Review, *Vadose Zone Journal*, *7*, 358-389, doi: 10.2136/vzj2007.0143.

125. Savard, M. (2000), Modelling risk, trade, agricultural and environmental policies to assess trade-offs between water quality and welfare in the hog industry, *Ecological Modelling*, *125*, 51 – 66, doi:10.1016/S0304-3800(99)00173-8.

126. Sánchez-Vila, X., J. Carrera, and J. P. Girardi (1996), Scale effects in transmissivity, *J. Hydrol. Amsterdam*, *183*, 1-22, doi:10.1016/S0022-1694(96)80031-X.

127. Scherrer, S., and F. Naef (2003), A decision scheme to indicate dominant hydrological flow processes on temperate grassland, *Hydrol. Processes, 17*, 391-401, doi:10.1002/hyp.1131.

128. Segeren, A. G., and T. J. Trout (1991), Hydraulic Resistance of Soil Surface Seals in Irrigated Furrows, *Soil Sci. Soc. Am. J., 5*, 640-646.

129. Serbin, G., and D. Or (2004), Ground-penetrating radar measurement of soil water content dynamics using a suspended horn antenna, *IEEE Transactions on Geosciences and Remote Sensing, 42*, 1695–1705, doi:10.1109/TGRS.2004.831693.

130. Sharpley, A., and P. Kleinman (2003), Effect of Rainfall Simulator and Plot Scale on Overland Flow and Phosphorus Transport, *J. Environ. Qual., 32*, 2172-2179.

131. Sihvola, A. H. (1999), Electromagnetic mixing formulas and application, Institute Of Electrical Engineers, London, UK.

132. Sivapalan, M. (2003), Process complexity at hillslope scale, process simplicity at the watershed scale: Is there a connection?, *Hydrol. Processes*, *17*, 1037– 1041, doi:10.1002/hyp.5109.

133. Sivapalan, M. (2005), Pattern, process and function: Elements of a new unified hydrologic theory at the catchment scale, 193– 219, *In* Anderson, M. G. (ed.), Encyclopaedia of Hydrologic Sciences, vol. 1, part 1, chap. 13., John Wiley, Hoboken, USA.

134. Solé-Benet, A., A. Calvo, A. Cerdá, R. Lázaro, R. Pini, and J. Barbero (2006), Influences of micro-relief patterns and plant cover on runoff related processes in badlands from Tabernás (SE Spain), *Catena, 31*, 23-28, doi:10.1016/S0341-8162(97)00032-5.

135. Sorensen, R., U. Zinko, and J. Seibert (2006), On the calculation of the topographic wetness index: evaluation of different methods based on field observations, *Hydrol. Earth Syst. Sc.,*10, 101-112, doi:10.5194/hessd-2-1807-2005.

136. Soulsby, C., D. Tetzlaff, S. M. Dunn, and S. Waldron (2006), Scaling up and out in runoff process understanding: insights from nested experimental catchment studies, *Hydrol. Processes, 20*, 2461-2465, doi:10.1002/hyp.6338.

137. Stieglitz, M., J. Sharman, J. McNamara, V. Engel, J. Shanley, and G. W. Kling (2003), An approach to understanding hydrologic connectivity on the hillslope and the implications for nutrient transport, *Global Biogeochemical Cycles, 17*, 1105, doi:10.1029/2003GB002041.

138. Tackett, J. L., and R. W. Pearson (1965), Some characteristics of soil surface seals formed by simulated rainfall, *Soil Science, 99*, 407–412.

139. Talebi, A., P. A. Troch, and R. Uijlenhoet (2008), A steady-state analytical slope stability model for complex hillslopes, *Hydrol. Processes, 22*, 546–553, doi:10.1002/hyp.6881.

140. Teklehaimanot, Z., P. G. Jarvis, and D. C. Ledger (1991), Rainfall interception and boundary layer conductance in relation to tree spacing, *J. Hydrol. Amsterdam*, *123*, 261-278, doi:10.1016/0022-1694(91)90094-X .

141. Tetzlaff, D., C. Soulsby, P. J. Bacon, A. F. Youngson, C. Gibbins, and I. A. Malcolm (2007), Connectivity between landscapes and riverscapes – a unifying theme in integrating hydrology and ecology in catchment science?, *Hydrol. Processes, 21*, 1385-1289, doi:10.1002/hyp.6701.

142. Tetzlaff, D., C. Soulsby, and C. Birkel (2010) Hydrological connectivity and microbial fluxes in montane catchments: the role of seasonality and climatic variability, *Hydrol. Processes, 24*, 1231-1235, doi:10.1002/hyp.7680.

143. Todini, E. (2001), Influence of parameter estimation uncertainty in Kriging: Part 1 – Theoretical Development, *Hydrol. Earth Syst. Sc., 5*, 215-223.

144. Todini, E., F. Pellegrini, and C. Mazzetti (2001), Influence of parameter estimation uncertainty in Kriging: Part 2 – Test and case study applications, *Hydrol. Earth Syst. Sc., 5*, 225-232.

145. Topp, G. C., and P. A. Ferre (2002), Thermogravimetric method using convective oven-drying, 422–424, *In* Dane, J. H., and G. C. Topp (eds.), Methods of Soil Analysis: Part 4. Physical methods, SSSA, Madison, USA.

146. Trimble, S. W., and A. C. Mendel (1995), The cow as a geomorphic agent – a critical review, *Geomorphology*, *13*, 233-253, doi:10.1016/0169-555X(95)00028-4.

147. Tromp-Van Meerveld, H. J., and J. J. McDonnell (2006), Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis, *Water Resour. Res., 42*, W02411, doi:10.1029/2004WR003800.

148. Turnbull, L., J. Wainwright, and R. E. Brazier (2008), A conceptual framework for understanding semi-arid land degredation: ecohydrological interactions across multiple-space and time scales, *Ecohydrology, 1*, 23-34, doi:10.1002/eco.4.

149. Ulaby, F. T., P. C. Dubois, and J. van Zyl (1996), Radar mapping of surface soil moisture, *J. Hydrol. Amsterdam*, *184*, 57–84, doi:10.1016/0022-1694(95)02968-0.

150. Van Dam, H., A. Mertens, and J. Sinkeldam (1994), A coded checklist and ecological indicator values of freshwater diatoms from The Netherlands, *Netherlands Journal of Aquatic Ecology, 28*, 117–133, doi:10.1007/BF02334251.

151. Van de Giesen N. C., N. De Ridder, T. J. Stomph, and K. A. Engels (1996), Surface runoff effects in a West-African Catena landscape, *Spring Meeting, American Geophysical Union EOS, 7*, 122.

152. Van de Giesen, N. C., T. J. Stomph, and N. De Ridder (2000), Scale effects of Hortonian overland flow and rainfall-runoff dynamics in a West-African catena landscape, *Hydrol. Processes, 14*, 165–175, doi: 10.1002/(SICI)1099-1085(200001)14:1<165::AID-HYP920>3.0.CO;2-1.

153. Vidon, P. G. F., and A. R. Hill (2004), Landscape controls on nitrate removal in stream riparian zones, *Water Resour. Res., 40*, W03201, doi:10.1029/2003WR002473.

154. Vivoni, E. R. (2007), Spatiotemporal Analysis of a Monsoon Flood Event in Northwestern Mexico: Insights from Remote Sensing and Hydrologic Modeling, *Eos Trans. Am. Geophys. Union, 88*, Joint Assembly Supplement.

155. Walker, J. P., G. R. Willgoose, and J. D. Kalma (2004), In situ measurement of soil moisture: A comparison of techniques, *J. Hydrol. Amsterdam, 293*, 85-99, doi:10.1016/j.jhydrol.2004.01.008.

156. Wang, J., B. Fu, Y. Qiu, L. Chen, and Z. Wang (2001), Geostatistical analysis of soil moisture variability on Da Nangou catchyment of the loess plateau, China. *Environmental Geology, 41*, 113-120.

157. Wainwright, J., and A. J. Parsons (2002), The effect of temporal variations in rainfall on scale dependency in runoff coefficients, *Water Resour. Res., 38*, 1271, doi:10.1029/2000WR000188.

158. Ward, P. R., F. X. Dunin, and S. F. Micin (2002), Water use and root growth by annual and perennial pastures and subsequent crops in a phase rotation, *Agricultural Water Management, 53*, 83-97, doi:10.1016/S0378-3774(01)00157-3.

159. Webster, R., and M. A. Oliver (1992), Sample adequately to estimate variograms of soil properties, *Eur. J. Soil Sci., 43*, 177–192, doi:10.1111/j.1365-2389.1992.tb00128.x.

160. Weiler, M., J. J. McDonnell, I. Tromp van Meerveld, and T. Uchida (2005), Subsurface stormflow runoff generation processes, 1719–1732, *In* Anderson, M. G. (ed.), *Encyclopaedia of Hydrological Sciences*, Wiley, Chichester, UK.

161. Weiler, M., and F. Naef (2003), An experimental tracer study of the role of macropores in infiltration in grassland soils, *Hydrol. Processes*, *17*, 477–493, doi:10.1002/hyp.1136.

162. Western, A. W., G. Blöschl, and R. B. Grayson (1998a), Geostatistical characterisation of soil moisture patterns in the Tarrawarra Catchment, *J. Hydrol. Amsterdam*, *205*, 20 – 37, doi:10.1016/S0022-1694(97)00142-X.

163. Western, A. W., G. Blöchl, and R. B. Grayson (1998b), How well do indicator variograms capture the spatial connectivity of soil moisture?, *Hydrol. Processes, 12*, 1851-1868, DOI: 10.1002/(SICI)1099-1085(19981015)12:12<1851::AID-HYP670>3.0.CO;2-P.

164. Western, A. W., G. Blöschl, and R. B. Grayson (2001), Toward capturing hydrologically significant connectivity in spatial patterns, *Water Resour. Res., 37*, 83-97, doi:10.1029/2000WR900241.

165. Western, A. W., and R. B. Grayson (1998), The Tarrawarra data set: soil moisture patterns, soil characteristics, and hydrological flux measurements, *Water Resour. Res., 34*, 2765–2768, doi:10.1029/98WR01833.

166. Western, A. W., R. B. Grayson, G. Bloschl, G. R. Willgoose, and T. A. McMahon (1999), Observed spatial organisation of soil moisture and its relation to terrain indices, *Water Resour. Res., 35*, 797–810, doi:10.1029/1998WR900065.

167. Western, A. W., S. Zhou, R. B. Grayson, T. McMahon, G. Bloschl, and D. J. Wilson (2005), Reply to comment by Tromp van Meerveld and McDonnell on Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes, *J. Hydrol. Amsterdam*, *303*, 313 -315, doi:10.1016/j.jhydrol.2004.09.001.

168. Wigington Jr., P. J., J. P. Baker, D. R. DeWalle, W. A. Kretser, P. S. Murdoch, H. A. Simonin, J. Van Sickle, M. K. McDowell, D. V. Peck, and W. R. Barchet (1996), Episodic acidification of small streams in the northeastern United States: Episodic Response Project, *Ecological Applications*, *6*, 374-388, doi:10.2307/2269377.

169. Woods, R., and L. Rowe (1996), The changing spatial variability of subsurface flow across a hillside, *Journal of Hydrology New Zealand*, *35*, 51–86.

170. Wraith, J. M., S. D. Comfort, B. L. Woodbury, and W. P. Inskeep (1993), A simplified waveform analysis approach for monitoring solute transport using time-domain reflectometry, *Soil Sci. Soc. Am. J., 57*, 637–642.

171. Yair, A. (1992), The control of headwater area on channel runoff in a small arid watershed, 53–68, *In* Parsons, A. J., and Abrahams, A. J. (eds.), Overland Flow: Hydraulics and Erosion Mechanics, UCL Press, London, UK.

172. Ziegler, A. D., R. A. Sutherland, and T. W. Giambelluca (2001), Acceleration of Horton overland flow and erosion by footpaths in an upland agricultural watershed in northern Thailand, *Geomorphology, 41*, 249–262, doi:10.1016/S0169-555X(01)00054-X.

9.0 Appendix A – Objective Connectivity Scores

CoV

CoV SCORES											
	dp10	dp25	dp50	dp75	dp90	sm20	sm30	sm40	sm50	sm60	sm70
SATAREA	2.91	3.39	7.27	4.32	8.25	4.58	30.93	52.14	71.44	99.07	130.13
CONTAREA	4.07	5.35	18.09	44.23	59.56	4.58	41.07	68.60	81.46	135.58	188.37
SATCLUST	0.00	75.87	24.78	10.40	17.71	0.00	158.75	144.08	111.70	107.76	86.00
SATAREA_BUF	2.71	3.24	7.15	4.28	8.08	4.32	30.19	51.39	70.86	98.02	129.43
CONTAREA_BUF	2.71	3.69	32.20	79.59	64.30	4.32	38.50	61.92	77.72	120.54	192.35
CA%	3.29	3.82	6.74	4.70	8.89	4.02	30.39	51.94	71.07	98.74	129.47
LPI	3.29	4.32	25.23	5.03	8.52	4.02	21.86	15.55	71.05	93.75	118.09
AI	3.48	4.34	7.10	2.50	19.00	4.04	17.85	27.15	28.56	45.32	81.21
DIVISION	23.46	9.65	6.88	0.37	2.96	232.87	163.75	132.16	73.33	37.51	4.76
COHESION	0.05	0.22	4.15	5.26	9.52	0.06	5.61	12.21	22.69	41.31	83.77
RANGE_OMNI	47.92	24.91	22.98	27.01	57.21	87.48	46.71	52.64	59.68	79.71	85.98
RANGE_EW	36.51	17.78	23.86	21.29	41.38	73.99	42.57	44.93	56.66	79.44	91.10
RANGE_NS	29.83	27.79	31.94	34.96	60.46	47.63	47.31	50.33	65.09	82.35	93.06

Objective Function: Black = 1 Red = 2 Purple = 3

Stage

	Q(SHRT) SCORE										
	dp10	dp25	dp50	dp75	dp90	sm20	sm30	sm40	sm50	sm60	sm70
SATAREA	0.00	0.00	0.00	0.51	0.59	0.00	0.00	0.00	0.77	0.77	0.86
CONTAREA	0.00	0.00	0.00	0.00	0.60	0.00	0.00	0.00	0.77	0.77	0.81
SATCLUST	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	-0.66	-0.71	0.51
SATAREA_BUF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.77	0.77	0.64
CONTAREA_BUF	0.00	0.00	0.77	0.00	0.00	0.00	0.00	0.00	0.77	0.77	0.64
CA%	0.00	0.00	0.00	0.60	0.54	0.00	0.00	0.71	0.77	0.77	0.81
LPI	0.00	0.00	0.00	0.66	0.54	0.00	0.00	0.54	0.77	0.77	0.81
AI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.71	0.77	0.81
DIVISION	0.00	0.00	0.00	0.00	-0.69	0.00	0.00	0.00	-0.77	-0.77	0.00
COHESION	0.00	0.00	0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.77	0.81
RANGE_OMNI	0.71	0.63	0.60	0.60	-0.20	0.71	0.77	0.77	0.71	0.81	0.81
RANGE_EW	0.71	0.63	0.60	0.60	-0.20	0.71	0.77	0.77	0.71	0.81	0.81
RANGE_NS	0.80	0.73	0.77	0.81	0.26	0.64	0.71	0.76	0.77	0.81	0.81

Objective Function: Black = 1 Red = 2 Purple = 3

Antecedent Precipitation

	AP14										
	dp10	dp25	dp50	dp75	dp90	sm20	sm30	sm40	sm50	sm60	sm70
SATAREA	0.61	0.63	0.54	0.71	0.62	0.39	0.51	0.57	0.71	0.90	0.94
CONTAREA	0.56	0.63	0.46	0.78	0.65	0.39	0.49	0.59	0.72	0.95	0.92
SATCLUST	0.00	-0.47	-0.59	0.37	0.46	0.00	-0.47	-0.57	-0.58	-0.31	0.54
SATAREA_BUF	0.63	0.66	0.55	0.71	0.66	0.39	0.51	0.57	0.72	0.90	0.94
CONTAREA_BUF	0.63	0.77	0.47	0.23	0.78	0.39	0.49	0.57	0.71	0.92	0.91
CA%	0.46	0.49	0.54	0.59	0.55	0.32	0.50	0.57	0.69	0.90	0.94
LPI	0.46	0.62	-0.06	0.73	0.61	0.32	0.57	0.52	0.71	0.83	0.93
AI	0.32	-0.04	-0.19	0.16	-0.18	0.39	0.49	0.54	0.74	0.77	0.76
DIVISION	-0.46	-0.62	-0.30	0.18	-0.25	-0.32	-0.53	-0.57	-0.77	-0.94	-0.85
COHESION	0.46	0.66	0.40	0.15	0.18	0.32	0.35	0.47	0.55	0.63	0.78
RANGE_OMNI	0.26	-0.45	-0.45	-0.25	-0.17	0.34	0.54	0.54	0.85	0.76	0.72
RANGE_EW	0.58	0.52	0.44	0.42	-0.36	0.54	0.84	0.87	0.59	0.72	0.76
RANGE_NS	0.68	0.60	0.62	0.69	0.00	0.74	0.70	0.73	0.81	0.69	0.76

Objective Function: Black = 1 Red = 2 Purple = 3