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Conceptualizing catchment processes: simply too complex?

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State of the Art—the 'How' and 'Why' Questions

Conceptualization is fundamentally important to both process understanding and prediction in catchment hydrology. This is reflected in it being a key theme within the Prediction in Ungauged Basins (PUB) science programme, urging a rethink about the different ways in which the form and function of catchment systems are conceptualized (Sivapalan *et al.*, 2003). Towards this goal, an international workshop 'From Catchment Scale Process Conceptualisation to Predictive Capability' was held in Ballater, Scotland, in 2007 (http://www.abdn.ac.uk/~wpg027/w_shop.php), which was attended by over 30 hydrologists. In this workshop—which focussed specifically on runoff generation processes—three key questions were asked: (1) What is meant by process conceptualization in catchment hydrology? (2) How do recent developments in data acquisition aid conceptualization? and (3) How do conceptualization and new data interface with hydrological modelling and prediction? This commentary deals with the first of these questions. Two related commentaries will follow, which will consider the issues of data (Soulsby *et al.*, 2008) and prediction (Dunn *et al.*, 2008b).

Conceptualization undoubtedly means different things to different hydrologists. Hydrological investigations are inevitably conducted for different reasons, in different geographical environments, and over different timescales. Correspondingly, hydrologists may employ a wide range of different approaches when describing catchment behaviour. The nature of the problem and the approach used have an important bearing on the conceptualization that is needed and the way in which it is articulated. In some cases this may mean developing a qualitative conceptual diagram or a mapping tool (e.g. Laudon *et al.*, 2007); in others it may mean a simple process equation (e.g. Beven, 2006) or a set of complex algorithms in a physical model (e.g. Qu and Duffy, 2007). Likewise, conceptualization is affected by spatial scale which ranges from soil profiles, to hillslope transects, to small experimental catchments (typically *ca* 1 km^2) and larger mesoscale (typically 10^2 km^2) river basins, all characterized by overlapping and sometimes unique forms of heterogeneity (Soulsby *et al.*, 2006a). Additionally, up-scaling understanding to larger scales where management decisions are needed requires empirically based conceptualization of the emergence of new processes (Reed *et al.*, 2006; Sidle, 2006).

Despite well-reasoned calls for unifying theories and laws in catchment hydrology (e.g. Sivapalan, 2005), even closure of the continuity equation remains a major challenge in many instances (e.g. Beven, 2006). It has recently been argued that a paradigm shift is needed to advance the science, based on fundamental organizational principles of catchment systems (McDonnell *et al.*, 2007). Process conceptualization is central to this and it has been suggested that there should be a focus on the *form* of catchments; that is, how and why they are geomorphologically, ecologically and pedologically structured in the way that they are. Further, there is the need to understand and quantify the ways in which this form determines how and why catchments *function* hydrologically and behave dynamically with temporal scale (Wagener *et al.*, 2007). In turn, function feeds back into the subsequent evolution of catchment

organization, or form (Phillips, 2006). This requires understanding of the geomorphic evolution of catchments through geological time; the role of vegetation and terrestrial ecosystems in regulating hydrological fluxes; and, increasingly, the importance of human impacts (Istanbulluoglu and Bras, 2005). Thus, catchments can be viewed as bio-physical systems with a history of transient features in the landscape, constantly evolving and changing. Indeed, recent work in this regard has advocated treating catchments as complex adaptive systems; thus focussing understanding on their self-organizing structure and how this has been, and continues to be, influenced by the stores, states and flows of water (Sivapalan, 2005).

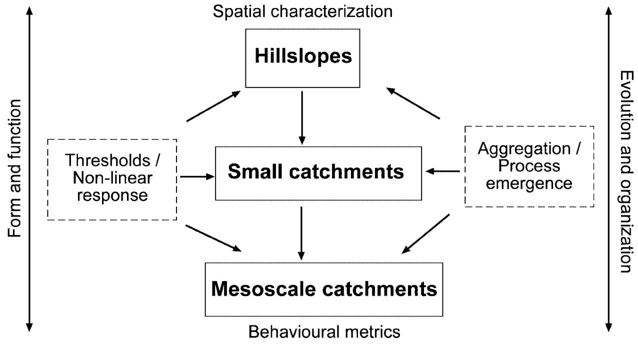

Figure 1. Some key, scale-independent overarching issues applicable at all scales that are useful in conceptualizing catchment form and function

Examples of Recent Progress in Process Conceptualization

Recently, such philosophical perspectives have been implicit or explicit in various attempts to facilitate conceptualization at different spatial scales. Such new developments are often driven by gaining new data by applying innovative technologies (Soulsby *et al.*, 2008). Moreover, integration of experimental work with model applications, or use of models in numerical experiments, has facilitated progress, specifically in the area of runoff generation and linking hillslope and surface water hydrological response (Seibert and McDonnell, 2002; Beven, 2007).

At the soil profile and hillslope scales, more experimental conditions and fine-resolution data collection (e.g. Kienzler and Naef, 2008), together with increasingly flexible modelling structures, have allowed significant progress. Amongst other things, this has provided the basis for conceptualizing and visualizing water movement in macropores (Weiler and Naef, 2003; Weiler and McDonnell, 2004), and the development of hillslope flow networks based on behavioural traits such as the 'fill and spill' flow paths connection (Spence and Woo, 2003; Tromp-van Meerveld and McDonnell, 2006) and have given insights into the emergent, threshold-like behaviour of storage and release of water in the cryptic sub-surface (Lehmann *et al.*, 2007). Promisingly, such studies are providing an empirical basis for holistic hypotheses suggesting that the ubiquitous nature of networks in hillslope drainage systems reflect hillslope and catchment evolution and possibly some optimality in response to water and sediment fluxes (Bejan, 2007).

A critical area of development is the need to test and upscale conceptualization of such non-linear, threshold-type responses of hillslope drainage networks to explain the stream response at the catchment scale (Figure 1). Recent work has shown potential in this regard, at least in terms of small catchment response (Zehe *et al.*, 2007). In larger mesoscale catchments, such emergent behaviour is also evident (Shaman *et al.*, 2004). Recent progress in characterizing the spatial structure of drainage networks is providing insight into how the integration of more complex hillslope units and small catchments influences spatial and temporal drainage patterns at the larger scale (Tetzlaff *et al.*, 2007b). In simple landscapes dominated by fluvial erosion and mass wasting, such as young orogens, the importance of topography in governing such hydrological function and behavioural indices such as residence times is becoming apparent and contributing to improved process conceptualizations (McGuire *et al.*, 2005; Bogaart and Troch, 2006). In terrain with a more complex history, such as where glaciation has rejuvenated the topography, the importance of soil hydrology and variation in drift permeability in governing the partitioning of runoff and catchment hydrological response has been highlighted (e.g. Scherrer and Naef, 2003; Soulsby *et al.*, 2006b).

In this work of up-scaling, geochemical and isotopic tracers have proved valuable as tools that can capture the integrated effect of runoff processes and provide information on the geographical sources of runoff and the transit times of water within catchments (McGuire and McDonnell, 2006). Different tracers have different values in different situations, and when combined with other approaches such as nested hydrometric monitoring, geophysical techniques and Geographic Information System (GIS) applications, they can provide powerful insights that aid conceptualization at the catchment scale (e.g. Covino and McGlynn, 2007).

These more integrated approaches are now also highlighting some of the linkages between hydrology, geomorphology, ecology and landscape evolution (Istanbulluoglu and Bras, 2005; Bogaart and Troch, 2006). For example, exciting new hypotheses about the self-organizing structure of ecosystems and hillslopes in terms of, for example, soil moisture control are becoming apparent. These hypotheses help define possible characteristics of hydrological behaviour, which are emergent at the catchment scale (Belyea and Baird, 2006). In addition, long-term datasets are revealing the non-stationary nature of catchments and their non-linear behaviour over longer time periods (Burt and Worall, 2007; Tetzlaff *et al.*, 2007a). Such

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improved approaches to conceptualization are providing fresh perspectives on how to use hydrological models as part of a learning process (e.g. Uhlenbrook *et al*., 2004; Dunn *et al*., 2008a).

Dealing with Complexity and Heterogeneity

It has been suggested that the paradigm shift needed in catchment hydrology must move beyond consideration of the complexity, heterogeneity and uniqueness of catchments, and look for unifying ideas and organizing principles (McDonnell *et al*., 2007). Given the importance of heterogeneity at all scales, this requires the development of diagnostic classification tools that integrate measurement and consider factors such as topography, topology and typology to develop indices of similarity. From this, there is a need for simple rules and/or clear procedures to determine the dominant processes operating in different catchments, and how these reflect variations in landscape controls (e.g. Buttle, 2006). Developing such tools would allow a much more systematic approach to understanding the interactions between catchment form and function in different parts of the world. However, numerical experimentation with models could examine further the types of 'rules' needed to produce the complexity associated with different types of hillslopes and the connections between them. Although concepts such as representative elementary watersheds have been used to examine the emergence of different processes at aggregated scales (Beven, 2007), advances in forest ecology which have modelled the self-organizing nature of forest ecosystems have potential applicability in hydrology (Hendry and McGlade, 1995).

Some Immediate Research Priorities

Despite considerable ongoing progress in conceptualization, there remains the need for better coordination in research and collaborative comparative studies to develop transferable tools to integrate theoretical perspectives and empirical studies. In relation to runoff processes, significant progress has been made in conceptualizing hillslope hydrology and the scaling relationships with catchment response. In addition, improved dialogue between experimentalists and modellers has proven to be fruitful; this is a long-underdeveloped research frontier where significant potential remains (Dunn *et al*., 2008b). Comparison of catchment behaviour in different geographical areas is an obvious need that will aid meaningful classification and lead to a more systematic understanding of catchment similarities and dissimilarities in catchment form and function. However, some issues are common to all catchments: most obviously the issue of handling heterogeneity and uncertainty in learning frameworks that involve both field and modelling studies. More specifically, areas with promise might be the improved characterization of the spatial and temporal resolution of precipitation inputs, and the relationship with runoff response. Developments like cheaper, portable weather radar systems have potential here. Similarly, more distributed hydrological monitoring with tools such as wireless networks and fibre optic technologies can give better integrated measurements than have been previously available (Soulsby *et al*., 2008). These, together with advances in tracer hydrology and hydrogeophysics, will allow improved conceptualization and quantification of control volumes regulating catchment response in both the unsaturated and saturated zones, and how these change with scales.

There are challenging opportunities in process conceptualization that are central to the development of hydrology as a mature and more integrated science, as well as being useful in approaching un-gauged catchment problems. The challenge for initiatives such as PUB is to provide a framework that can guide developments in a structured and coherent manner, yet facilitate the creative flexibility needed to foster multiple parallel pathways that enhance conceptualization in a range of appropriate ways including interdisciplinary perspectives. It is also to be hoped that advances in conceptualization in catchment hydrology will go beyond hydrologists and impact the wider scientific community researching the implications of rapid environmental change. An obvious need in this regard is the requirement to consider the conceptualization of catchment scale processes in general circulation model(s) (GCM) for climate change predictions. Despite the complexity described here, these processes are often considered as a sub-grid-scale parameterization in most GCMs, even though these may determine the emergent response to climate change.

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