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

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14 **Abstract**

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

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37 **Key words**

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

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43 **1 Introduction**

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

54

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

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71 Despite a series of published review articles (e.g. Bracken and Croke, 2007; Tetzlaff *et al.*, 2007;
72 Turnbull *et al.* 2008; Ali and Roy, 2009; Lexartza-Artza and Wainwright, 2009) there is no consensus
73 about how to define and measure hydrological connectivity. The research community has been
74 content to work with multiple, slightly different and nuanced meanings of the concept to enable the
75 colour and depth of the topic to be investigated as fully as possible (Ali and Roy, 2009). However,
76 certain definitions and interpretations of hydrological connectivity are starting to be more

77 commonly used and so it seems timely that these are evaluated to determine how this may shape
78 and direct future research investigations. The aims of this paper are therefore to: i) evaluate the
79 extent to which different concepts of hydrological connectivity have emerged from different
80 approaches to measure and predict flow in different environments; ii) discuss the extent to which
81 these different concepts are mutually compatible; and iii) assess what further research needs to be
82 carried out to contribute to a unified understanding of hydrological processes. In section 2 we
83 discuss the different definitions that have been used to interpret hydrological connectivity, we then
84 explore the different approaches that have been used to investigate connectivity (section 3) and
85 analyse the locations where research has been conducted (section 4). In section 5 we explore the
86 relationship between approach and definition before evaluating whether it is possible to develop a
87 unified definition (section 6). Section 7 and 8 present suggestions for future research and
88 conclusions. A different group of authors may have produced a different interpretation of research
89 around hydrological connectivity; we hope the ideas and thoughts presented become an agenda for
90 debate. In this paper we do not address sediment connectivity.

91

92 **2 Definitions**

93 In their 2009 paper, Ali and Roy present a synthesis of definitions (Table 1). Of these definitions we
94 feel that number 11, concerning hillslope-riparian-stream (HRS) hydrologic connectivity via the
95 subsurface flow system, seems to be coming to the fore as the most used interpretation of
96 hydrological connectivity (e.g. Jensco *et al.*, 2009; 2010; Detty and McGuire, 2010; Jensco and
97 McGlynn, 2011). This definition emerges from the approach to hydrological connectivity based on
98 assessing flow processes, in particular from research which proposes that the timing and duration of
99 groundwater connectivity between riparian zones and the stream network is the dominant control
100 on the magnitude and timing of observed catchment discharge (e.g. McGlynn and McDonnell 2003;
101 McGlynn and Seibert 2003; Jensco *et al.*, 2009; Detty and McGuire, 2010; Jensco and McGlynn,
102 2011). This research was conducted in locations with steep slopes that exhibit a seasonal runoff
103 response. We question however whether this is the most suitable definition for other geomorphic
104 regions. On one hand, this definition is process-based, but on the other it is more about a certain
105 type of connection which could be considered only part of the idea behind the concept of
106 hydrological connectivity, and hence only represents one particular process in certain landscape
107 settings: Hillslope-riparian-stream connectivity is best suited to humid temperate settings (Beven,
108 1997; Bracken and Croke, 2007). We do not think it is possible to develop a single, overarching and
109 agreed definition of hydrological connectivity that works across all environments, but we do wish to

110 highlight that there are different definitions that relate to different aspects of hydrological
111 connectivity.

112

113 **3 Approaches to understanding hydrological connectivity**

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

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

139

140 Research to date has been successful at describing the elements defining structural connectivity
141 (Kirkby *et al.*, 2002; Bull *et al.*, 2003; Lexartza-Artza and Wainwright, 2009); however, the elements
142 defining functional aspects of hydrological connectivity are more difficult to measure and quantify
143 (Bracken and Croke, 2007; Lexartza-Artza and Wainwright, 2009; Birkel *et al.*, 2010). This difficulty

144 may be due to the term 'functional' not being well defined. Some definitions of connectivity may be
145 popular because of their close association with an experimental methodology (see section 5).
146 Indeed, this association is how connectivity moved from being an abstract concept to a "hands on"
147 approach. It therefore follows that because the definition of functional connectivity lacks a practical
148 aspect in that it is not associated with key variables to measure, it has not been taken forward. In
149 contrast the term 'structural connectivity' is readily understandable (and measurable) and seems to
150 have a common understanding to reflect the different states of catchment response gleaned by
151 measuring/recording 'snapshots' of catchment characteristics and the existence (or not) of
152 connections/pathways.

153

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

166 What is meant by *process connectivity* and how can we develop sampling approaches to capture
167 process based understandings? Processes are the sequences of actions within a catchment that
168 result in changes in the form of an area (Ahnert, 1998). We propose the term *process connectivity* to
169 capture the evolutionary dynamics of how systems operate. Following the fundamental principles of
170 the philosophy of science, processes are observable and the dynamics of a system can be
171 characterised by measureable attributes and characteristics. However, recognition of processes is
172 arbitrary and subjective and depends on circumstance, such as; location, observer's goal, perception,
173 conceptualisation and methods used (Schumm, 1991). In hydrology and geomorphology we tend to
174 measure catchment characteristics and attributes which we then extrapolate, interpolate and
175 accumulate to infer process. For example, at Panola USA, there are 135 crest stage piezometers used
176 to measure the [piezometric head](#) of [groundwater](#) at a specific point and 29 continuous/recording wells
177 recording 15-minute observations of depth of water; it is one of the most densely instrumented sites

178 in which to conduct hydrological research (Tromp van Meerveld and McDonnell, 2006; McGuire and
179 McDonnell, 2007). By analysing the piezometer data from all wells the direction of flowing water in
180 the subsurface can be inferred, but is still not actually measuring process (see Richards, 1990;1994).
181 These snap-shots at many different points can also be analysed to determine spatial and temporal
182 change in fluxes of water, sediment and nutrients from which the processes responsible for
183 producing hydrological connectivity can once again be inferred. In this way approaches based on
184 soil-moisture and/or water-table data continue to demand interpretation of repeated snap-shots,
185 but they provide more and new types of information which are an improvement over solely
186 topography-based approaches. With purely structural approaches (e.g. terrain connectivity), we can
187 only infer *potential* runoff sources and infer *potential* hydrological connectivity.

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190 How we understand and interpret catchment processes may help us understand whether we should
191 develop indices of connectivity, how indices vary between environments and why. More
192 fundamentally we need to understand how different approaches and definitions of hydrological
193 connectivity can be linked, especially in different environments where processes will operate in
194 different ways to produce connected flow in catchments. Since it is impossible to observe processes
195 directly (Richards, 1990;1994) there is usually a conceptual model (which is rarely outlined) linking
196 patterns observed at different timescales to processes about which we strive to know more. It is
197 easy to think that more frequent observation is related to more closely measuring processes;
198 however, this is not the case. For instance it does not matter whether soil moisture is measured at
199 time intervals of 1 day, 15 minutes or 5 nanoseconds, it is still not a measure of process (Richards,
200 1990;1994). So how we can bring the different approaches and resulting definitions together
201 around measuring process differently to develop understanding of hydrological connectivity?

202

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

212 conceptualisation of the concept and approach taken to try to measure process as closely as
213 possible.

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215

216 **4 Does location matter?**

217

218 Table 2 presents characteristics of the study sites that have been dominant locations for research
219 around hydrological connectivity. Figure 2 illustrates site location and in which type of biome they
220 fall whilst Figure 3 demonstrates the characteristics of the study sites used to derive empirical data.
221 Concentration of empirical data collection in small, temperate, forested catchments with steep
222 slopes and relatively deep soils (Figure 3) has resulted in exciting developments using the ‘lots of
223 points’ approach to collect and analyse empirical field evidence to determine how different areas of
224 river catchments connect to produce runoff. These data have led to interesting insights, especially
225 the ‘fill and spill’ concept for how bedrock topography can control source areas of subsurface runoff
226 which then connect to produce flow at the catchment outlet (Tromp van Meerveld and McDonnell
227 2006).

228

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

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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

280 freely draining soils in the USA demonstrate different controls and suggest that soil depth and
281 bedrock topography direct the pattern of active flow generated during storm events (Tromp van
282 Meerveld and McDonnell, 2005;2006). At an intermediate point on the continuum between these
283 two environments, research conducted in temperate forest watersheds dominated by podsoles and
284 underlain by glacial till, suggested a non-linear response in runoff for small variations in antecedent
285 moisture, but did not observe a significant change in geostatistical hydrologic connectivity with
286 variations in antecedent conditions (James and Roulet, 2007).

287

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

301

302 Research into spatial patterns of soil moisture has resulted in exciting developments using the ‘lots
303 of points’ approach to collect and analyze empirical field evidence (Table 3). This research has led to
304 novel ways of thinking about hydrology, especially the ‘fill and spill’ concept (Tromp van Meerveld
305 and McDonnell, 2006). Despite suggestions that Panola may be an ‘outlier’ in terms of processes of
306 runoff production (McNamara *et al.* 2011) , similar runoff-production mechanisms have been found
307 in the Hermine catchment, Canada, but this time controlled by an impervious soil layer (Ali *et al.*,
308 2011). However, we wish to question the assumption that spatial patterns of soil moisture reflect
309 the hydrological connections being made in all catchments. This assumption may be appropriate for
310 some areas and environments –particularly regions where vertical flow is dominating due to more
311 freely draining soils (such as podsoles) with some kind of impervious layer in combination with a
312 strong seasonal pattern in precipitation input, but not for all.

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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 between 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

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

352

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

376

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

382 Smith *et al.*, (2010) maps more directly onto definition 2: ‘all the former and subsequent positions,
383 and times, associated with the movement of water or sediment passing through a point in the
384 landscape’ (Bracken and Croke, 2007). The approaches taken by Gomi *et al.*, (2008) and Ali *et al.*,
385 (2010b) also map onto definition 2, but also definition 3: ‘Flows of matter and energy (water,
386 nutrients, sediments, heat, etc.) between different landscape components’ (Tetzlaff *et al.*, 2007a).
387 Research by Tetzlaff *et al.* (2007b) and Sen *et al.* (2010) also maps on to definition 3. Finally the
388 approach to exploring flow processes used by McGlynn, McDonnell and Jensco directly relates to
389 definition 11: ‘Connection, via the subsurface flow system, between the riparian (near stream) zone
390 and the upland zone (also known as the hillslope) occurs when the water table at the upland-riparian
391 zone interface is above the confining layer’ (Vidon and Hill, 2004; Ocampo *et al.*, 2006). Thus,
392 research exploring flow-processes of hydrological connectivity bridges a range of definitions at a
393 range of scales and is not clearly linked to only one perspective of hydrological connectivity. There is
394 not such an explicit relationship between methodology and definition as with soil-moisture and
395 water-table based approaches.

396

397 *5.3 Terrain Connectivity*

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

412

413 More recently, research into terrain connectivity has tried to assess other components of system
414 coupling and landscape connectivity that control the flow of water. Callow and Smettem (2009)
415 proposed that hillslope water capture and diversion infrastructure (e.g. terraces, check dams and

416 canals) need to be included into simulation models, especially in dryland regions, since changes in
417 areas retaining water can make large differences to potential runoff pathways. Similarly, Meerkerk
418 *et al.* (2009) examined the effect of terrace removal and failure on hydrological connectivity and
419 peak discharge in an agricultural catchment. Connectivity was quantified using connectivity
420 functions, specifically a contributing area function, and related to storm characteristics, land use and
421 topography. Results demonstrated that a decrease in intact terraces can lead to a strong increase in
422 hydrological connectivity and catchment discharge.

423

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

438

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

447

448 As with soil-moisture approaches to investigating hydrological connectivity, terrain approaches also
449 have a direct link between approach and definition. Research falls into Ali and Roy's (2009) category

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

461

462 *5.4 Models of hydrological connectivity*

463 The earliest modelling attempts using the Soil Conservation Service Curve Number method (Beasley
464 *et al.*, 1980; Savard, 2000; Brocca *et al.*, 2009) did not address connectivity itself, but instead
465 estimated the continuity of runoff through statistical estimations of hillslope interactions. Simple
466 weighted delivery approaches of water and sediment subsequently developed as a function of slope
467 distance which led to the beginning of physical estimation of connectivity within modelling (Johnes
468 and Heathwaite, 1997; Munafo *et al.*, 2005). With the development of fully distributed, physically
469 based models, equations are solved for vertical and lateral water flows across the landscape (e.g. De
470 Roo and Jetten, 1999). At these larger scales, detailed information about topography, soil
471 characteristics, antecedent conditions and vegetation elements like density and type are lacking
472 (McGuire and McDonnell, 2007) with some models using resolutions of as much as 1 km² despite
473 typical control structures for connectivity in the landscape being less than 0.0025 km² (Blackwell *et al.*
474 *et al.*, 1999; Lane *et al.*, 2009; Meerkerk *et al.*, 2009; Callow and Smettem, 2009). Model accuracy is
475 further undermined by using physical models at greater spatial scales than they can adequately
476 represent, given the spatial difference at that resolution (Lane *et al.*, 2009), unless processes are
477 parameterized at the sub-grid-cell resolution (e.g. Muller *et al.*, 2007).

478

479 More recently, models have been developed using the concept of hydrological connectivity to
480 explore factors affecting the development of flow connections with changing topographic features
481 (e.g. Callow and Smettem, 2009; Meerkerk *et al.*, 2009). Whilst spatially distributed hydrological
482 models that allow lateral flow to shut off under certain conditions do already exist, few models have
483 been explicitly designed to enable hydrological connectivity to develop as an emergent property and

484 hence enable prediction or exploration of changes in connectivity as the catchment and climate
485 evolve. Lane *et al.* (2009) assessed the extent to which a topographically defined description of the
486 spatial arrangement of catchment wetness can be used to represent the hydrological connectivity in
487 temperate catchments. They found that a static descriptor based on topography can be successfully
488 used to generalize spatial variability in hydrological connectivity. Birkel *et al.* (2010) developed a
489 catchment scale, parsimonious rainfall-runoff model for upland catchments in Scotland using a
490 dynamic conceptualization of the hydrologic characteristics of the saturation zones in the
491 catchment. Their function representing the dynamic expansion and contraction of saturation zones
492 is an integrated measure of hydrological connectivity. Again, they showed that this dynamic process-
493 representation improved model performance. Lesschen *et al.* (2009) used the LAPSUS model to
494 simulate runoff and sediment dynamics at the catchment scale in SE Spain; the spatial distribution of
495 vegetation patches and agricultural terraces were found to determine hydrological connectivity at
496 the catchment scale.

497

498 Lane *et al.* (2004;2009) propose that modelling can be used to represent temporal variation in
499 connectivity presuming the limits of modelling are recognised and understood. We propose that to
500 do this well, modelling should enable hydrological connectivity to emerge due to the operation of
501 process laws, rather than be defined as a concept that is put into the model in the first place. Lane *et*
502 *al.* (2004;2009) proposed that the strength of their modelling approach is through topographic
503 estimation because this is the easiest parameter to be measured at any resolution and used the
504 Topographic Wetness Index (TWI) in order to characterise connectivity. TWI is a function of
505 contributing area and slope creating a cumulative index deriving a topographically based method of
506 estimating areas of high soil moisture (Beven and Kirkby, 1979). The Network Index identifies the
507 lowest value for the flow paths across the catchment using the theory that the lowest value
508 determines the potential for connectivity. This representation of the likelihood of physical
509 connection indicates not only a probability of structural connection but also the probability that flow
510 paths with lower potential to connect are likely to be less frequent and for a shorter period of time
511 (Lane *et al.*, 2009). However, the modelling approach of Lane *et al.* (2004) does not allow the
512 hydrological connections to emerge during the course of a model run since it is founded on static
513 catchment characteristics, namely topography. In contrast, the agent-based modelling undertaken
514 by Reaney (2008) enables the agents to trace the path taken by water through the catchment and is
515 hence capable of giving a novel picture of the temporal and spatial dynamics of flow generation and
516 transmission during a storm event. In this way hydrological connections emerge during the model
517 run.

518

519 We note that the topographic wetness index (as originally defined in TOPMODEL: Beven and Kirkby,
520 1979) is widely used to represent areas susceptible to accumulate soil moisture and hence identify
521 potential flowpaths. However, this approach ignores the importance of transient saturation and so is
522 only relevant to systems in which it is not important. The topographic wetness index approach also
523 presumes that there are no other forms of driver on soil-moisture creation and connectivity other
524 than topographic forcing, which has been identified as an unsatisfactory approach to understanding
525 hydrological connectivity in all environments (Bracken and Croke, 2007). For example, generation of
526 connected flow may not always follow the network of topographic lows, and 'fill and spill' may be
527 dominated by either hummocky surface topography, bedrock or an impermeable confining layer
528 (Spence, 2006; Tromp van Meerveld and McDonnell, 2006; Ali *et al.*, 2011).

529

530 Research based on modelling hydrological connectivity maps onto Ali and Roy's (2009) category of
531 landscape features at the watershed scale, and in particular definition 4 proposed by Lane *et al.*
532 (2004) 'the extent to which water and matter that move across the catchments can be stored within
533 or exported out of the catchment'. This definition underpins the SCIMAP model developed by Lane
534 *et al.* (2004) so understandably there is a direct link between definition and approach. Research in
535 this category maps onto both structural and process-based aspects of connectivity.

536

537 *5.5 Indices of hydrological connectivity*

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

548

549 Knudby and Carrerra (2005) evaluated nine indicators of connectivity: three account for the
550 presence of flow connectivity (preferential flow paths); two account for the presence of transport
551 connectivity (the existence of fast paths allowing early solute arrival); and four are based on

552 statistical indicators. The indicators were tested on heterogeneous hydraulic conductivity fields with
553 different visual connectivity (Table 4). The indicators of flow connectivity and one of the transport-
554 connectivity indicators succeeded in identifying the increased presence of connected high saturated
555 hydraulic conductivity features through a geologic media. Using indicators of flow connectivity
556 improved on the use of traditional statistical methods which failed to identify preferential flow
557 paths. None of the statistical indicators were found to correlate with the flow and transport
558 indicators. Hence Knudby and Carrerra (2005) suggested that transport connectivity is much less
559 sensitive to barriers which may control flow connectivity. Instead, transport connectivity appears to
560 be controlled by the existence of narrow, possibly discontinuous high saturated conductivity paths.
561 This proposal suggests that connectivity needs the continuity of features to be represented, not just
562 the variability which is supported by existing modelling approaches to understanding hydrological
563 connectivity (Muller *et al.*, 2007).

564

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

577

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

585

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

595

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

603

604 **6 Is a unified understanding of hydrological connectivity possible?**

605

606 Many factors influence connectivity; some of them are well understood such as the impact of
607 surface properties, slope and vegetation on runoff production (Poesen, 1984; Van Oost *et al.*, 2000;
608 Ludwig *et al.*, 2005), how runoff coefficients scale with slope (Parsons *et al.*, 2006) and rainfall
609 (Wainwright and Parsons, 2002) and ways and implications of classifying runoff units (Bull *et al.*,
610 2003). Less well understood are the ways in which patterns and processes at the hillslope scale
611 determine water transfer at the catchment scale, especially how changing storm characteristics and
612 antecedent moisture interact with mosaics of catchment properties such as patterns of land use,
613 slope and lithology to produce connected flow through drainage basins. For example, a catchment
614 can be characterized by classifying the mosaic of land use, slope, lithology and channel patterns to
615 understand potential runoff units and potential hydrological connectivity. However, empirical
616 evidence of the impact of changing rainfall intensity, storm duration, areal distributions of rainfall
617 and antecedent soil moisture on producing hydrological connectivity in a catchment and the
618 difference it makes to water transfer is sparse, despite the recent advances in tracer techniques
619 (Tetzlaff *et al.*, 2007b). Storm dynamics will interact with the range of hillslope lengths within a

620 catchment, which will either enable or disable connected flow for a particular storm event; a
621 comprehensive understanding of this interaction has yet to emerge. These gaps in our knowledge
622 prevent accurate and precise prediction of changing water transfers under climate and land-use
623 change.

624

625 A second key issue with the concept of hydrological connectivity is how it can be applied across and
626 between environments. For the concept to be useful and a way forward to further our
627 understanding of flow transfer and pathways at a range of scales, it must be relevant and/or flexible
628 to be applicable across all environments. Some of the initial fundamental building blocks
629 underpinning the concept were developed for both dryland and temperate areas (Western *et al.*,
630 2005; Bracken and Croke, 2007), but many of the recent developments have arisen from research
631 focused on small-scale, forested, humid-temperate environments (James and Roulet 2007, Tromp
632 van Meerveld and McDonnell 2005, Ali and Roy 2010a). How do new developments in
633 understanding apply to dramatically different environments such as drylands, colder regions or
634 formally glaciated landscapes characterised by subdued topography? One initial assumption would
635 be that since most flow is generated from surface runoff rather than subsurface mechanisms, it
636 would be difficult to utilise the idea of 'fill and spill' in dryland basins. However, some dryland areas
637 have perched aquifers and underlying confined layers which may operate in a similar manner to that
638 identified in humid temperate catchments and will combine with surface runoff generation to
639 produce connected areas of flow. Dryland researchers have also used the overtopping bucket
640 analogy for spatially isolated soil patches for many years (Kirkby *et al.*, 2002). The idea of storage
641 and how it operates is one key way of linking the mechanism and processes responsible for
642 producing connections in flow in all environments (Ali *et al.*, 2011). However, in drylands stores tend
643 to fill from the top down, rather than the bottom up, so what appears to be a potential similarity
644 between mechanism and processes between environments may lead to confusion because of
645 underlying differences. The fill and spill hypothesis is however easily transferable to lake-dominated
646 catchments and to the US and Canadian Prairie Pothole Region where topographic depressions can
647 act as closed basins while filling up and then as stormflow transition zones when overspilling
648 (Spence, 2007; Spence and Hosler 2007; Shaw et al 2012).

649

650 In ancient glaciated landscapes, such as large parts in Canada, Fennoscandia and the Scottish
651 Highlands, the combination of complex drift distributions and topography determines soil hydrology
652 which plays a key role in controlling catchment rainfall-runoff responses reflecting the interactions
653 between climate, topography, parent material and land use (Soulsby *et al.*, 2006). Field and

654 modelling studies in such environments have shown that flatter, poorly drained areas on glacial drift
655 deposits often result in the development of histosols where runoff is dominated by overland flow
656 (Seibert et al., 2003; Soulsby et al., 2006). In such environments, dynamically expanding and
657 contracting riparian saturation zones reflect catchment connectivity and control the generation of
658 quick, near-surface runoff processes (Tetzlaff et al., 2007b; Birkel et al. 2010). These runoff
659 mechanisms are dependent on the connections between the saturated areas and their surrounding
660 hillslopes which can result in a highly non-linear hydrological response in relation to antecedent
661 conditions. In regions with both limited topographic variations and relatively uniform soils it is the
662 topology of landscape features adjacent to the channel network that is a strong driver for
663 hydrological connectivity and response (Buttle, 2006). For example, Devito et al. (2005) advocate
664 that topography be one of the last aspects considered when classifying runoff pathways in the
665 boreal plain of Alberta, Canada. In this environment, precipitation is only slightly greater than
666 evaporation, moisture deficits are seasonally prevalent, and the regional water table does not
667 directly reflect the land surface as is common in wet environments.

668 Similar rainfall inputs in similar antecedent conditions do not always yield the same outputs (Bracken
669 *et al.*, 2008; Ali *et al.*, 2010;2011). Hence, characterising antecedent soil-moisture is not a sufficient
670 characterisation of the antecedent conditions. This complexity highlights several points, among
671 which is the possibility that our approaches to hydrological mechanisms are too simple with respect
672 to the variety and complexity of the processes involved in different environments and that we
673 impose known mechanisms as a framework to our understanding of catchment hydrology. In that
674 respect, we have to diversify our approaches. Not only do we need research into hydrological
675 connectivity across different environments but investigations have to be conducted in various basin
676 types with different geology, soils and vegetation covers, as long as these data can be interpreted in
677 light of a conceptual underpinning (Carey *et al.*, 2010; McNamara *et al.*, 2011). Vegetation is
678 probably the most responsive element of catchment structure and forms an important interface
679 with catchment function. Vegetation has a complex relationship with runoff production and is a
680 major influence on hydrological connectivity at all scales (Bracken and Croke, 2007). Vegetation can
681 influence water inputs and runoff through interception, formation of leaf litter and transpiration.
682 Within ecology there has been a lot of research based on spatial variations in vegetation and how
683 this is related to hydrological processes (Cammeraat and Imeson, 1999; Ludwig *et al.*, 2000;2005).
684 Currently, most active research into understanding relevant processes and patterns is being
685 undertaken in forested catchments with flow generation dominated by bedrock (Panola and St
686 Hilaire, Canada) or a confining layer (Hermine), although a notable exception is the Tarawarra
687 catchment, Australia (Table 2). Some differences will be captured by working in catchments with

688 different environmental characteristics, but we also need to establish whether mechanisms are
689 similar for grassland catchments and other types of land covers. Several researchers have
690 attempted to do this using numerical techniques to explore rainfall and catchment characteristics
691 that influence the development of hydrological connections (e.g. Wainwright and Parsons 2002;
692 Reaney *et al.*, 2007; Muller *et al.*, 2007; Hopp and McDonnell, 2009).

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

711

712 The challenge of working across different environments and at a range of scales dictates that we
713 need to find new ways of thinking and working in hydrology. If we remain bounded by established
714 practices and existing ways of approaching runoff generation and flow production we may not be
715 able to exploit the full potential of the concept of hydrological connectivity. It follows that we
716 should evaluate current methodologies and practices in data collection. If we are able to capitalize
717 on the excitement and momentum that currently exist around the concept of hydrological
718 connectivity we need to develop new approaches to data collection and combine methods in new
719 ways. We have been successful at using soil moisture as a surrogate for hydrological connectivity,
720 but research has demonstrated that changes in the catchment hydrographs are not always explained
721 by the patterns of increasing soil moisture (Tromp van Meerveld and McDonnell, 2006). Research

722 has also questioned the appropriateness of using topography to determine flow paths and runoff
723 connections for all catchments (Ambroise, 2004; Buttle, 2006). Thus two of most used conceptual
724 foundations for interpreting landscape processes contributing to catchment runoff and connected
725 flow may not be the most useful to further develop the concept of hydrological connectivity. We
726 should further explore the synergies with other disciplines more fully, such as ecology, and also
727 investigate the potential of remotely sensed data for understanding patterns and processes of
728 hydrological connectivity at intermediate spatial scales.

729

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

746

747 However, we need more research into the role and influence of rainfall events on hydrological
748 connectivity, especially the interaction between input of water to the system and emerging
749 hydrological properties. Investigating the response to different hydrological events could be
750 conceived as variance within storm versus variance of hydrological characteristics. This work needs
751 to factor in the role of antecedent moisture conditions; a subject that benefits from a systematic
752 approach to identify surrogate measures for soil water content. As surrogate measures are derived
753 from rainfall data, we need to clarify the relevant temporal scales over which we cumulate rainfall
754 for an adequate prediction of connectivity patterns and of hydrological responses to a given rainfall
755 event. As shown by Ali and Roy (2010b) in the Hermine watershed, there is a wide range of

756 potential models describing the relations between various surrogate measures of AMC and
757 discharges at the outlet and an even more variable set of relationships between soil-moisture
758 content at discrete locations within the watershed and AMC surrogates.

759

760 **7 Suggestions for future research**

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

773

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

790 common thread to understanding, exploring and using hydrological connectivity across a range of
791 environments and at different scales to develop a workable and useful concept to further hydrology.

792

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

810

811 In conjunction with technological developments, environmental and isotopic tracers are a powerful
812 tool to enhance our understanding of hydrological connectivity as an important means of separating
813 stream flow into different temporal sources of flow contribution within catchments (Soulsby *et al.*,
814 2003; Tetzlaff *et al.*, 2007b). They can reveal the integration of smaller-scale hydrological processes
815 that underpin signatures of catchment response at larger spatial scales (Soulsby *et al.* 2006).
816 Generally, tracers are useful tools for characterizing and understanding complex flow through
817 catchments, soils, channels, over land surfaces, and through hillslopes and aquifers (Buttle *et al.*,
818 1998). Using environmental tracers to assess hydrological characteristics has the advantage that less
819 *a priori* information is required (e.g. head gradients, hydraulic conductivity fields and porosities) and
820 the results integrate physical heterogeneity providing a useful tool for calibrating more detailed
821 conceptual or numerical models (e.g. Maloszewski and Zuber, 1993; Fenicia *et al.*, 2008; Birkel *et al.*
822 2011). One common technique employing tracers is the use of input-output dynamics of
823 conservative isotopic tracers for estimating the travel time of water through catchments which is the

824 time it takes from when water enters a catchment to when it exits a catchment as stream discharge
825 at an outlet of a catchment (Etcheverry and Perrochet, 2000; Soulsby et al., 2004; McGuire and
826 McDonnell, 2006; Kirchner *et al.*, 2010). Transit times provide information on flow paths, storage,
827 release and chemical quality of water and integrate various catchment functions and processes
828 (McDonnell et al., 2010; Soulsby et al., 2011).

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

835 **8 Conclusions**

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

855

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

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

888

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

896

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902

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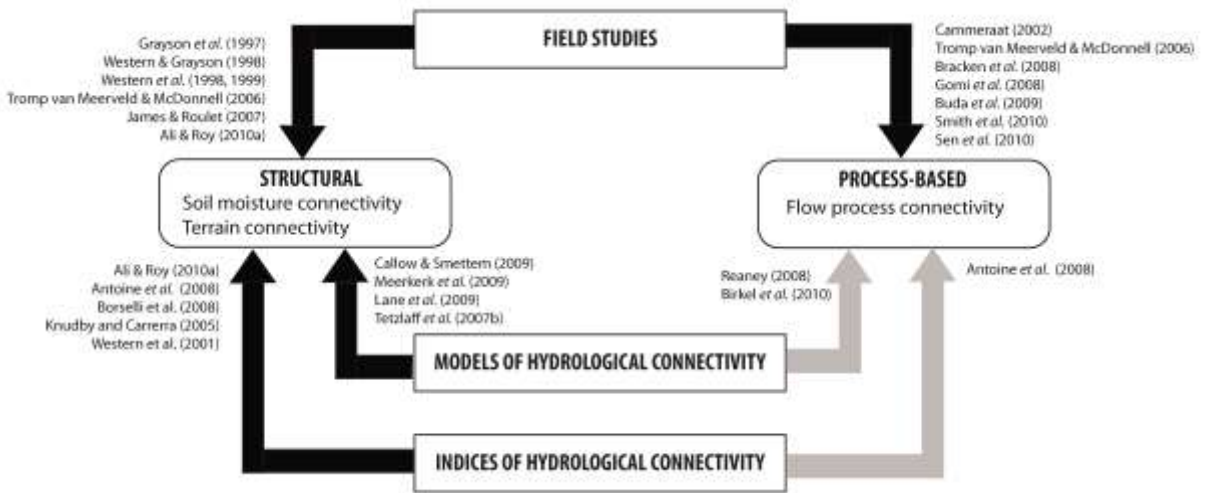
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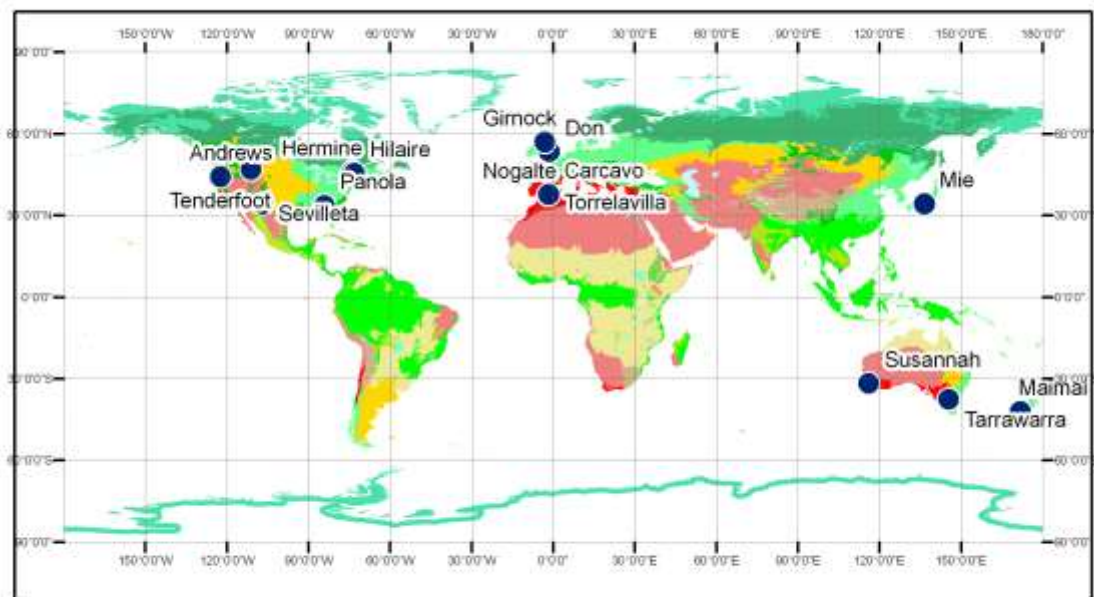
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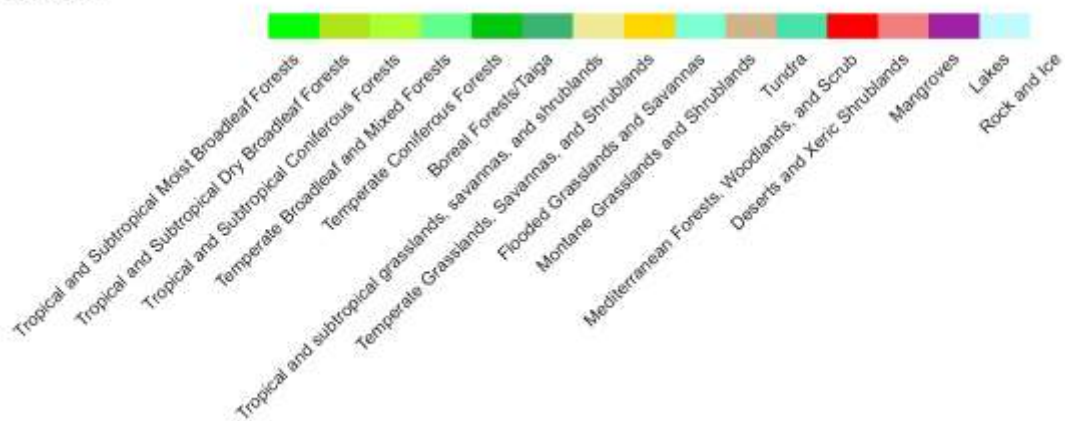
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1235 Figure 1: Relationships between approaches investigating hydrological connectivity



Legend



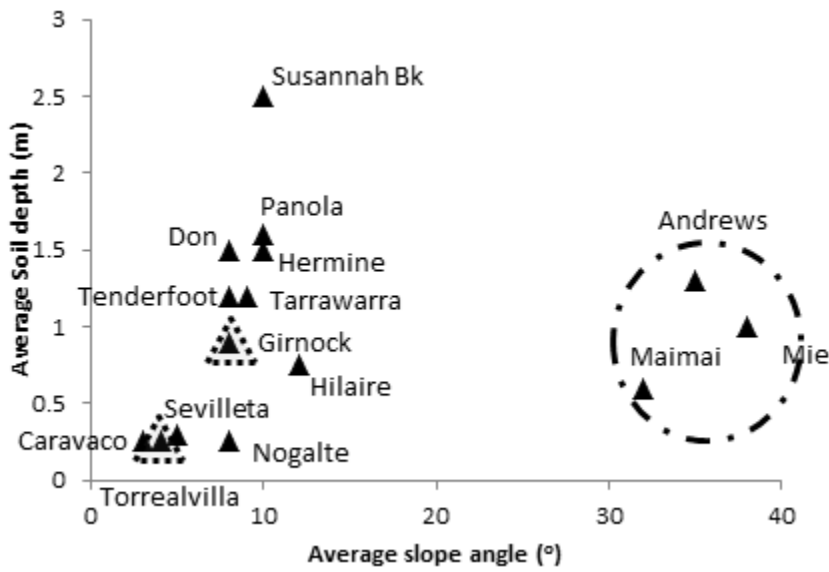
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1237 Figure 2: Location of sites used to investigate hydrological connectivity.

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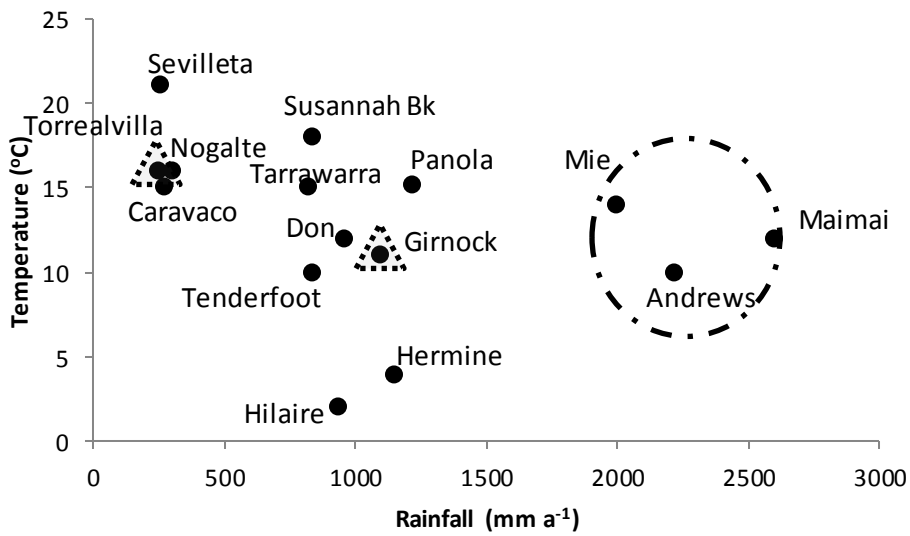
1240 **A**



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1243 **B**



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1246 Figure 3: Characteristics of sites used to explore hydrological connectivity. A) Morphology and B)

1247 hydro-meteorological conditions. The dotted circle highlights the very steep forested catchments of

1248 Maimai, Mie and HJ Andrews. The dark triangle denotes the two existing process based studies.

1249

1250	Water cycle – Watershed scale
1251	1. An ecological context to refer to water-mediated transfer of matter, energy and/or
1252	organisms within or between elements of the hydrologic cycle (Pringle, 2003)
1253	
1254	Landscape Features – Watershed scale
1255	2. All the former and subsequent positions, and times, associated with the movement of water
1256	or sediment passing through a point in the landscape (Bracken and Croke, 2007)
1257	3. Flows of matter and energy (water, nutrients, sediments, heat, etc.) between different
1258	landscape components (Tetzlaff <i>et al.</i> , 2007a)
1259	4. The extent to which water and matter that move across the catchments can be stored within
1260	or exported out of the catchment (Lane <i>et al.</i> , 2004)
1261	
1262	Landscape Features – Hillslope scale
1263	5. Physical linkage of sediment through the channel system, which is the transfer of sediment
1264	from one zone or location to another and the potential for a specific particle to move
1265	through the system (Hooke, 2003)
1266	6. The physical coupling between discrete units of the landscape, notably, upland and riparian
1267	zones, and its implication for runoff generation and chemical transport (Stieglitz <i>et al.</i> , 2003)
1268	7. The internal linkages between runoff and sediment generation in upper parts of catchments
1269	and the receiving waters [. . .] two types of connectivity: direct connectivity via new
1270	channels or gullies, and diffuse connectivity as surface runoff reaches the stream network
1271	via overland flow pathways (Croke <i>et al.</i> , 2005)
1272	
1273	Spatial Patterns – Watershed and hillslope scale
1274	8. Hydrologically relevant spatial patterns of properties (e.g. high permeability) or state
1275	variables (e.g. soil moisture) that facilitate flow and transport in a hydrologic system (e.g. an
1276	aquifer or watershed) (Western <i>et al.</i> , 2001)
1277	9. Spatially connected features which concentrate flow and reduce travel times (Knudby and
1278	Carrera, 2005)
1279	
1280	Flow Processes – Hillslope scale
1281	10. The condition by which disparate regions on a hillslope are linked via lateral subsurface
1282	water flow (Hornberger <i>et al.</i> , 1994; Creed and Band, 1998)
1283	11. Connection, via the subsurface flow system, between the riparian (near stream) zone and
1284	the upland zone (also known as the hillslope) occurs when the water table at the upland-
1285	riparian zone interface is above the confining layer (Vidon and Hill, 2004; Ocampo <i>et al.</i> ,
1286	2006)
1287	
1288	Table 1: Definitions of hydrological connectivity from Ali and Roy (2009).
1289	

1290 Table 2: Study Site Details

Site	Coordinates	Area (km ²)	Elevation (m)	Relief (m)	Average slope (°)	Land use	Geology	Soil depth (m)	Rainfall (mm a ⁻¹)	Temp (°C)
HJ Andrews, USA	44°02'N 122°02.5'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 Bum, 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)
Guadelentín, Spain – Nogalte	37°61'N 01°95'W	171	800	755	8 (2-35)	Bare, matorral, tree crops	Schists	0.10-0.5	300	16.4 (9 Jan – 36 July)
Guadelentín, 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)
Guadelentín, Spain – Carcavo	37°40'N 01°41'W	4.74	380	150	3	Bare, matorral, 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	Podzols 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)

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1293 **Table 3: Groups researching hydrological connectivity**

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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	WesternAW 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 KRI	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/Illinois	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 element
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 element
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 element
	James Al 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 element
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 element

Netherlands					
Amsterdam	Camaraat E	SE Spain - Toreavilla	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
Wageningen	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
Wageningen	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 element
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 element
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 connectivity Structural/ Process based element
Aberdeen	Tetzlaff D Soulsby C Birkel C	Scottish Highlands: Girnock catchment and Bruntland Bum 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 connectivity 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, <i>in situ</i> 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 element
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 element
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 subsurface flow at the hillslope scale.	Structural/ Process based elements
Virginia/Oregon	McGuire KJ McDonnell J Dettly 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 elements
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 elements

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1298 **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 <i>et al.</i> 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 macrotopography.	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 Carrera 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 Carrera 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 Carrera 2005
Integral scales	(1) Variogram; (2) Indicator variogram and (3) Bivariate entropy integral scales	Soil moisture data, topography.	Knudby and Carrera 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 <i>et al.</i> 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 <i>et al.</i> 2008

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