Concepts of hydrological connectivity: research approaches, pathways and future agendas

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Abstract

For effective catchment management and intervention in hydrological systems a process-based understanding of hydrological connectivity is required so that: i) conceptual rather than solely empirical understanding drives how systems are interpreted; and ii) there is an understanding of how continuous flow fields develop under different sets of environmental conditions to enable managers to know when, where and how to intervene in catchment processes successfully. In order to direct future research into process-based hydrological connectivity this paper: i) evaluates the extent to which different concepts of hydrological connectivity have emerged from different approaches to measure and predict flow in different environments; ii) discusses the extent to which these different concepts are mutually compatible; and iii) assesses further research to contribute to a unified understanding of hydrological processes. Existing research is categorised into five different approaches to investigating hydrological connectivity: i) evaluating soil-moisture patterns (soil-moisture connectivity); ii) understanding runoff patterns and processes on hillslopes (flow-process connectivity); iii) investigating topographic controls (terrain-connectivity) including the impact of road networks on hydrological connectivity and catchment runoff; iv) developing models to explore and predict hydrological connectivity; and v) developing indices of hydrological connectivity. Analysis of published research suggests a relationship between research group, approach, geographic setting and the interpretation of hydrological connectivity. To further understanding of hydrological connectivity our knowledge needs to be developed using a range of techniques and approaches, there should be common understandings between researchers approaching the concept from different perspectives, and these meanings need to be communicated effectively with those responsible for land management.

Key words

Hydrological connectivity; run-off; flow processes; terrain; indices.

1 Introduction

'Hydrologic connectivity is the water-mediated transport of matter, energy and organisms within or between elements of the hydrologic cycle' (Freeman *et al.,* 2007, p1). The concept of hydrological connectivity is a useful frame for understanding spatial variations in runoff and runon and (Bracken and Croke, 2007; Ali and Roy, 2009). The development of hydrological connections via overland and subsurface flows is a function of water volume (supplied by rainfall and runon, depleted by infiltration, evaporation, transpiration and transmission losses) and rate of transfer (a function of pathway, hillslope length and flow resistance). These processes interact with flow resistance, varying as a function of flow depth. This interaction establishes a feedback between rainfall, infiltration and flow routing which produces the nonlinearity seen in river hydrographs and scale-dependence of runoff coefficients (Wainwright and Bracken, 2011).

Catchment management is an important application of understanding hydrological connectivity. Catchment management is necessary to protect habitats and species, improve flood resistance and resilience, and to support enjoyment of our landscapes. The purpose of management is usually to maintain appropriate (dis)connectivity for different niches (hydrological, ecological, geomorphological), especially when catchment processes and characteristics are perturbed. Thus, for effective management and intervention in catchments a process-based understanding of connectivity is required so that: i) conceptual rather than solely empirical understanding drives how managers interpret a system; and ii) there is an understanding of how continuous flow fields develop under different sets of environmental conditions to enable managers to know when, where and how to intervene successfully in catchment processes to achieve sustainable management. Presently there is confusion around the definition of hydrological connectivity since it has been interpreted and measured differently between groups of researchers. One aspect ripe for confusion is the structure-process dichotomy, shifting focus from producing static indices influencing hydrological connectivity, to understanding the dynamics of processes (see Bracken and Croke, 2007; Turnbull *et al.*, 2008; Birkel *et al.*, 2010).

Despite a series of published review articles (e.g. Bracken and Croke, 2007; Tetzlaff et al., 2007; Turnbull *et al.* 2008; Ali and Roy, 2009; Lexartza-Artza and Wainwright, 2009) there is no consensus about how to define and measure hydrological connectivity. The research community has been content to work with multiple, slightly different and nuanced meanings of the concept to enable the colour and depth of the topic to be investigated as fully as possible (Ali and Roy, 2009). However, certain definitions and interpretations of hydrological connectivity are starting to be more commonly used and so it seems timely that these are evaluated to determine how this may shape and direct future research investigations. The aims of this paper are therefore to: i) evaluate the extent to which different concepts of hydrological connectivity have emerged from different approaches to measure and predict flow in different environments; ii) discuss the extent to which these different concepts are mutually compatible; and iii) assess what further research needs to be carried out to contribute to a unified understanding of hydrological processes. In section 2 we discuss the different definitions that have been used to interpret hydrological connectivity, we then explore the different approaches that have been used to investigate connectivity (section 3) and analyse the locations where research has been conducted (section 4). In section 5 we explore the relationship between approach and definition before evaluating whether it is possible to develop a unified definition (section 6). Section 7 and 8 present suggestions for future research and conclusions. A different group of authors may have produced a different interpretation of research around hydrological connectivity; we hope the ideas and thoughts presented become an agenda for debate. In this paper we do not address sediment connectivity.

2 Definitions

In their 2009 paper, Ali and Roy present a synthesis of definitions (Table 1). Of these definitions we feel that number 11, concerning hillslope-riparian-stream (HRS) hydrologic connectivity via the subsurface flow system, seems to be coming to the fore as the most used interpretation of hydrological connectivity (e.g. Jensco *et al.*, 2009; 2010; Detty and McGuire, 2010; Jensco and McGlynn, 2011). This definition emerges from the approach to hydrological connectivity based on assessing flow processes, in particular from research which proposes that the timing and duration of groundwater connectivity between riparian zones and the stream network is the dominant control on the magnitude and timing of observed catchment discharge (e.g. McGlynn and McDonnell 2003; McGlynn and Seibert 2003; Jensco *et al.*, 2009; Detty and McGuire, 2010; Jensco and McGlynn, 2011). This research was conducted in locations with steep slopes that exhibit a seasonal runoff response. We question however whether this is the most suitable definition for other geomorphic regions. On one hand, this definition is process-based, but on the other it is more about a certain type of connection which could be considered only part of the idea behind the concept of hydrological connectivity, and hence only represents one particular process in certain landscape settings: Hillslope-riparian-stream connectivity is best suited to humid temperate settings (Beven, 1997; Bracken and Croke, 2007). We do not think it is possible to develop a single, overarching and agreed definition of hydrological connectivity that works across all environments, but we do wish to highlight that there are different definitions that relate to different aspects of hydrological connectivity.

3 Approaches to understanding hydrological connectivity

Closely linked to the definitions outlined in Table 1 are the ways in which hydrological connectivity is conceptualised. Two elements to hydrological connectivity have been identified: static/structural and dynamic/functional connectivity (Bracken and Croke, 2007; Turnbull *et al.*, 2008). Bracken and Croke (2007) proposed that static elements of hydrological connectivity were 'spatial patterns, such as hydrological runoff units (HRUs), that can be categorized, classified and estimated' (p1757). They used the term dynamic hydrological connectivity to mean 'both the longer term landscape development, such as changes following abandonment of agriculture, and short-term variation in antecedent conditions and rainfall inputs to systems that result in non-linearities in hillslope and catchment response to rainfall' (p1758). In this way the structural patterns within a landscape (of hillslopes, soils, vegetation) produce different hydrological responses with varying amounts of hydrological runoff and resulting connectivity for different rainfall events or for different time periods.

Turnbull *et al.* (2008) refined the terms to structural and functional connectivity. Structural was used to refer to the spatial patterns in the landscape, such as the spatial distribution of landscape units which influence water transfer patterns and flow paths. Functional aspects of connectivity refer to how these spatial patterns interact with catchment processes to produce runoff, connected flow and hence water transfer in catchments (Turnbull *et al.*, 2008). The key refinement by using the term functional is the inclusion of the idea that the spatial patterns in the landscape themselves change over long periods of time, not implied by the term static, but the term structural also captures the notion that the processes operating can modify the structural elements and characteristics of a catchment to produce connected runoff differently. Bracken and Croke (2007), Turnbull *et al.* (2008) and Wainwright *et al.* (2011) all emphasise the importance of the interaction between topographic controls and catchment processes as the key to understanding dynamics of hydrological connectivity.

Research to date has been successful at describing the elements defining structural connectivity (Kirkby *et al.*, 2002; Bull *et al.*, 2003; Lexartza-Artza and Wainwright, 2009); however, the elements defining functional aspects of hydrological connectivity are more difficult to measure and quantify (Bracken and Croke, 2007; Lexartza-Artza and Wainwright, 2009; Birkel et al, 2010). This difficulty may be due to the term ‘functional’ not being well defined. Some definitions of connectivity may be popular because of their close association with an experimental methodology (see section 5). Indeed, this association is how connectivity moved from being an abstract concept to a “hands on” approach. It therefore follows that because the definition of functional connectivity lacks a practical aspect in that it is not associated with key variables to measure, it has not been taken forward. In contrast the term ‘structural connectivity’ is readily understandable (and measureable) and seems to have a common understanding to reflect the different states of catchment response gleaned by measuring/recording ‘snapshots’ of catchment characteristics and the existence (or not) of connections/pathways.

One issue is how many snapshots do we need, and how close in time do they need to be before we can be confident to capture the “dynamic or functional” aspect of connectivity? Functional connectivity is more than just inferring what is happening between snap-shots, but trying to determine the actual processes operating to produce fluxes of water, sediment and nutrients. The key word ripe for confusion is ‘functional’, since this has many uses/interpretations in hydrology already, especially around discussions of the function of catchment processes in ecology. We therefore propose that the term ‘process based connectivity’ may be more readily understandable and more useful to capture the evolutionary dynamics of how systems operate and how different processes link in space and time to develop flow connections. For the remainder of this paper, we use *structural connectivity* to refer to the physical adjacency of landscape elements and *functional connectivity* to illustrate how that physical adjacency translates to fluxes of water, sediments and solutes (e.g. Larsen *et al*, accepted).

What is meant by *process connectivity* and how can we develop sampling approaches to capture process based understandings? Processes are the sequences of actions within a catchment that result in changes in the form of an area (Ahnert, 1998). We propose the term *process connectivity* to capture the evolutionary dynamics of how systems operate. Following the fundamental principles of the philosophy of science, processes are observable and the dynamics of a system can be characterised by measureable attributes and characteristics. However, recognition of processes is arbitrary and subjective and depends on circumstance, such as; location, observer’s goal, perception, conceptualisation and methods used (Schumm, 1991). In hydrology and geomorphology we tend to measure catchment characteristics and attributes which we then extrapolate, interpolate and accumulate to infer process. For example, at Panola USA, there are 135 crest stage piezometers used to measure the piezometric head of groundwater at a specific point and 29 continuous/recording wells recording 15-minute observations of depth of water; it is one of the most densely instrumented sites in which to conduct hydrological research (Tromp van Meerveld and McDonnell, 2006; McGuire and McDonnell, 2007).By analysing the piezometer data from all wells the direction of flowing water in the subsurface can be inferred, but is still not actually measuring process (see Richards, 1990;1994). These snap-shots at many different points can also be analysed to determine spatial and temporal change in fluxes of water, sediment and nutrients from which the processes responsible for producing hydrological connectivity can once again be inferred. In this way approaches based on soil-moisture and/or water-table data continue to demand interpretation of repeated snap-shots, but they provide more and new types of information which are an improvement over solely topography-based approaches. With purely structural approaches (e.g. terrain connectivity), we can only infer *potential* runoff sources and infer *potential* hydrological connectivity.

How we understand and interpret catchment processes may help us understand whether we should develop indices of connectivity, how indices vary between environments and why. More fundamentally we need to understand how different approaches and definitions of hydrological connectivity can be linked, especially in different environments where processes will operate in different ways to produce connected flow in catchments. Since it is impossible to observe processes directly (Richards, 1990;1994) there is usually a conceptual model (which is rarely outlined) linking patterns observed at different timescales to processes about which we strive to know more. It is easy to think that more frequent observation is related to more closely measuring processes; however, this is not the case. For instance it does not matter whether soil moisture is measured at time intervals of 1 day, 15 minutes or 5 nanoseconds, it is still not a measure of process (Richards, 1990;1994). So how we can bring the different approaches and resulting definitions together around measuring process differently to develop understanding of hydrological connectivity?

Figure 1 summarizes how existing approaches come together to further understandings of hydrological connectivity. What is strongly evident is that most studies have tended to focus on the structural elements of hydrological connectivity. The 'lots of points' approach has led to a 'lots of states' understanding about the complex variation of rainfall, infiltration, flow routing and feedbacks between them that produce hydrological connectivity over even a single hillslope and within one runoff event. This type of empirical research has proved a fruitful approach and has furthered investigation of hydrological connectivity (and hydrological processes more generally), but has only enabled us to infer water pathways and processes, rather than actually measuring and monitoring processes. Thus we propose that to advance understandings of hydrological connectivity further we should focus research on *process connectivity* by evaluating the conceptualisation of the concept and approach taken to try to measure process as closely as possible.

4 Does location matter?

Table 2 presents characteristics of the study sites that have been dominant locations for research around hydrological connectivity. Figure 2 illustrates site location and in which type of biome they fall whilst Figure 3 demonstrates the characteristics of the study sites used to derive empirical data. Concentration of empirical data collection in small, temperate, forested catchments with steep slopes and relatively deep soils (Figure 3) has resulted in exciting developments using the 'lots of points' approach to collect and analyse empirical field evidence to determine how different areas of river catchments connect to produce runoff. These data have led to interesting insights, especially the 'fill and spill' concept for how bedrock topography can control source areas of subsurface runoff which then connect to produce flow at the catchment outlet (Tromp van Meerveld and McDonnell 2006).

The fill and spill hypothesis asserts that significant subsurface stormflow (>1 mm) occurs only when the subsurface saturated area becomes connected to the river channels. This occurs when bedrock depressions are filled and the water level in these depressions rises high enough for water to start spilling over the bedrock microtopography. Once spilling occurs, water flows over the bedrock, through (and mixes with soil water in) the connected lows in the bedrock topography toward the channel. When the flux of water reaches the channel and the subsurface saturated area becomes connected to it, there is an immediate increase in subsurface storm flow rate (Tromp van Meerveld and McDonnell 2006). If the storm is large enough for the water level to rise high enough that spilling and connectivity can occur, total subsurface stormflow can be up to 75 times larger than when spilling and connectivity do not occur (Tromp van Meerveld and McDonnell 2006). Tromp van Meerveld and McDonnell (2006) thus conclude that the bedrock micro topography is responsible for the observed precipitation threshold for significant subsurface stormflow to occur. Similar mechanisms have been found in the Hermine catchment, but this time controlled by an impervious soil layer (Ali *et al.,* 2011). But what can be taken from these studies and transposed to how hydrological connectivity operates in other environments? For instance 'fill and spill' does not apply to all catchments, nor across all environments for instance in lowland, loam catchments (McNamara *et al.* (2011).

5 The relationship between definition, conceptualization and research undertaken

Table 3 presents the major groupings of both researchers and approaches to exploring hydrological connectivity found in the literature and their main contributions to understandings. There are around 20 groups of researchers actively investigating hydrological connectivity. Different groups tend to work in certain areas and environments and research hydrological connectivity using a favoured suite of approaches which tends to reflect the dominant controls in runoff in these different environments, but also their conceptualisation of hydrological connectivity. In this way there is a relationship between group, approach, geographic setting and the interpretation of hydrological connectivity. Groups continually evolve and whilst we have tried to be as inclusive as possible, we realise we may have inadvertently missed some emerging groups and research. Research can be categorised into five different approaches to investigating hydrological connectivity: i) evaluating soil-moisture patterns (soil-moisture connectivity); ii) understanding runoff patterns and processes on hillslopes (flow-process connectivity); iii) investigating topographic controls (terrain-connectivity) (including the impact of road networks on hydrological connectivity and catchment runoff); iv) developing models to explore and predict hydrological connectivity; and v) developing indices of hydrological connectivity. Each of these approaches is evaluated in turn.

5.1 Soil-moisture connectivity and water- table connectivity

This approach is based on the premise that the soil-moisture patterns that emerge during storm events reflect how water is moving through the catchment, in particular linking how stores of water fill up to produce hydrological connections (Tetzlaff *et al.*, 2011); using implicit conceptualization of catchment behaviour developed according to systems concepts. Extensive soil-moisture-monitoring campaigns have been conducted in a variety of environments (e.g. Western *et al.*, 1998; 1999; Grayson *et al.*, 1997; Western and Grayson, 1998; Tromp van Meerveld and McDonnell, 2006; James and Roulet, 2007; Ali and Roy, 2010a), with measurements being conducted at a range of depths, and results have provided a distributed perspective of catchment response. These valuable datasets opened up the opportunity to observe and quantify the spatial patterns that are responsible for runoff generation at the catchment outlet and have provided an appropriate focus for connectivity metrics (see section 5.5). Research in rangeland catchments in SE Australia and New Zealand characterised by siltstones (Table 2) demonstrated that patterns in shallow soil moisture can be used as an indication of saturation excess processes which control the fluxes of water in their catchments (Western *et al.*, 2004). However, studies conducted in bedrock-controlled catchments with deep freely draining soils in the USA demonstrate different controls and suggest that soil depth and bedrock topography direct the pattern of active flow generated during storm events (Tromp van Meerveld and McDonnell, 2005;2006). At an intermediate point on the continuum between these two environments, research conducted in temperate forest watersheds dominated by podsols and underlain by glacial till, suggested a non-linear response in runoff for small variations in antecedent moisture, but did not observe a significant change in geostatistical hydrologic connectivity with variations in antecedent conditions (James and Roulet, 2007).

At this juncture it is important to consider the details of the methodology employed by different researchers, which has implications for their results. James and Roulet (2007) did not find significant changes because the sampling undertaken was based on time variable indicator thresholds (spatial surveys of shallow soil moisture over a sequence of storms) to compute connectivity functions. When Ali and Roy (2010a) did the same for the Hermine catchment, they did not find any significant change either, but when they used fixed indicator thresholds (e.g. when they focused on the connectivity of locations with a moisture content exceeding 30%) then the change was significant. Hence it matters how connectivity is defined and how it is assessed. With the Western et al. approach, connectivity is assessed after partitioning the catchment into “wet” and “dry” areas based on a time-variable statistical criterion (i.e. a percentile). Connectivity is thus presumed to be a statistical property and not a process-induced one. With the Ali and Roy (2010a) approach, however, the definition of “wet” and “dry” is made from a experimental criterion (e.g. 30% moisture content) and therefore the assessment is less of a statistical one and more of a “process-based” one.

Research into spatial patterns of soil moisture has resulted in exciting developments using the ‘lots of points’ approach to collect and analyze empirical field evidence (Table 3). This research has led to novel ways of thinking about hydrology, especially the ‘fill and spill’ concept (Tromp van Meerveld and McDonnell, 2006). Despite suggestions that Panola may be an ‘outlier’ in terms of processes of runoff production (McNamara *et al.* 2011) , similar runoff-production mechanisms have been found in the Hermine catchment, Canada, but this time controlled by an impervious soil layer (Ali *et al.*, 2011). However, we wish to question the assumption that spatial patterns of soil moisture reflect the hydrological connections being made in all catchments. This assumption may be appropriate for some areas and environments – particularly regions where vertical flow is dominating due to more freely draining soils (such as podsols) with some kind of impervious layer in combination with a strong seasonal pattern in precipitation input, but not for all.

The soil-moisture approach to investigating hydrological connectivity led to the development of definitions of hydrological connectivity numbered 8 and 9 (Table 1), proposed by Western *et al.*, (2001) and Knudby and Carrera (2005) respectively. These definitions are focused on spatial patterns at the watershed and hillslope scale. They propose that hydrologically spatial patterns of catchment characteristics facilitate flow and transport in a hydrological system (Western *et al.*, 2001) and that spatially connected features concentrate flow and reduce travel times (Knudby and Carrera, 2005). The definitions therefore are explicitly linked to the type of data collected and have then formed the basis for other key studies which employed the 'lots of points' approach of measurement of spatial variation in soil moisture as an attempt to understand fluxes and routes of transmission of water (e.g. Spence and Woo, 2003; Western and Grayson, 1998; Tromp van Meerveld and McDonnell, 2006; James and Roulet, 2007; Ali and Roy, 2010a). We suggest that whilst the methods employed attempt to infer routes of water transfer, what they actually record are changes at many points in a catchment and hence are in fact a static interpretation of catchment scale soil water redistribution processes along with evapotranspiration.

The research which developed and then applied the 'fill and spill' hypothesis of stream-flow generation (e.g. Tromp van Meerveld and McDonnell, 2006; Spence, 2006; Shaw *et al.*, 2011) maps on to definition number 10, classified as flow processes at the hillslope scale: 'the condition by which disparate regions on a hillslope are linked via lateral subsurface water flow' (Creed and Band, 1998). Whilst at a similar scale to definitions 8 and 9, this definition of hydrological connectivity is focused on flow processes, including the transfer of water, rather than the emergence of spatial patterns from which transfer can then be derived.

5.2 Flow-process connectivity

Intense data collection has been used at the plot scale in semi-arid areas to explore the interaction been rainfall and runoff, including the role of surface roughness, and how hydrological connections develop (Abrahams *et al.*, 1986; Smith *et al.*, 2010). Cammeraat (2002) demonstrated that hydrologic connectivity is an important factor in runoff-contributing and runoff-absorbing areas from the micro-plot to the catchment scale by monitoring surface runoff at all scales. In this study runoff of open plots, micro-catchments and sub-catchments was continuously measured over V-notches, equipped with pressure transducers. Cammeraat's findings provided the foundation for later research which demonstrated that rainfall-runoff relationships in semi-arid areas emphasise the influence of antecedent moisture and temporal storm structure on hillslope-scale flood generation

(Wainwright and Parsons, 2002; Bracken *et al.,* 2008). Research has also shown that patterns of infiltration and resistance across entire flow paths and their variability throughout a storm event are the key to understanding dynamic hydrological connectivity at the hillslope scale (Yair, 2002; 2004; Wainwright *et al.* 2002; Reaney, 2008; Smith *et al*., 2010; Kidron, 2011).

Research into connectivity of flow processes in temperate forested environments has also examined scaling effects and connectivity of overland flow, but on steep, vegetated hillslopes as in the Mie catchment, Japan(Gomi *et al.,* 2008). Runoff from large plots was shown to be less than for small plots, although this relationship was complicated by differences in vegetation. The development of hydrological connectivity was shown to be more closely related to hourly rainfall intensity rather than total storm rainfall (Gomi *et al.,* 2008). In the Hermine catchment, which receives much less rainfall and is on average 10^{o}C cooler than the Mie catchment (Table 2), Ali *et al.* (2010b) identified a switch between different types of catchment response (connected and disconnected flow) produced by different hydro-meteorological variables leading to a change in catchment behaviour. Sen *et al.* (2010) demonstrated that runoff at the outlet of a 0.12 ha pasture plot was mainly observed when runoff-contributing areas at the downslope section of the hillslope showed runoff generation and were connected to areas in the middle section of the hillslope. Sen *et al.* results support and build on the body of research by McGlynn and co-workers which has demonstrated that the size and spatial arrangement of hillslope and riparian zones along a stream network and the timing and duration of groundwater connectivity between them controls the magnitude and timing of water and solutes observed at the catchment outlet (e.g. McGlynn and McDonnell, 2003; McGlynn and Seibert, 2003; Jensco *et al*., 2009; Jensco and McGlynn, 2011). Research has been mainly conducted in the Tenderfoot catchment, USA, which is dominated by steep slopes with hydrological connectivity mainly occurring during a short snowmelt period in spring. In contrast, the Sand Mountain Research and Extension Centre in Alabama is an area of low slopes underlain by moderately deep, well drained, sandstone derived soils, without much snow, but most rainfall occurs in the winter and spring (Sen *et al.,* 2010). Hence despite different catchment characteristics there are some similarities in generation of runoff and hydrological connectivity.

The research exploring flow-process aspects of hydrological connectivity maps onto many different definitions of the concept of hydrological connectivity and does not explicitly relate to the methodological approach as with soil-moisture connectivity. The research by Cammeraat (2002) maps on to definition 8, concerned with spatial patterns of properties which facilitate flow and transport in a hydrological system at the hillslope scale. The approach taken by Reaney (2008) and

Smith *et al.*, (2010) maps more directly onto definition 2: '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). The approaches taken by Gomi *et al.*, (2008) and Ali *et al.*, (2010b) also map onto definition 2, but also definition 3: 'Flows of matter and energy (water, nutrients, sediments, heat, etc.) between different landscape components' (Tetzlaff *et al.*, 2007a). Research by Tetzlaff *et al.* (2007b) and Sen *et al.* (2010) also maps on to definition 3. Finally the approach to exploring flow processes used by McGlynn, McDonnell and Jensco directly relates to definition 11: 'Connection, via the subsurface flow system, between the riparian (near stream) zone and the upland zone (also known as the 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). Thus, research exploring flow-processes of hydrological connectivity bridges a range of definitions at a range of scales and is not clearly linked to only one perspective of hydrological connectivity. There is not such an explicit relationship between methodology and definition as with soil-moisture and water-table based approaches.

5.3 Terrain Connectivity

This approach investigates topographic controls on runoff and flood production. We have included the impact of road networks on hydrological connectivity and catchment runoff in this category. Research focused on forest roads in Australia established conceptual and modelling frameworks that that underlined that roads and tracks are key components of catchment hydrological connectivity (Wemple *et al.* 1996; Tague and Band, 2001). Hairsine *et al.* (2002) proposed a probabilistic model of diffuse overland flow that predicted the hillslope lengths required to infiltrate road discharge, based on the concept of volume to breakthrough (Vbt). Croke *et al.* (2005) developed this work and identified two types of connectivity: direct connectivity via established and/or new channels or gullies, and diffuse connectivity such as surface runoff which reaches the stream network via overland-flow pathways. Research around hydrological connectivity caused by roads and tracks led to the development of a comprehensive account of how best to manage timber harvesting for both on-site sustainability and off-site water resource protection (e.g. Croke and Hairsine, 2006). The application of this research highlights the explicit link between pure research and application for catchment management.

More recently, research into terrain connectivity has tried to assess other components of system coupling and landscape connectivity that control the flow of water. Callow and Smettem (2009) proposed that hillslope water capture and diversion infrastructure (e.g. terraces, check dams and canals) need to be included into simulation models, especially in dryland regions, since changes in areas retaining water can make large differences to potential runoff pathways. Similarly, Meerkerk *et al*. (2009) examined the effect of terrace removal and failure on hydrological connectivity and peak discharge in an agricultural catchment. Connectivity was quantified using connectivity functions, specifically a contributing area function, and related to storm characteristics, land use and topography. Results demonstrated that a decrease in intact terraces can lead to a strong increase in hydrological connectivity and catchment discharge.

Lexartza-Artza and Wainwright (2011) developed understanding of terrain connectivity further by investigating changing patterns of connectivity over longer timescales in the UK using a multiple methodology approach combining the analysis of reservoir-sediment records with knowledge of recent land-use history, high resolution rainfall records, catchment characteristics and management aspects. Sedimentation rates inferred from reservoir-sediment cores showed sedimentation peaks which coincided with periods of significant changes in the catchment, such as the introduction of arable crops, the establishment of land drainage and the widespread intensification and mechanization of agriculture. Rainfall patterns contributed to increased sediment transfer under catchment conditions in which more sediment and/or new pathways are made available due to catchment changes. However, the research suggested that sedimentation rates were related to the establishment of different pathways increasing sediment connectivity (Lexartza-Artza and Wainwright, 2011). In this example, 'terrain' is represented through land use (especially the impact of roads and field boundaries) rather than topography and the term 'landscape connectivity' may be more appropriate.

Although topography is usually significant for routing runoff, it is not the exclusive driver for catchment response and it does not represent the only important structural feature (Buttle, 2006). For instance, in semi-arid areas and steep, snow-dominated watersheds knowledge of soil-surface structure has been shown to be paramount over topography in understanding the potential for runoff response and connection (e.g. Puigdefabregas *et al*., 1998). The focus laid by Callow and Smettem (2009) and Meerkerk *et al*. (2009) on topographic connectivity focuses on the interventions for controlling fluxes of water and sediment rather than understanding how processes promote and route flux.

As with soil-moisture approaches to investigating hydrological connectivity, terrain approaches also have a direct link between approach and definition. Research falls into Ali and Roy's (2009) category of definitions around landscape features at the hillslope scale. The work on connectivity provided by roads and tracks supports definition 7 developed by Croke *et al.* (2005); research by Callow and Smettem (2009) and Meerkerk *et al.* (2009) both link through to definition 6 by Stieglitz et al. (2003) (Table 1). However, the link between approach and definition is not a product of the methods employed, as with soil-moisture approaches, but has rather to do with the conception of research. In all instances research on terrain connectivity is framed around the impact of a particular infrastructural element, or its removal, (be it roads, terraces or check dams) on flow processes. This framing necessitates a certain perspective, although different methods (different types of modelling or fieldwork) are then used to explore the change in flow routing with or without the infrastructure in question. Terrain-based approaches tend to explore structural aspects of hydrological connectivity (Figure 1).

5.4 Models of hydrological connectivity

The earliest modelling attempts using the Soil Conservation Service Curve Number method (Beasley *et al.*, 1980; Savard, 2000; Brocca *et al.,* 2009) did not address connectivity itself, but instead estimated the continuity of runoff through statistical estimations of hillslope interactions. 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, equations 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 and McDonnell, 2007) with some models using resolutions of as much as 1 km^2 despite typical control structures for connectivity in the landscape being less than 0.0025 km^2 (Blackwell *et al.*, 1999; Lane *et al.*, 2009; Meerkerk et al., 2009; Callow and Smettem, 2009). Model accuracy is further undermined by using physical models at greater spatial scales than they can adequately represent, given the spatial difference at that resolution (Lane *et al.*, 2009), unless processes are parameterized at the sub-grid-cell resolution (e.g. Muller *et al.,* 2007).

More recently, models have been developed using the concept of hydrological connectivity to explore factors affecting the development of flow connections with changing topographic features (e.g. Callow and Smettem, 2009; Meerkerk *et al.*, 2009). Whilst spatially distributed hydrological models that allow lateral flow to shut off under certain conditions do already exist, few models have been explicitly designed to enable hydrological connectivity to develop as an emergent property and hence enable prediction or exploration of changes in connectivity as the catchment and climate evolve. Lane *et al*. (2009) assessed the extent to which a topographically defined description of the spatial arrangement of catchment wetness can be used to represent the hydrological connectivity in temperate catchments. They found that a static descriptor based on topography can be successfully used to generalize spatial variability in hydrological connectivity. Birkel *et al*. (2010) developed a catchment scale, parsimonious rainfall-runoff model for upland catchments in Scotland using a dynamic conceptualization of the hydrologic characteristics of the saturation zones in the catchment. Their function representing the dynamic expansion and contraction of saturation zones is an integrated measure of hydrological connectivity. Again, they showed that this dynamic process-representation improved model performance. Lesschen *et al*. (2009) used the LAPSUS model to simulate runoff and sediment dynamics at the catchment scale in SE Spain; the spatial distribution of vegetation patches and agricultural terraces were found to determine hydrological connectivity at the catchment scale.

Lane *et al*. (2004;2009) propose that modelling can be used to represent temporal variation in connectivity presuming the limits of modelling are recognised and understood. We propose that to do this well, modelling should enable hydrological connectivity to emerge due to the operation of process laws, rather than be defined as a concept that is put into the model in the first place. Lane *et al*. (2004;2009) proposed that the strength of their modelling approach is through topographic estimation because this is the easiest parameter to be measured at any resolution and used the Topographic Wetness Index (TWI) in order to 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). 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 flow paths with lower potential to connect are likely to be less frequent and for a shorter period of time (Lane *et al.*, 2009). However, the modelling approach of Lane *et al*. (2004) does not allow the hydrological connections to emerge during the course of a model run since it is founded on static catchment characteristics, namely topography. In contrast, the agent-based modelling undertaken by Reaney (2008) enables the agents to trace the path taken by water through the catchment and is hence capable of giving a novel picture of the temporal and spatial dynamics of flow generation and transmission during a storm event. In this way hydrological connections emerge during the model run.

We note that the topographic wetness index (as originally defined in TOPMODEL: Beven and Kirkby, 1979) is widely used to represent areas susceptible to accumulate soil moisture and hence identify potential flowpaths. However, this approach ignores the importance of transient saturation and so is only relevant to systems in which it is not important. The topographic wetness index approach also presumes that there are no other forms of driver on soil-moisture creation and connectivity other than topographic forcing, which has been identified as an unsatisfactory approach to understanding hydrological connectivity in all environments (Bracken and Croke, 2007). For example, generation of connected flow may not always follow the network of topographic lows, and 'fill and spill' may be dominated by either hummocky surface topography, bedrock or an impermeable confining layer (Spence, 2006; Tromp van Meerveld and McDonnell, 2006; Ali *et al.,* 2011).

Research based on modelling hydrological connectivity maps onto Ali and Roy's (2009) category of landscape features at the watershed scale, and in particular definition 4 proposed by Lane *et al.* (2004) 'the extent to which water and matter that move across the catchments can be stored within or exported out of the catchment'. This definition underpins the SCIMAP model developed by Lane *et al.* (2004) so understandably there is a direct link between definition and approach. Research in this category maps onto both structural and process-based aspects of connectivity.

5.5 Indices of hydrological connectivity

There is some debate around developing indices of hydrological connectivity (Troch *et al.*, 2009; Antoine *et al.*, 2009) and investigating how they vary between catchments. Research to date has been poor at trying to understand the variation of both hydrological connectivity and indices between catchments. The common indices used are presented in Table 4. Studies can be divided into those deriving pathways from topography (e.g. Lane *et al.*, 2009; Lesschen *et al.*, 2009; Tetzlaff *et al.*, 2009), those developing understandings informed by water infiltration and transfer at the plot or catchment scale (Gomi et al., 2008; Buda *et al.*, 2009) and those that occasionally bring these two approaches together (Jensco *et al.*, 2009; Meerkerk *et al.*, 2009). However, no one index of hydrological connectivity has emerged to be better than any other and there is no consensus amongst researchers that this is indeed even a desirable outcome of research.

Knudby and Carrerra (2005) evaluated nine indicators of connectivity: three account for the presence of flow connectivity (preferential flow paths); two account for the presence of transport connectivity (the existence of fast paths allowing early solute arrival); and four are based on statistical indicators. The indicators were tested on heterogeneous hydraulic conductivity fields with different visual connectivity (Table 4). The indicators of flow connectivity and one of the transport-connectivity indicators succeeded in identifying the increased presence of connected high saturated hydraulic conductivity features through a geologic media. Using indicators of flow connectivity improved on the use of traditional statistical methods which failed to identify preferential flow paths. None of the statistical indicators were found to correlate with the flow and transport indicators. Hence Knudby and Carrerra (2005) suggested that transport connectivity is much less sensitive to barriers which may control flow connectivity. Instead, transport connectivity appears to be controlled by the existence of narrow, possibly discontinuous high saturated conductivity paths. This proposal suggests that connectivity needs the continuity of features to be represented, not just the variability which is supported by existing modelling approaches to understanding hydrological connectivity (Muller *et al.*, 2007).

Borselli *et al*. (2008) developed two indices of connectivity: the Index of Connectivity (IC) defined from GIS and based on landscape information and a Field Index of Connectivity (FIC) defined though field assessment. IC can be used to express the general properties of the catchment under evaluation, especially the potential connectivity between different parts of a catchment; FIC is developed from actual field measurements (terrain mapping) of connected flowpaths taken as soon as possible after an event (Borselli *et al.*, 2008). FIC is thus a measure of the cumulative effect of processes occurring over a certain time period. Indices were designed to complement each other and combined use was shown to improve accuracy. Birkel *et al*. (2010) described an integrated measure of hydrological connectivity as a function of antecedent precipitation index, evapotranspiration and dominant soil coverage, converting a spatially static parameter into a dynamic conceptualization of the hydrologic characteristics of the saturation zones in the catchment.

Different quantitative indicators of hydrological connectivity have also been evaluated and tested on microtopography (Antoine *et al*. 2009). The results of the investigation of Antoine *et al*. (2009) proposed a functional connectivity indicator by adapting the volume to breakthrough: the degree of surface connection as a function of the surface-storage filling. This indicator was capable of discriminating between micro-topographic types and it was suggested that it could become an effective characteristic of an elementary representative area in large scale hydrologic models (Antoine *et al.*, 2009; Smith *et al*. 2010).

In an in-depth study of hydrologically representative connectivity metrics in a humid temperate forested catchment (the Hermine), Ali and Roy (2010a) argued that capturing critical spatial organization in soil-moisture patterns depends on the way the chosen connectivity metric is built and so tested a large selection of 2-D and 3-D connectivity measures based on quasi-continuous soil-moisture patterns. The results of assessments of connectivity were variable depending on the computed metric. In particular, topography-based connectivity metrics reflected changes in catchment macrostate and stormflow response better than omnidirectional methods. Also, source-to-stream connectivity metrics were more hydrologically sensitive than metrics that did not consider the spatial linkage to the stream channel.

As with flow-process approaches to understanding hydrological connectivity, approaches based around developing indices map on to the full range of definitions summarised by Ali and Roy (2009), which is to be expected since researchers have attempted to capture differing perspectives of hydrological connectivity at different scales. In this way specific indices tend to be a product of the working definition used of hydrological connectivity. More interesting, perhaps, is that the research attempting to develop indices has not converged on a preferred foundation for an index of hydrological connectivity.

6 Is a unified understanding of hydrological connectivity possible?

Many factors influence connectivity; some of them are well understood such as the impact of surface properties, slope and vegetation on runoff production (Poesen, 1984; Van Oost *et al.,* 2000; Ludwig *et al.,* 2005), how runoff coefficients scale with slope (Parsons *et al.,* 2006) and rainfall (Wainwright and Parsons, 2002) and ways and implications of classifying runoff units (Bull *et al.,* 2003). Less well understood are the ways in which patterns and processes at the hillslope scale determine water transfer at the catchment scale, especially how changing storm characteristics and antecedent moisture interact with mosaics of catchment properties such as patterns of land use, slope and lithology to produce connected flow through drainage basins. For example, a catchment can be characterized by classifying the mosaic of land use, slope, lithology and channel patterns to understand potential runoff units and potential hydrological connectivity. However, empirical evidence of the impact of changing rainfall intensity, storm duration, areal distributions of rainfall and antecedent soil moisture on producing hydrological connectivity in a catchment and the difference it makes to water transfer is sparse, despite the recent advances in tracer techniques (Tetzlaff *et al.,* 2007b). Storm dynamics will interact with the range of hillslope lengths within a catchment, which will either enable or disable connected flow for a particular storm event; a comprehensive understanding of this interaction has yet to emerge. These gaps in our knowledge prevent accurate and precise prediction of changing water transfers under climate and land-use change.

A second key issue with the concept of hydrological connectivity is how it can be applied across and between environments. For the concept to be useful and a way forward to further our understanding of flow transfer and pathways at a range of scales, it must be relevant and/or flexible to be applicable across all environments. Some of the initial fundamental building blocks underpinning the concept were developed for both dryland and temperate areas (Western *et al.*, 2005; Bracken and Croke, 2007), but many of the recent developments have arisen from research focused on small-scale, forested, humid-temperate environments (James and Roulet 2007, Tromp van Meerveld and McDonnell 2005, Ali and Roy 2010a). How do new developments in understanding apply to dramatically different environments such as drylands, colder regions or formally glaciated landscapes characterised by subdued topography? One initial assumption would be that since most flow is generated from surface runoff rather than subsurface mechanisms, it would be difficult to utilise the idea of 'fill and spill' in dryland basins. However, some dryland areas have perched aquifers and underlying confined layers which may operate in a similar manner to that identified in humid temperate catchments and will combine with surface runoff generation to produce connected areas of flow. Dryland researchers have also used the overtopping bucket analogy for spatially isolated soil patches for many years (Kirkby *et al.,* 2002). The idea of storage and how it operates is one key way of linking the mechanism and processes responsible for producing connections in flow in all environments (Ali *et al.*, 2011). However, in drylands stores tend to fill from the top down, rather than the bottom up, so what appears to be a potential similarity between mechanism and processes between environments may lead to confusion because of underlying differences. The fill and spill hypothesis is however easily transferable to lake-dominated catchments and to the US and Canadian Prairie Pothole Region where topographic depressions can act as closed basins while filling up and then as stormflow transition zones when overspilling (Spence, 2007; Spence and Hosler 2007; Shaw et al 2012).

In ancient glaciated landscapes, such as large parts in Canada, Fennoscandia and the Scottish Highlands, the combination of complex drift distributions and topography determines soil hydrology which plays a key role in controlling catchment rainfall-runoff responses reflecting the interactions between climate, topography, parent material and land use (Soulsby et al., 2006). Field and modelling studies in such environments have shown that flatter, poorly drained areas on glacial drift deposits often result in the development of histosols where runoff is dominated by overland flow (Seibert et al., 2003; Soulsby et al., 2006). In such environments, dynamically expanding and contracting riparian saturation zones reflect catchment connectivity and control the generation of quick, near-surface runoff processes (Tetzlaff et al., 2007b; Birkel et al. 2010). These runoff mechanisms are dependent on the connections between the saturated areas and their surrounding hillslopes which can result in a highly non-linear hydrological response in relation to antecedent conditions. In regions with both limited topographic variations and relatively uniform soils it is the topology of landscape features adjacent to the channel network that is a strong driver for hydrological connectivity and response (Buttle, 2006). For example, Devito et al. (2005) advocate that topography be one of the last aspects considered when classifying runoff pathways in the boreal plain of Alberta, Canada. In this environment, precipitation is only slightly greater than evaporation, moisture deficits are seasonally prevalent, and the regional water table does not directly reflect the land surface as is common in wet environments.

Similar rainfall inputs in similar antecedent conditions do not always yield the same outputs (Bracken *et al.*, 2008; Ali *et al.*, 2010;2011). Hence, characterising antecedent soil-moisture is not a sufficient characterisation of the antecedent conditions. This complexity highlights several points, among which is the possibility that our approaches to hydrological mechanisms are too simple with respect to the variety and complexity of the processes involved in different environments and that we impose known mechanisms as a framework to our understanding of catchment hydrology. In that respect, we have to diversify our approaches. Not only do we need research into hydrological connectivity across different environments but investigations have to be conducted in various basin types with different geology, soils and vegetation covers, as long as these data can be interpreted in light of a conceptual underpinning (Carey *et al.*, 2010; McNamara *et al.*, 2011). Vegetation is probably the most responsive element of catchment structure and forms an important interface with catchment function. Vegetation has a complex relationship with runoff production and is a major influence on hydrological connectivity at all scales (Bracken and Croke, 2007). Vegetation can influence water inputs and runoff through interception, formation of leaf litter and transpiration. Within ecology there has been a lot of research based on spatial variations in vegetation and how this is related to hydrological processes (Cammeraat and Imeson, 1999; Ludwig *et al.,* 2000;2005). Currently, most active research into understanding relevant processes and patterns is being undertaken in forested catchments with flow generation dominated by bedrock (Panola and St Hilaire, Canada) or a confining layer (Hermine), although a notable exception is the Tarawarra catchment, Australia (Table 2). Some differences will be captured by working in catchments with different environmental characteristics, but we also need to establish whether mechanisms are similar for grassland catchments and other types of land covers. Several researchers have attempted to do this using numerical techniques to explore rainfall and catchment characteristics that influence the development of hydrological connections (e.g. Wainwright and Parsons 2002; Reaney *et al.*, 2007; Muller *et al.*, 2007; Hopp and McDonnell, 2009).

A third issue is how the concept of hydrological connectivity works at different scales. Little research explicitly acknowledges the different scales over which hydrological connections are made and investigated (except, for example, Wainwright *et al.*, 2011). Scale is directly linked to the methodological approach taken to collect empirical data (Table 3), which in turn is related to the questions being investigated. The studies producing the most exciting developments in thinking about the concept tend to be focused at the relatively small scale (<10 ha) (Table 2; Figure 1), especially in the use of soil moisture as a way in to understanding the production of connected flow (e.g. Grayson *et al.*, 1997; Western *et al.*, 1998; James and Roulet 2007; Tromp Van Meerveld and McDonnell 2006; Ali and Roy 2010b). Intense data collection has also been used at the plot scale in semi-arid areas to explore the interaction been rainfall and runoff, including the role of surface roughness, and how hydrological connections develop (Smith *et al.*, 2010;2011). However, we need to initiate investigations to interrogate how overarching themes can be useful at a range of scales. Which aspects will work at different scales? For example it would be difficult to apply the lots of points approach to large catchments without significant technical developments and we do not yet understand the key drivers to connections, although we have some understanding of the factors influencing discharge production (e.g. Bull *et al.*, 2000; Bracken and Croke, 2007). It may be better to attempt to determine an appropriate number of points using a considered sampling strategy as has been done with the characteristic soil-moisture-modelling (CASMM) sites methodology.

The challenge of working across different environments and at a range of scales dictates that we need to find new ways of thinking and working in hydrology. If we remain bounded by established practices and existing ways of approaching runoff generation and flow production we may not be able to exploit the full potential of the concept of hydrological connectivity. It follows that we should evaluate current methodologies and practices in data collection. If we are able to capitalize on the excitement and momentum that currently exist around the concept of hydrological connectivity we need to develop new approaches to data collection and combine methods in new ways. We have been successful at using soil moisture as a surrogate for hydrological connectivity, but research has demonstrated that changes in the catchment hydrographs are not always explained by the patterns of increasing soil moisture (Tromp van Meerveld and McDonnell, 2006). Research has also questioned the appropriateness of using topography to determine flow paths and runoff connections for all catchments (Ambroise, 2004; Buttle, 2006). Thus two of most used conceptual foundations for interpreting landscape processes contributing to catchment runoff and connected flow may not be the most useful to further develop the concept of hydrological connectivity. We should further explore the synergies with other disciplines more fully, such as ecology, and also investigate the potential of remotely sensed data for understanding patterns and processes of hydrological connectivity at intermediate spatial scales.

The fourth issue is that we still do not have a good understanding of the role of spatial and temporal variability in input rainfall and how this influences functional controls on hydrological connectivity. Numerical experiments have been used to test whether the temporal variability of rainfall intensity during a storm can cause a decrease in runoff coefficients with increasing slope length. Wainwright and Parsons (2002) demonstrated significant effects over even relatively short slope lengths with the scale dependency of measured runoff coefficients most sensitive to the rainfall variability. In semi-arid areas temporal fragmentation of high-intensity rainfall is important for determining the travel distances of overland flow and, hence, the amount of runoff that leaves the slope as discharge (Reaney *et al.*, 2007). This research demonstrated that storms with similar amounts of high-intensity rainfall can produce very different amounts of discharge depending on the storm characteristics. It has also been shown that interactions between slope angle, soil depth and storm size can cause unexpected behaviour of hydrograph peak times as a result of the interplay between subsurface topography and the overlying soil mantle with its spatially varying soil-depth distribution (Hopp and McDonnell 2009). Ali *et al.* (2011) also underline the importance of understanding the role of rainfall by their recent paper on the River Dee in Scotland with results suggesting that the temporal variability in dominant flow paths is predominantly controlled by hydro-climatic conditions.

However, we need more research into the role and influence of rainfall events on hydrological connectivity, especially the interaction between input of water to the system and emerging hydrological properties. Investigating the response to different hydrological events could be conceived as variance within storm versus variance of hydrological characteristics. This work needs to factor in the role of antecedent moisture conditions; a subject that benefits from a systematic approach to identify surrogate measures for soil water content. As surrogate measures are derived from rainfall data, we need to clarify the relevant temporal scales over which we cumulate rainfall for an adequate prediction of connectivity patterns and of hydrological responses to a given rainfall event. As shown by Ali and Roy (2010b) in the Hermine watershed, there is a wide range of potential models describing the relations between various surrogate measures of AMC and discharges at the outlet and an even more variable set of relationships between soil-moisture content at discrete locations within the watershed and AMC surrogates.

7 Suggestions for future research

It is difficult to know the most suitable sampling strategy to capture the signals of hydrological connection, especially between basins and between environments, but also at larger spatial scales. Similar connectivity patterns in soil moisture do not necessarily lead to a similar hydrological response at the watershed outlet. This difference may be due to: i) variability in the permeability and saturation of the subsurface soil layers due to antecedent moisture conditions; or ii) different stream-flow generating processes that are not captured in the spatial sampling network; or iii) the combination of saturation with variation in ampunt and intensity of rainfall. We firmly believe that researchers working on hydrological connectivity should thus evaluate what, where and how we have developed our existing research approaches so that we can now come together to develop new ways of capturing process understandings of runoff production and water transfer. We should no longer rely on statistical criterion to determine when and where we sample, but be better guided by experimental criterion.

One suggestion for future research is to move away from the use of topographic and soil-moisture indices to determine hydrological connections. One possible way to do so is to investigate how storage of water occurs in different catchments and how these stores fill up (or down) and link (or not) to produce (dis)connected flow. One empirical approach is to monitor changes in water-table level along a spatially dense network of wells or piezometers (e.g. Ali *et al.*, 2011). If the depth to an impervious sublayer is known throughout the watershed, the simultaneous monitoring of the water-table levels at several points through a rainstorm is particularly instructive to identify the patterns of connectivity and to infer the zones of water storage in some environments. We should push for a concerted effort to initiate comparative experimental research across different environments and different sizes of basin (Tetzlaff *et al.*, 2009; McNamara *et al.*, 2011). We need to be imaginative and find a common thread that links the production of connected flow in these study areas and then develop appropriate methodologies so results and understandings can be compared across environments and basins of different size. For instance, monitoring spatial variations in the water table during the course of a rainfall event is suitable in small-scale, humid-temperate watersheds, but this methodology would not be suitable in drylands, permafrost regions or very large basins. We propose that approaches need to be comparable across environments and study basins to find a common thread to understanding, exploring and using hydrological connectivity across a range of environments and at different scales to develop a workable and useful concept to further hydrology.

Investigations into hydrological connectivity should take advantage of technical developments in monitoring equipment. For example, recent advances in sensor design offer an opportunity for affordable yet distributed datasets of surface water. Simple, cheap devices could be used to monitor ephemeral stream network expansion (Bhamjee and Lindsay, 2011) or the development and expansion of areas of disconnected surface flows over small catchments. Blash *et al.* (2002), Goulsbra *et al. (*2009) and Bhamjee and Lindsay (2011) document the design of cheap electrical resistance sensors suitable for distributed field deployment. These devices are capable of detecting water at the soil surface. Where deployed at different levels they could be used to constrain water height; alternatively, they could be deployed alongside simple crest-stage measurement devices (Bracken and Kirkby, 2005). Electrical resistance sensors could provide distributed data for indicator metrics of connectivity (using a simple wet/dry threshold) analogous to those developed for soil-moisture measurements although this may encourage a technology rather than process led course of research. An advantage of obtaining surface flow datasets is that they facilitate comparison between observed patterns of surface water and topographic signatures of such flow development (e.g. the Morphological Runoff Zones of Bracken and Kirkby, 2005) which, alongside simple laboratory erosion experiments and field mapping, could yield still further insight into the spatial patterns of catchment response and emerging patterns and similarity at the catchment scale.

In conjunction with technological developments, environmental and isotopic tracers are a powerful tool to enhance our understanding of hydrological connectivity as an important means of separating stream flow into different temporal sources of flow contribution within catchments (Soulsby et al., 2003; Tetzlaff et al., 2007b). They can reveal the integration of smaller-scale hydrological processes that underpin signatures of catchment response at larger spatial scales (Soulsby et al. 2006). Generally, tracers are useful tools for characterizing and understanding complex flow through catchments, soils, channels, over land surfaces, and through hillslopes and aquifers (Buttle et al., 1998). Using environmental tracers to assess hydrological characteristics has the advantage that less *a priori* information is required (e.g. head gradients, hydraulic conductivity fields and porosities) and the results integrate physical heterogeneity providing a useful tool for calibrating more detailed conceptual or numerical models (e.g. Maloszewski and Zuber, 1993; Fenicia et al., 2008; Birkel et al. 2011). One common technique employing tracers is the use of input-output dynamics of conservative isotopic tracers for estimating the travel time of water through catchments which is the time it takes from when water enters a catchment to when it exits a catchment as stream discharge at an outlet of a catchment (Etcheverry and Perrochet, 2000; Soulsby et al., 2004; McGuire and McDonnell, 2006; Kirchner *et al*., 2010). Transit times provide information on flow paths, storage, release and chemical quality of water and integrate various catchment functions and processes (McDonnell et al., 2010; Soulsby et al., 2011).

Developments in remote sensing technology should also be harnessed and may be particularly useful to aid with scaling up process capture. For instance LIDAR could be used to track fine-scale detention storage or to monitor vegetation patterns and understand the interplay with processes responsible for producing hydrological connectivity (e.g. Hwang *et al.* 2012). An exciting possibilityis the potential to develop hybrid approaches utilising developments in a range of technolgoes together to achieve a better approximation of process.

8 Conclusions

It is timely for researchers studying hydrological connectivity to reflect on the way in which we approach, conceptualise and implement our research design. For instance spatial soil moisture patterns not dot always reflect the hydrological connections being made, highlighting that sometimes our assumptions are not always correct, nor applicable across all catchments and environments. In this paper we have classified the research around hydrological connectivity into five broad themes based on: i) soil moisture; ii) flow processes; iii) terrain; iv) models and; v) indices. These divisions reflect both the definition used of hydrological connectivity, which in turn tends to dictate the researcher's conceptualisation and methodology. The key and novel outcome of the analysis presented in this paper is that we need to focus future research much strongly on attempting to capture the processes responsible for and controlling hydrological connectivity. This notion cuts across all themes. Process is a widely used term and process capture is the fundamental aspiration of most researchers, but we do not think that we are always doing this to the best of our abilities, which is often exacerbated by need for practical and achievable sampling (e.g. measurement approach and scale). This paper highlights that flow process hydrological connectivity lends itself most closely to capture the process. Yet we need to evaluate how the characteristic and attributes of the catchment that we measure, or model, lend themselves to inference and extrapolation about process. We should ensure at a minimum that we capture data from which we can infer process, rather than potential process and make sure that criterions we use in our research are experimental rather than statistical.

To conclude, we need to develop our knowledge of hydrological connectivity using a range of techniques with a common understanding between researchers with varying perspectives, and to communicate effectively with those responsible for land management. The analysis of research and new thinking presented in this paper has led to the identification of a number of key suggestions as follows:

1) Research around hydrological connectivity can be linked to the researchers themselves and the approach and techniques that they employ to investigate the concept.
2) There is some interlinkage between groups undertaking research into hydrological connectivity, but often in terms of location and methods; conceptual approaches remain separate.
3) There is little overlap between methods used to gather empirical data on hydrological connectivity which has led to implicit relationships between the definitions used, perspective of the researcher and measurement techniques employed.
4) There is confusion about the terms used to classify approaches such as structural and functional hydrological connectivity.
5) To ascertain the future usefulness of the concept comparative research using multiple methods and definitions needs to be developed.
6) We propose the term 'process-based' hydrological connectivity as a more readily understandable phrase than functional connectivity to convey how spatial patterns of catchment characteristics interact with processes to produce connected flow and hence water transfer.
7) Comparative inter-site research across different environments, vegetation and scales of basins is also necessary to study a range of mechanisms and processes of runoff production to inform our understandings.
8) The research community should focus on developing research around better understanding 'process-based' measurements to enable comparisons approaches and indices in different locations. In striving to capture the evolutionary dynamics of runoff production and the development of connected pathways of flow we need to move away from solely terrain based characteristics and move towards flow based studies and hybrid studies, reflecting on trying to capture the process as best as possible.
9) New sensors and field techniques provide excellent opportunities to understand processes of hydrological connectivity in new ways.

We hope that these suggestions can form the bases for further discussion and a foundation to develop the concept of hydrological connectivity still further. Environmental management is one area of policy implementation that is both complex and dynamic requiring the engagement of a range of practitioners with overlapping and multiple objectives (Fish *et al.* 2010). A better understanding of process-based connectivity at multiple timescales will support more holistic and joined-up thinking about how and when to intervene in catchment processes to encourage (dis-) connectivity.

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10 References

Abrahams, A.D., Parsons A.J. and Luk, S.H. 1986. Field measurement of the velocity of overland flow using dye tracing. *Earth Surface Processes Landforms*, 11: 653–657.

Ali, G.A., and A.G. Roy 2009. Revisiting hydrologic sampling strategies for an accurate assessment of hydrologic connectivity in humid temperate systems. *Geography Compass* 3: 350–374.

Ali, G.A., and A.G. Roy 2010a. Shopping for hydrologically representative connectivity metrics in a humid temperate forested catchment. *Water Resources Research* 46: W12544.

Ali, G.A., and Roy, A.G. 2010b. A case study on the use of appropriate surrogates for antecedent moisture conditions (AMCs). *Hydrology and Earth System Sciences*, 14: 1843-1861.

Ali, G.A., Roy, A.G., Turmel, M.C. and Courchesne, F. 2010. Multivariate analysis as a tool to infer hydrologic response types and controlling variables in a humid temperate catchment. *Hydrological Processes,* 24: 2912–2923.

Ali, G.A., L'Heureux, C., Roy, A.G., Turmel, M.C. and Courchesne, F. 2011. Linking spatial patterns of perched groundwater storage and stormflow generation processes in a headwater forested catchment *Hydrological Processes*, 25(25): 3843-3857, doi: 10.1002/hyp.8238.

Ali, G., Tetzlaff, D., Soulsby C. and McDonnell, J.J. 2011. Topographic, pedologic and climate interactions influencing streamflow generation at multiple catchment scales. *Hydrological Processes,* DOI: 10.1002/hyp.8416.

Ambroise, B. 2004. Variable active versus contributing areas or periods: a necessary distinction. *Hydrological Processes,* 18: 1149 – 1155.

Antoine, M., Javaux, M. and Bielders, C. 2009. What indicators can capture runoff relevant connectivity properties of the micro-topography at the plot scale? *Advances in Water Resources,* 32: 1297-1310.

Beasley, D. B., Huggins, L. F. and Monke, E. J. 1980. ANSWERS — A model for watershed planning, *Transactions of the American Society of Agricultural Engineers*, 23: 938– 944.

Betson, R.P. 1964. What is watershed runoff? *Journal of Geophysical Research* 69: 1541–1552.

Beven, K. 1997. Topmodel: a critique. *Hydrological Processes*, **11**: 1069-1085.

Beven, K.J. and Kirkby, M.J. 1979. A physically-based, variable contributing area model of basin hydrology, *Hydrological Sciences Bulletin,* 24: 43–69.

Birkel, C., Tetzlaff, D., Dunn, S.M., Soulsby, C. 2010. Towards simple dynamic process conceptualization in rainfall runoff models using multi-criteria calibration and tracers in temperate, upland catchments. *Hydrological Processes*, 24: 260-275.

Bhamjee, R. and Lindsay, J.B. 2011. Ephemeral stream sensor design using state loggers. *Hydrology and Earth System Sciences,* 15: 1009−1021.

Blackwell, M. S. A., Hogan, D.V. and Maltby, E. 1999. The use of conventionally and alternatively located buffer zones for the removal of nitrate from diffuse agricultural run-off. *Water Science and Technology*, 39: 157– 164.

Blasch, K.W., Ferré, T.P.A., Christensen, A.H. and Hoffman, J.P. 2002. New field method to determine streamflow timing using electrical resistance sensors. *Vadose Zone Journal,* 1: 289– 299.

Borselli, L., P. Cassi, et al. 2008. Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. *Catena*, 75: 268-277.

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

Bracken, L.J. and Kirkby, M.J. 2005. Differences in hillslope runoff and sediment transport rates within two semi-arid catchments in southeast Spain. *Geomorphology* 68: 183–200.

Bracken L.J., N.J. Cox and Shannon, J. 2008. The relationship between rainfall inputs and flood generation in south-east Spain. *Hydrological Processes* 22: 683−696.

Brocca, L., Melone, F, Moramarco, T., and Singh, V. P. 2009. Assimilation of Observed Soil Moisture Data in Storm Rainfall-Runoff Modelling. *Journal of Hydrologic Engineering,* 14: 153-165.

Buda, A.R., Kleinman, P.J.A. et al. 2009. Factors influencing surface runoff generation from two agricultural hillslopes in central Pennsylvania. *Hydrological Processes,* 23: 1295-1312.

Bull, L.J., Kirkby, M.J., Shannon, J. and Hooke J. 2000. The variation in estimated discharge in relation to the location of storm cells in South East Spain. *Catena,* 38: 191-209.

Bull, L.J., Kirkby, M.J., Shannon, J. and Dunsford, H. 2003. Predicting Hydrological Similar Surfaces (HYSS) in semi-arid environments. *Advances in Monitoring and Modelling,* 1(2): 1-26.

Buttle, J.M. 1998. Fundamentals of small catchment hydrology. In: Isotope tracers in catchment hydrology, Edited by Kendall, C. and McDonnell. J.J. Elsevier.

Buttle, J.M. 2006. Mapping first order controls on streamflow from drainage basins: The T^3 template. *Hydrological Processes,* 20: 3415-3422.

Callow, J.N. and Smettem, K.R. J. 2009. The effect of farm dams and constructed banks on hydrologic connectivity and runoff estimation in agricultural landscapes. *Environmental Modelling & Software*, 24: 959-968.

Cammeraat, L.H. 2002. A review of two strongly contrasting geomorphological systems within the context of scale. *Earth Surface Processes and Landforms*, 27: 1201-1222.

Cammeraat, L.H., Imeson, A.C. 1999. The significance of soil-vegetation patterns following land abandonment and fire in Spain. *Catena*, 37: 107-127.

Carey, S.K., Tetzlaff, D., Seibert, J., Soulsby, C., Buttle, J., Laudon, H., McDonnell. J., McGuire, K., Caissie, D., Shanley, J., Kennedy, M., Devito, K., and Pomeroy J.W. 2010. Inter-comparison of hydro-climatic regimes across northern catchments: synchronicity, resistance and resilience. *Hydrological Processes,* 24: 3591–3602.

Creed, I. F., and Band. L.E. 1998. Exploring functional similarity in the export of Nitrate-N from forested catchments: a mechanistic modelling approach. *Water Resources Research,* 34: 3079–3093.

Croke, J. C. and Hairsine, P. B. 2006. Sediment delivery in managed forests: a review. *Environmental Reviews*, 14: 59-87.

Croke, J., Mockler, S. et al. 2005. Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity. *Geomorphology*, 68(3-4): 257-268.

De Roo, A. P. J., and Jetten, V. G. 1999. Calibrating and validating the LISEM model for two data sets from the Netherlands and South Africa. *Catena,* 37: 477– 493.

Detty J.M. and McGuire K,J. 2010. Topographic controls on shallow groundwater dynamics: implications of hydrologic connectivity between hillslopes and riparian zones in a till mantled catchment. *Hydrological Processes*, 24(16): 2222-2236.

Devito, K., Creek. I., Gan,T., Mendoza, C., Petrone, R., Silins, U., Smerdon, B. 2005. A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider? *Hydrological Processes*, 19: 1705-1714.

Etcheverry, D., Perrochet, P. 2000. Direct simulation of groundwater transit-time distributions using the reservoir theory. *Hydrogeology Journal*, 8(2): 200-208.

Fenicia, F., McDonnell, J. J. and Savenije, H.H.G. 2008. Learning from model improvement: On the contribution of complementary data to process understanding, *Water Resources Research*, 44: W06419, doi:10.1029/2007WR006386.

Fish, R.D., Ioris, A.A.R., Watson, N.M. 2010. Integrating water and agricultural management: collaborative governance for a complex policy problem. *Science of the Total Environment* 408: 5623-5630.

Freeman, M.C., Pringle, C.M., and Jackson, R.C. 2007. Hydraulic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. *Journal of the American Water Resources Association,* 43(1), 5-14.

Gomi, T., R.C. Sidle, S. Miyata, K. Kosugi, and Onda, Y. 2008. Dynamic runoff connectivity of overland flow on steep forested hillslopes: Scale effects and runoff transfer. *Water Resources Research,* 44: W08411.

Goulsbra, C.S., Lindsay, J.B. and Evans, M.G. 2009. A new approach to the application of electrical resistance sensors to measuring the onset of ephemeral streamflow in wetland environments. *Water Resources Research*, 45: W09501.

Grayson, R.B., A.W. Western, F.H.S. Chiew, and Blöschl, G. 1997. Preferred states in spatial soil moisture patterns: local and nonlocal controls. *Water Resources Research,* 33: 2897-2908.

Hairsine, P. B., Croke, J. C. Matthews, H. Fogarty, P. and Mockler, S. P. 2002. Modelling plumes of overland flow from roads and logging tracks. *Hydrological Processes,* 16: 2311–2327.

Hewlett, J.D. and Hibbert, A.R. 1967. Factors affecting the response of small watersheds to precipitation in humid areas. In W.E. Sopper and H.W. Lull (eds) *Forest Hydrology*, 345–360, Pergamon Press, New York.

Hooke, J. 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. *Geomorphology*, 56: 79-94.

Hopp, L. and McDonnell, J.J. 2009. Connectivity at the hillslope scale: Identifying interactions between storm size, bedrock permeability, slope angle and soil depth. *Journal of Hydrology*, 376: 378-391.

Hwang, T., Band, L.E., Vose, J.M. and Tague, C. 2012. Ecosystem processes at the watershed scale: Hydrologic vegetation gradient as an indicator for lateral hydrologic connectivity of headwater catchments. Water Resources Research: 48, Article Number: W06514.

James, A.L., and Roulet, N.T. 2007. Investigating hydrologic connectivity and its association with threshold change in runoff response in a temperate forested watershed. *Hydrological Processes* 21: 3391–3408.

Jencso, K. G., and B. L. McGlynn. 2011. Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. Water Resources Research, 47: Article Number: W11527 DOI: 10.1029/2011WR010666.

Jencso, K. G., McGlynn, B. L. et al. 2009. Hydrologic connectivity between landscapes and streams: Transferring reach-and plot-scale understanding to the catchment scale. *Water Resources Research* 45.

Jencso, K.G., McGlynn, B.L. et al. 2010. Hillslope hydrologic connectivity controls riparian groundwater turnover: Implications of catchment structure for riparian buffering and stream water sources. *Water Resources Research,* 46.

Johnes, P.J., and Heathwaite, A. L. 1997. Modelling the impact on water quality of land use change in agricultural catchments. *Hydrological Processes,* 11: 269– 286.

Kidron, G.J. 2011. Runoff generation and sediment yield on homogeneous dune slopes: scale effect and implications for analysis. *Earth Surface Landforms and Processes*, 36(13): 1809-1824.

Kirchner JW, Tetzlaff D, Soulsby C. 2010. Comparing chloride and water isotopes as hydrological tracers in two Scottish catchments. *Hydrological Processes*, 24: 1631–1645.

Kirkby, M.J., Bracken, L., and Reaney, S. 2002. The influence of landuse, soils and topography on the delivery of hillslope runoff to channels in SE Spain. *Earth Surface Landforms and Processes*, 27: 1459-1473.

Knudby, C. and Carrera, J. 2005. On the relationship between indicators of geostatistical, flow and transport connectivity. *Advances in Water Resources,* 28(4): 405-421.

Lane, P. N. J., Hairsine, P.B. et al. 2006. Quantifying diffuse pathways for overland flow between the roads and streams of the Mountain Ash forests of central Victoria Australia. *Hydrological Processes*, 20(9): 1875-1884.

Lane S.N., et al 2004. A network-index based version of TOPMODEL for use with high-resolution digital topographic data. *Hydrological Processes*, 18: 191-201.

Lane, S.N., Reaney, S.M. et al. 2009. Representation of landscape hydrological connectivity using a topographically driven surface flow index. *Water Resources Research*, 45.

Larsen, L.G., Choi, J., Nungesser, M.K and Harvey, J.W. (accepted). Directional Connectivity in Hydrology and Ecology. *Ecological Applications.*

Lesschen, J.P., Schoorl, J.M. et al. 2009. Modelling runoff and erosion for a semi-arid catchment using a multi-scale approach based on hydrological connectivity. *Geomorphology,* 109(3-4): 174-183.

Lexartza-Artza I. and Wainwright, J. 2009. Hydrological connectivity: Linking concepts with practical implications. *Catena*, 79: 146-152.

Lexartza-Artza I. and Wainwright, J. 2011. Making connections: changing sediment sources and sinks in an upland catchment. *Earth Surface Processes and Landforms***,** 36**(**8): 1090-1104**.**

Ludwig, J.A., Wiens, J., Tongway, D.J. 2000. A scaling rule for landscape patches and how it applies to conserving soil resources in savannas. *Ecosystems,* **3**: 82-97.

Ludwig, J.A., Wilcox, B.P., Breshears, D.D., Tongway D.J., and Imeson, A.C. 2005. Vegetation patches and runoff–erosion as interacting ecohydrological processes in semiarid landscapes. *Ecology* 86: 288–297.

Maloszewski, P. and Zuber, A., 1993. Principles and practice of calibration and validation of mathematical models for the interpretation of environmental tracer data. *Advances in Water Resources*, 16: 173-190.

McNamara, J.P., Tetzlaff, D., Bishop, K., Soulsby, C., Seyfried, M., Peters, N., Hooper, R. 2011. Storage as a metric of catchment comparison. *Hydrological Processes,* 25: 3364-3371.

McDonnell, J.J., Sivapalan, M., Vaché, K., Dunn, S., Grant, G., Haggarty, R., Hinz, C., Hooper, R., Kirchner, J., Roderick, M.L., Selker, J., Weiler, M. 2007. Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology. *Water Resources Research,* 43: W07301.

McDonnell, J.J., McGuire, K., Aggarwal, P., Beven, K., Biondi, D., Destouni ,G., Dunn, S., James, A., Kirchner, J., Kraft, P., Lyon, S., Malowszewski ,P., Newman, L., Pfister, L., Rinaldo, A., Rodhe, A., Sayama, T., Seibert, J., Soloman, K., Soulsby, C., Stewart, M., Tetzlaff, D., Tobin, C., Troch, P., Weiler, M., Western, A., Wormann, A., Wrede, S. 2010. How old is the water? Open questions in catchment transit time conceptualisation, modelling and analysis. *Hydrological Processes,* 24: 1745–1754.

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

McGlynn, B.L. and Seibert, J. 2003. Distributed assessment of contributing area and riparian buffering along stream networks. *Water Resources Research*, 39(4).

McGlynn, B.,J. McDonnell, et al. 2003. On the relationships between catchment scale and streamwater mean residence time. *Hydrological Processes,* 17(1): 175-181.

McGuire, K.J. and McDonnell, J.J., 2006. A review and evaluation of catchment transit time modeling. *Journal of Hydrology*, 330(3-4): 543-563.

McGuire, K.J. and McDonnell, J.J. 2007. Hydrological connectivity of hillslopes and streams: Characteristic time scales and nonlinearities. *Water Resources Research,* 46.

Meerkerk, A.L., van Wesemael, B. and Bellin, N. 2009. Application of connectivity theory to model the impact of terrace failure on runoff in semi-arid catchments**.** *Hydrological Process,* 23: 2792–2803.

Miller, G.R., Cable, J.M., McDonald, A.K., Bond, B., Franz, T.E., Wang, L., Gou, S., Tyler, A.P., Zou, C.B. and Scott, R.L. 2012. Understanding ecohydrological connectivity in savannas: a system dynamics modelling approach. *Ecohydrology,* 5: 200-220

Munafo, M., G. Cecchi, F. Baiocco, and L. Mancini. 2005. River pollution from non-point sources: A new simplified method of assessment. *Journal of Environmental Management*, *77:* 93– 98.

Mueller, E. N., Wainwright, J. and Parsons, A. 2007. Impact of connectivity on the modelling of overland flow within semiarid shrubland environments, Water Resources Research, 43, W09412, doi:10.1029/2006WR005006.

Ocampo, C.J., Sivapalan, M. et al. 2006. Hydrological connectivity of upland-riparian zones in agricultural catchments: Implications for runoff generation and nitrate transport. *Journal of Hydrology*, 331(3-4): 643-658.

Parsons, A.J., Brazier, R.E., Wainwright, J. and Powell, D.M. 2006. Scale relationships in hillslope runoff and erosion. *Earth Surface Processes and Landforms,* 31: 1384–1393.

Parsons, A.J., Wainwright, J., Abrahams, A.D. and Simanton, J.R. 1997. Distributed dynamic modelling of interrill overland flow. *Hydrological Processes*, 11: 1833-1859.

Poesen, J. 1984. The influence of slope gradient on infiltration rate and Hortonian overland flow volume. *Zeitschrift für Geomoprhologie Supplement Band,* 49: 117-131.

Pringle, C. 2003. What is hydrologic connectivity and why is it ecologically important? *Hydrological Processes*, 17(13): 2685-2689.

Puigdefabregas, J., del Barrio, G., Boer, M.M., Gutiérrez, L., and Solé, A. 1998. Differential responses of hillslope and channel elements to rainfall events in a semi-arid area. *Geomorphology*, 23: 337-351

Reaney, S.M., Bracken, L.J., and Kirkby, M.J. 2007. Use of the Connectivity of Runoff Model (CRUM) to investigate the influence of storm characteristics on runoff generation and connectivity in semi-arid areas. *Hydrological Processes***,** 21(7): 894-906**.**

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 Surface Processes and Landforms*, 33: 317-327**.**

Richards, K. 1990. Editorial. 'Real' geomorphology. *Earth Surface Processes and Landforms*, 15: 195–197.

Richards, K. 1994. ‘Real’ geomorphology revisited. *Earth Surface Processes and Landforms*, 19: 277–281.

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.

Seibert, J., A.Rodhe, K.Bishop. 2003. Simulating interactions between saturated and unsaturated storage in a conceptual runoff model, Hydrological Processes, 17: 379-390.

Sen S., Srivastava P., Jacob, D.H. et al. 2010. Spatial-temporal variability and hydrologic connectivity of runoff generation areas in a North Alabama pasture-implications for phosphorus transport. Hydrological Processes, 24: 342-356.

Soulsby, C., Rodgers, P., Smart, R., Dawson, J. and Dunn, S.M. 2003. A tracer-based assessment of hydrological pathways at different spatial scales in a mesoscale watershed in NE Scotland. *Hydrological Processes*. 17: 759-777.

Soulsby, C., Rogers, P, Petry, J., Hannah, D. Dunn, S.M. and Malcolm, I.A. 2004. Using tracers to upscale flow path understanding in mesoscale mountainous catchments: two examples from Scotland. *Journal of Hydrology*, 291: 172-294.

Soulsby C, Tetzlaff D, Rodgers P, Dunn S, Waldron A. 2006. Runoff processes, stream water residence times and controlling landscape characteristics in a mesoscale catchment: an initial evaluation. *Journal of Hydrology*, 325: 197–221.

Soulsby C, Piegat KG, Seibert J, Tetzlaff D. 2011. Catchment-scale estimates of flow path partitioning and water storage based on transit time and runoff modelling. *Hydrological Processes,* 25: 3960-3976.

Spence, C. 2006. Hydrological processes and streamflow in a lake dominated watercourse, Hydrological Processes, 20: 3665-3681.

Spence, C. 2007. On the relation between dynamic storage and runoff: A discussion on thresholds, efficiency, and function. *Water Resources Research*, 43: W12416, doi:10.1029/2006WR005645.

Spence, C. and Hosler, J. 2007: Representation of stores along drainage networks in heterogeneous landscapes for runoff modelling. *Journal of Hydrology*, 347: 474–486, doi:10.1016/j.jhydrol.2007.09.035.

Spence, C. and M. K. Woo 2003. Hydrology of Subarctic Canadian Shield: Soil-Filled Valleys. *Journal of Hydrology,* 279: 151-166.

Smith, M.W., Bracken, L.J. and Cox, N.J. 2010. Toward a dynamic representation of hydrological connectivity at the hillslope scale in semiarid areas. *Water Resources Research*, 46: W12540.

Smith, M.W., Cox, N.J. and Bracken, L.J. 2011. Terrestrial laser scanning soil surfaces: a field methodology to examine soil surface roughness and overland flow hydraulics. *Hydrological Processes* 25: 842-860.

Stieglitz, M., Shaman, J., McNamara, J., Engel, V., Shanley, J., Kling, G,W. 2003. An approach to understanding hydrologic connectivity on the hillslope and the implications for nutrient transport. *Global Biogeochemical Cycles*, 17(4): Article Number: 1105, DOI: 10.1029/2003GB002041. Tague, C.L., Band, L.E. 2001. Evaluating explicit and implicit routing for watershed hydro-ecological models of forest hydrology at the small catchment scale . *Hydrological Processes*, 15, 8, 1415-1439.

Tetzlaff D, et al 2007a. Connectivity between landscapes and riverscapes – a unifying theme in integrating hydrology and ecology in catchment science? *Hydrological Processes*, 21: 1385-1389.

Tetzlaff, D., Soulsby, C., Waldron, S., Malcolm, I.A., Bacon, P.J., Dunn S.M., Lilly. A. 2007b. Conceptualisation of runoff processes using GIS and tracers in a nested mesoscale catchment. *Hydrological Processes* 21: 1289-1307.

Tetzlaff, D., Seibert, J, McGuire, K.J., Laudon, H., Burn, D.A., Dunn, S.M. and Soulsby, C. 2009. How does landscape structure influence catchment transit time across different geomorphic provinces? *Hydrological Processes* 23: 945–953.

Tetzlaff, D., McNamara, J.P., Carey S.K. 2011. Measurements and modelling of storage dynamics across scales. *Hydrological Processes.* 25: 3831-3835.

Troch, P. A., G. A. Carrillo, I. Heidbüchel, S. Rajagopal, M. Switanek, T. H. M. Volkmann, and M. Yaegar. 2009. Dealing with landscape heterogeneity in watershed hydrology: A review of recent progress toward new hydrological theory. *Geography Compass*, 3: 375–392, oi:10.1111/j.1749-8198.2008.00186.x.

Tromp van Meerveld, I. and McDonnell J.J. 2005. Comment to 'Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes'. *Journal of Hydrology,* 303: 307-312.

Tromp-Van Meerveld, H.J. and McDonnell J.J. 2006. Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. *Water Resources Research* 42 (2): W02411.

Turnbull L., J. Wainwright and R.E. Brazier. 2008. A conceptual framework for understanding semi-arid land degradation: ecohydrological interactions across multiple-space and time scales. *Ecohydrology* 1: 23-34.

Van Oost, K., Govers, G. and Desmet, P. 2000. Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. *Landscape Ecology,* 15: 577-589.

Vidon, P. G. F. and A. R. Hill. 2004. Landscape controls on nitrate removal in stream riparian zones, *Water Resources Research,* 40: W03201.

Wainwright J and Parsons AJ. 2002. The effect of temporal variations in rainfall on scale dependency in runoff coefficients. *Water Resources Research,* 38(12): 1271-1282.

Wainwright, J. And Bracken, L.J. 2011. Runoff generation, overland flow and erosion on hillslopes. In Thomas DSG (ed.) *Arid Zone Geomorphology, 3rd ed.*, John Wiley and Sons, Chichester.

Wainwright, J., Parsons, A.J., Schlesinger, W.H., Abrahams, A.D. 2002. Hydrology-vegetation interactions in areas of discontinuous flow on a semi-arid Bajada, Southern New Mexico. *Journal of Arid Environments*, 51(3): 319-338.

Wainwright, J., Turnbull, L., Ibrahim, T.G., Lexartza-Artza, I., Thornton, S.F., Brazier, R. 2011. Linking environmental regimes, space and time: Interpretations of structural and functional connectivity. *Geomorphology* 126: 387-404.

Wang, L., Zou, C., O'Donnell, F., Good, S., Franz, T., Miller, G.R., Caylor, K.K., Cable, J.M. and Bond, B 2012. Characterizing ecohydrological and biogeochemical connectivity across multiple scales: a new conceptual framework. *Ecohydrology,* 5:221-233.

Wemple, B.C., Jones, J.A., Grant, G.E. 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. *Water Resources Research,* 32, 6, 1195-1207.

Western, A.W., Blöschl, G., Grayson, R.B. 2001. Toward capturing hydrologically significant connectivity in spatial patterns. *Water Resources Research,* 37 (1): 83-97

Western, A.W., et al 2005. Reply to comment on Tromp van Meerveld and McDonnell on 'Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes'. *Journal of Hydrology,* 303: 313-315.

Western, A.W., Grayson, R.B. Blöschl, G., Willgoose, G.R., and McMahon, T.A. 1999. Observed spatial organisation of soil moisture and its relation to terrain indices, *Water Resources Research*, 35: 797–810.

Western, A.W., G. Bloschl, et al. 1998. How well do indicator variograms capture the spatial connectivity of soil moisture? *Hydrological Processes,* 12(12): 1851-1868.

Western, A. W., S.L. Zhou, et al. 2004. Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes. *Journal of Hydrology,* 286(1-4): 113-134.

Western, A.W., and R.B. Grayson. 1998. The Tarrawarra data set: soil moisture patterns, soil characteristics and hydrological flux measurements. *Water Resources Research* 34: 2765-2768.

Yair, A. and A. Kossovsky. 2002. Climate and surface properties: hydrological response of small arid and semi-arid watersheds. *Geomorphology*, 42*:* 43–57.

Yair, A. and N. Raz-Yassif. 2004. Hydrological processes in a small arid catchment: scale effects of rainfall and slope length. *Geomorphology*, 61: 155–169.

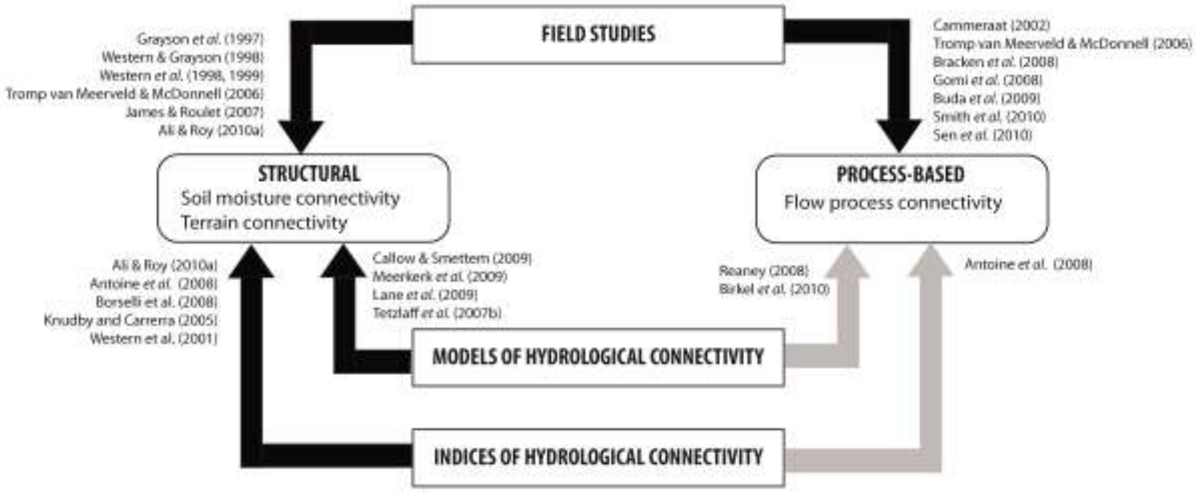


Figure 1: Relationships between approaches investigating hydrological connectivity

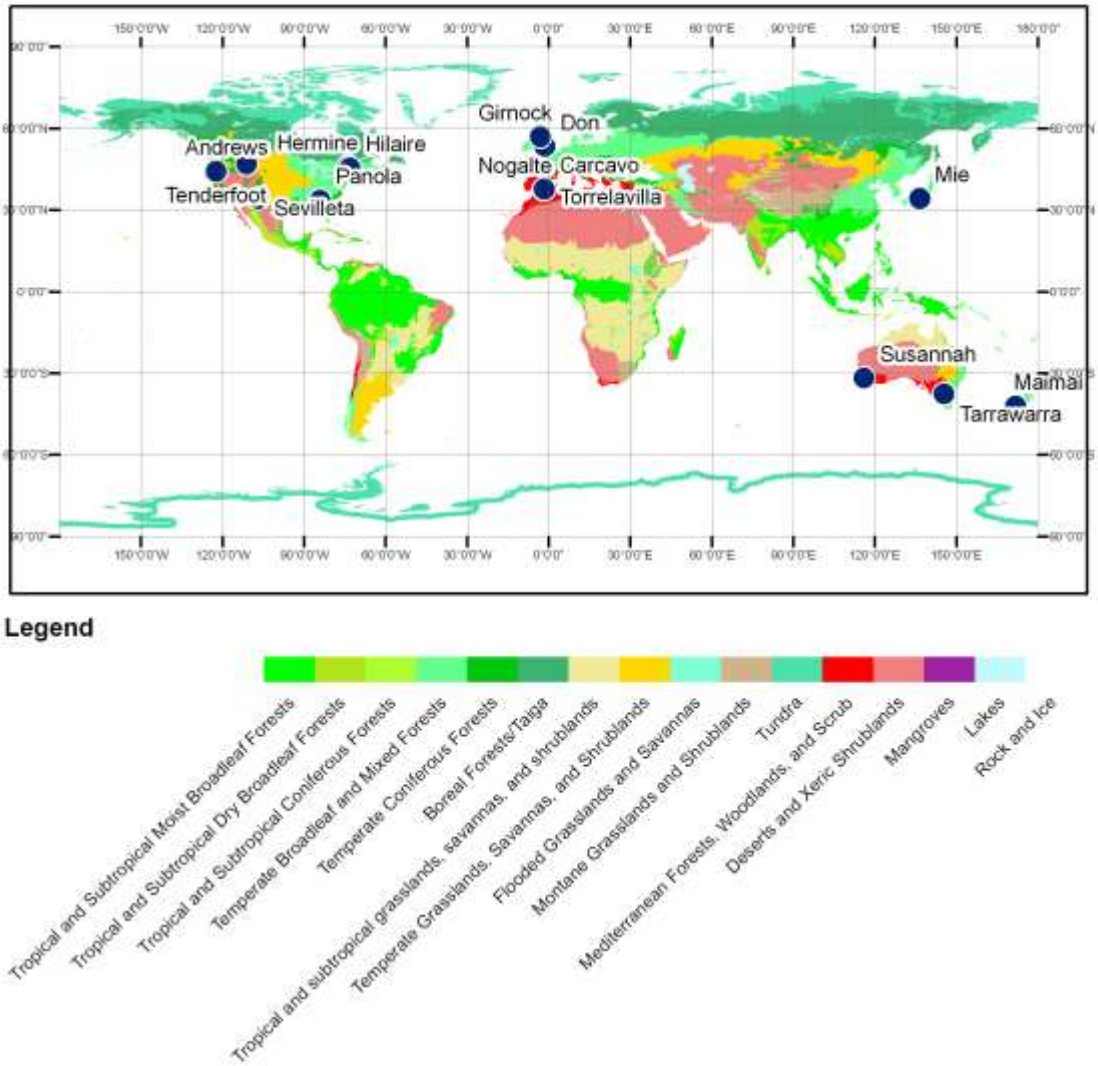
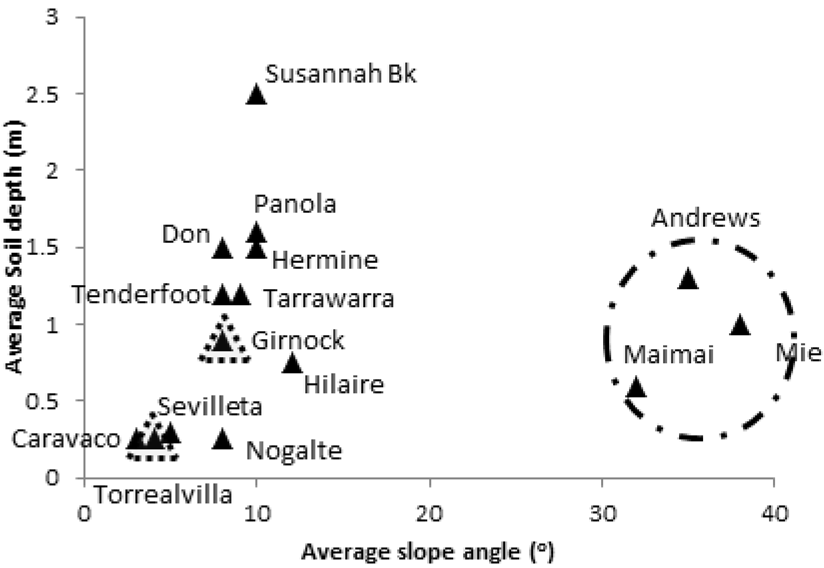


Figure 2: Location of sites used to investigate hydrological connectivity.

A



B

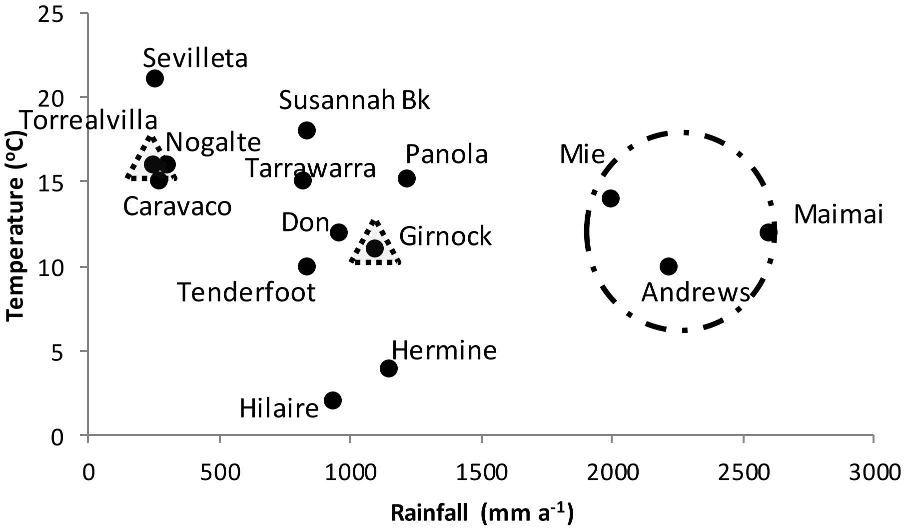


Figure 3: Characteristics of sites used to explore hydrological connectivity. A) Morphology and B) hydro-meteorological conditions. The dotted circle highlights the very steep forested catchments of Maimai, Mie and HJ Andrews. The dark triangle denotes the two existing process based studies.

Water cycle – Watershed scale

1. 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)

Landscape Features – Watershed scale

2. 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)
3. Flows of matter and energy (water, nutrients, sediments, heat, etc.) between different landscape components (Tetzlaff *et al.*, 2007a)
4. 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)

Landscape Features – Hillslope scale

5. Physical linkage of sediment through the channel system, which is the transfer of sediment from one zone or location to another and the potential for a specific particle to move through the system (Hooke, 2003)
6. 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)
7. 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)

Spatial Patterns – Watershed and hillslope scale

8. 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)
9. Spatially connected features which concentrate flow and reduce travel times (Knudby and Carrera, 2005)

Flow Processes – Hillslope scale

10. The condition by which disparate regions on a hillslope are linked via lateral subsurface water flow (Hornberger *et al.*, 1994; Creed and Band, 1998)
11. Connection, via the subsurface flow system, between the riparian (near stream) zone and the upland zone (also known as the 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)

Table 1: Definitions of hydrological connectivity from Ali and Roy (2009).

Table 2: Study Site Details

Site	Coordinates	Area (km^2)	Elevation (m)	Relief (m)	Av slope (°)	Land use	Geology	Soil depth (m)	Rainfall (mm a^{-1})	Temp (°C)
HJ Andrews, USA	44°02'N 122°25'W	0.102	576	207	30-45	Forest	Tuffs and breccias	1.3 Clay loam	2220	(1 Jan – 18 July)
Don, England (Ingbirchworth	53°33'N 01°40'W	9	280			Agriculture	Carboniferous coal measures	Sandstones and clays	960	12 (2 Jan – 22 July)
Girnock Burn, Scotland	57° 02'N 03° 06'W	31	400	632	6-11	Heather moorland and grazing	Granite, schist and metamorphic	Glacial drift, gleys and peat, 0.3-0.8	1100	11 (0 Jan – 16 July)
Guadelentin, Spain – Nogalte	37° 61'N 01°95'W	171	800	755	8 (2-35)	Bare, mattoral, tree crops	Schists	0.10-0.5	300	16.4 (9 Jan – 36 July)
Guadelentin, Spain –Torrelavilla	37°40'N 01° 41'W	200	370	200	3	Bare, shrubs, tree crops	Marls	0.10-0.5	300	16.4 (9 Jan – 36 July)
Guadelentin, Spain –Carcavo	37°40'N 01° 41'W	4.74	380	150	3	Bare, mattoral, tree crops	Marls	0.10-0.5	300	16.4 (9 Jan – 36 July)
Hermine, Canada	45°59'N 74°01'W	0.051	400	31		Forest	Podsols over glacial till	1-2 podzols	1150 (30% as snow)	3.93 (-13.6 Jan – 18.9 July
Maimai, New Zealand	42°09'S 171°45'E	0.03-2.80	306	150	32	Forest	Pleistocene conglomerate	0.6 Silt loams	2600	(22 Jan 0 2 July)
Mie, Japan	34°21'N 136°25'E	0.05	180	160	35-45	Forest		0.6-1.8 Brown forest	2000	14
Mont St Hilaire, Canada	45°32'N 73°10'W	0.07-1.47	250			Woodland		0-1.5	940 (22% as snow)	(-10.3 Jan – 20.8 July)
Panola, USA	84°10'W 33°37'N	0.41	200	56	10	Forest	Granite	1.6 ultisols	1220 (<1% as snow)	15.2 (5.5 Jan – 25.2 July)
Sevilleta, USA	34° 19'N 106° 42'W					Grassland and creosote bush			256	21 (8 Jan – 33 July)
Susannah Brook, Australia	31°50'S 116°8'E	12.3	291	118		Native pasture and grazing	Granite	2-3.3 Sandy gravel/ kaolinitic clays	841	13-23 (17-30 Jan – 9-18 July)
Tarrawarra, Australia	37°39'S 145°26'E	0.105		30	9	Improved pasture	Lower Devonian siltstone	0.9-1.4 Clay loam over loam	820	(18 Jan – 7 July)
Tenderfoot Creek, USA	46°55'N 110°53'W	22.8	2169		8	Forest	Flathead sandstone, Wolsey shale	0.5–2.0 Loams and clays	840 (75% as snow)	(-6.0 Jan – 20.1 July)

Table 3: Groups researching hydrological connectivity

Grouping	Authors	Catchment (see Table 3 for more details)	Methods	Key findings	Classification and Approach
Australia					
Melbourne/Canberra/ CSIRO	Hairsine P Croke J Takken I Lane P	Upper Tyers Cuttagee Creek	Runoff plots Volume to breakthrough experiments.	Established roads and tracks as key components of hydrological connectivity. Determined hillslope lengths required to infiltrate road discharge in variety of catchments.	Terrain connectivity Structural
Melbourne	Western AW Grayson RB	Tarrawarra	High resolution spatial patterns of soil moisture; moisture profiles; remotely sensed images (airborne- and satellite); weather station; hillslope runoff plots.	Spatial soil moisture useful to understand HC and runoff thresholds. Distribution and controls on soil moisture fluxes changed dynamically between seasons. Connectivity functions are able to distinguish between connected and disconnected patterns.	Soil moisture connectivity Structural
Brisbane/Western Australia	Callow KN Smettem KRJ	Upper Kent River, Western Australia	Topographic data and modelling.	Hydrologic descriptors of runoff indicate that hillslope processes are significantly altered by farm dams and banks.	Terrain connectivity Structural
Western Australia/Illinnois	Ocampo CJ Sivapalan	Susannah Brook	Two transects of six shallow-partially penetrating wells, across riparian, mid-slope, and upland zones.	Riparian zones control the catchment storm response while upland zones can be considered as storage units, controlling the base flow component of streamflow Associated with the establishment of connectivity is a sharp increase in the hydraulic gradient that drives shallow subsurface flow to the stream.	Flow –process connectivity Structural/ Process based eler
Belgium					
Louvain	Meerkerk AL Van Wesemael B Bellin N	Carcavo, Murcia, Spain	Topographic analysis.	Removal and/or degradation of agricultural terraces and dams can significantly increase hydrological connectivity and hence influence runoff and flood generation.	Terrain connectivity Structural
Louvain	Antoine, M	Virtual	Modelling, quantitative analysis.	Proposed a functional connectivity indicator by adapting the 'volume to breakthrough' concept: the degree of surface connection as a function of the surface storage filling. This indicator was capable of discriminating between micro-topographical types.	Flow –process connectivity Structural/ Process based eler
Canada					
Montreal	Roy A Ali G	Hermine	Soil moisture analysis; tracers; hydrograph analysis; shallow water table measurements, metrics,' lots of points' approach; soil water wells; subsurface topography.	No convergence on processes from different approaches. Humid temperate systems do not comply with the traditional single threshold-driven theory of catchment connectivity.	Soil moisture connectivity Structural/ Process based eler
	James AI Roulet N	St-Hilaire	Soil moisture analysis; tracers; metrics; 'lots of points'.	Non-linear response in runoff response over small changes in soil moisture. Spatial patterns in soil moisture not always good predictor of connectivity that leads to threshold change in runoff generation. Spatial organization of shallow soil moisture did not exhibit strong seasonality in a humid temperate watershed despite seasonal changes in the total catchment wetness.	Soil moisture connectivity Structural/ Process based eler
Japan					
Tokyo	Gomi T	Mie	Saturated areas, soil characteristics, surface topography, runoff plots.	Hydrologic connectivity of runoff generation areas depends on rainfall intensity and soil conditions on a hillslope.	Soil moisture connectivity Structural/ Process based eler

Netherlands					
Amsterdam	Camaraat E	SE Spain - Torealvilla	Field measurement; runoff troughs, crest stage gauges, mapping.	Hydrologic connectivity is an important factor in runoff-contributing and -absorbing areas from the microplot to the catchment scales.	Flow –process connectivity Process based
Waginingen	Lesschen JP	Carcavo, Spain	Terrain analysis, modelling.	Spatial distribution of vegetation patches and agricultural terraces largely determined hydrological connectivity at the catchment scale.	Terrain connectivity Structural
Waginingen	Appels WM	Virtual	Modelling of functional connectivity.	Connectivity behaviour determined by large depressions and organisation of micro-topography. Topographic effects suppress effect of spatial variation in infiltration capacity.	Modelling connectivity Process based
United Kingdom					
Durham/Leeds	Bracken LJ Kirkby MJ Smith M Reaney S	Guadelentin	Micro topography, overland flow, rainfall and runoff simulation, modelling, virtual experiments, GIS analysis (geol, luse, slope), flow peak data	Rainfall-runoff analysis emphasizes the influence of antecedent moisture and temporal storm structure on hillslope-scale flood generation. Patterns of infiltration and resistance across entire flow paths and their variability throughout a storm event are the key to understanding dynamic hydrological connectivity at the hillslope scale.	Flow –process connectivity Structural/ Process based eler
Durham/ Lancaster	Lane SN Reaney S Heathwaite L	Upper Rye	Modelling; terrain analysis; GIS analysis of land use, modelling, biological data	Network Index – ratio of effective contributing area to tangent of local slope.	Modelling connectivity Structural/ Process based eler
Sheffield	Wainwright J Turnbull L Lexa Arta I	New Mexico and River Don	Soil moisture; hydrograph analysis; lots of points; nesting of measurements; vegetation structure; soil characteristics; overland flow measurements; modelling.	A refinement which distinguishes structural connectivity from functional connectivity can be used to explain patterns observed in very different environmental systems. Even in cases where connectivity cannot be directly quantified (at least at present), this limitation does not prevent the concept from being a useful heuristic device for exploring responses of complex systems. The relation between catchment changes and climatic inputs has subsequent effect on catchment conditions, transfer networks and hence connectivity.	Flow process and modelling co Structural/ Process based eler
Aberdeen	Tetzlaff D Soulsby C Birkel C	Scottish Highlands: Girnock catchment and Bruntland Burn subcatchment	GIS modelling; hydrological (tracer-aided) modelling; extensive mapping of saturation areas and their dynamics	Dominant fast near-surface runoff generation processes are directly related to the dynamic expansion and contraction of riparian saturation zones. Geographic source and time-domain tracers support this, but also show a much more complex behaviour in terms of water and solute mixing indicating that the saturation area functions as a distinct storage.	Soil moisture and flow process Process based connectivity
United States of America					
Auburn University	Sen S	Sand Mountains	surface runoff and subsurface sensors at 31 points, rain gauge, and a 0.3-m HS-flume, *in situ* hydraulic conductivity	Runoff at the outlet was mainly observed when runoff-contributing areas at the downslope section of the hillslope showed runoff generation and were connected to areas in the middle section of the hillslope.	Flow process connectivity. Structural/ Process based eler
Montana	McGlynn B Jencso K Nippgen F Pacific V	Tenderfoot Creek	Surface topography; soil water wells; vegetation characteristics; surface-subsurface interactions.	The size and spatial arrangement of hillslope and riparian zones along a stream network and the timing and duration of groundwater connectivity between them is a first-order control on the magnitude and timing of water and solutes observed at the catchment outlet.	Flow process connectivity. Structural/ Process based eler
Oregon/ Simon Fraser (Canada)	McDonnell J Tromp van	Panola	Sub-surface topography; soil water wells; outflow	Fill and spill hypothesis: soil depth and bedrock topography determine HC and	Soil moisture connectivity.

	Meerveld I		monitoring.	active flow. Patterns of transient water table on the slope are related to thresholds in rainfall amounts necessary to initiate lateral sub-surface flow at the hillslope scale.	Structural/ Process based eler
Virginia/Oregon	McGuire KJ McDonnell J Detty JM	Andrews Hubbard Brook	Groundwater wells and stream stage recorders; electronic soil moisture sensors installed at depth.	Hysteretic effects dominate hillslope-stream connectivity. Threshold response exists between precipitation and stormflow. Transit times in the soil vary only with depth vertically in the profile. Transit times for flow at hillslope and at the catchment outlet were on the order of 1–2 years. Hydrologic connectivity between riparian and hillslope areas displayed a strong seasonal signature reflecting the effects of climate and evapotranspiration on soil moisture storages and shallow groundwater development.	Soil moisture connectivity. Structural/ Process based eler
Montana/Oregon/ Stockholm	McGlynn B McDonnell J Seibert J	Maimai, NZ	Hydrometric and tracer data.	Analysis of landscape-scale organization and the distribution of dominant landscape features provide a structure for investigation of runoff production and solute transport, especially as catchment-scale increases from headwaters to the mesoscale.	Flow process connectivity. Structural/ Process based eler

Table 4: Indices of hydrological connectivity

Index	Description	Data requirements	Source
Integral connectivity scale lengths (ICSL)	The average distance over which wet locations are connected using :(1) Euclidean distances; (2) topographically-defined hydrologic distances.	Soil moisture data, topography.	Western *et al.* 2001
Subsurface ICSL	As above but for subsurface macro-topography. Considers both Euclidean and hydrologic distances.	Soil moisture at multiple depths, topography, subsurface topography.	Ali and Roy 2010a
Outlet ICSL	ICSL where connected saturated paths must reach catchment outlet. Both Euclidean and hydrologic distances using surface and subsurface marcotopography.	Soil moisture at multiple depths, topography, subsurface topography.	Ali and Roy 2010a
Variation of conductivity in a geological medium	(1) Exponent of relationship between effective conductivity and average of point values. (2) Ratio of effective conductivity to the geometric mean of point values.	Geologic structure on which to base the distribution of connectivity values.	Knudby and Carrerra 2005
Critical path conductivity	Ratio of the critical path conductivity (conductivity at which a connected path is found) to the geometric mean of conductivity values. Related to percolation theory.	Geologic structure on which to base the distribution of connectivity values.	Knudby and Carrerra 2005
Breakthrough-curve related approaches	(1) Ratio between mean and early arrival times of runoff. (2) Skewness of distribution of arrival times of runoff.	Solute travel times.	Knudby and Carrerra 2005
Integral scales	(1) Variogram; (2) Indicator variogram and (3) Bivariate entropy integral scales	Soil moisture data, topography.	Knudby and Carrerra 2005
Semivariogram-derived metrics	Range of (1) omni-directional; (2) north-south and (3) east-west experimental variograms	Soil moisture.	Ali and Roy 2010a
Index of connectivity	Potential connectivity from weighted topographic analysis	Topography.	Borselli *et al.* 2008
Field index of connectivity	The actual connectivity in an event between the different parts of a watershed. Evidence of erosion used as the basis for a scoring method.	Field maps, topography.	Borselli *et al.* 2008