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

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ABSTRACT

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

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

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

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

2. Definitions

In their 2009 paper, Ali and Roy present a synthesis of hydrological connectivity definitions (Table 1). Of these definitions we feel that number 11, concerning hillslope-riparian-stream (HRS) hydrologic connectivity via the subsurface flow system, seems to be coming to the fore as the most used interpretation of hydrological connectivity (e.g. Jencso et al., 2009, 2010; Detty and McGuire, 2010; Jencso and McGlynn, 2011). This definition emerges from the approach to hydrological connectivity based on assessing flow processes, in particular from research which proposes that the timing and duration of groundwater connectivity between riparian zones and the stream network is the dominant control on the magnitude and timing of observed catchment discharge (e.g. McGlynn and McDonnell, 2003; McGlynn and Seibert, 2003; Jencso et al., 2009; Detty and McGuire, 2010; Jencso and McGlynn, 2011). This research was conducted in locations with steep slopes that exhibit a seasonal runoff response. We question however whether this is the most suitable definition for other geomorphic domains. On one hand, this definition is process-based, but

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

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

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