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Catchment data for process conceptualization: simply not enough?

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Background

Technology-driven improvements in data capture methods have been a cornerstone of the development of hydrology as a geoscience. The complex, interactive nature of hydrological systems, plus the scaling of hydrological processes, dictate that measurement is exceptionally difficult (Kirchner, 2006). Thus, with increasing computer power, the pace of developments in modelling has far outpaced supporting field investigations. Hydrological data collection is invariably carried out for different reasons, in different regions, in different ways, over varying timescales, by scientists with different backgrounds, biases and inevitable budget constraints (Hamilton, 2007). This means that precipitation and stream runoff are usually the only measures that can be considered extensive, and even these are known to be poorly characterized at smaller spatial scales. Uncertainty is inherent in even the best data sets and hydrometric data programmes seem to live perpetually under the threat of cuts (Shiklomanov *et al.*, 2006). Other hydrological measures (e.g. soil moisture storage, groundwater recharge) are poorly characterized by field data in all but a handful of experimental sites. Moreover, apart from national hydrometric data records, hydrological data are generally project specific, poorly archived and generally unavailable beyond the data collection team (Vorosmarty *et al.*, 2002).

Despite this, high quality data sets facilitate empirically based conceptualization of hydrological processes that may be linked with elegant modelling, providing scientific advance and richer insights into catchment function (Kirchner *et al.*, 2001; Sivapalan, 2005; Tetzlaff *et al.*, 2008). In an ideal world, catchment scientists might wish to collect as much data, on as many processes, at as many places, as frequently and for as long as possible! Often such data collection yields unexpected results, as unanticipated behavioural features of catchment systems become apparent (see Kirchner *et al.*, 2000; Neal *et al.*, 2004a). However, resource constraints will always militate against such idealism and much monitoring will continue to be focused on relatively few long-term experimental catchments that arguably provide the best places where new technologies can be applied to enhance understanding (Lovett *et al.*, 2007). Concurrently, however, there has also been a major paradigm shift towards integrated, interdisciplinary studies (e.g. surface water–groundwater interactions coupled with freshwater ecology) as opposed to previous multi-disciplinary studies to gain a more holistic understanding of catchment systems. Finally, measurements relevant at larger scales that are of more practical interest to land–water management are possible and highlight the need for larger scale comparative studies (McDonnell *et al.*, 2007). Within the above framework, the remainder of this Commentary, which results from a workshop on 'From Catchment Scale Process Conceptualization to Predictive Capability' held in Ballater, Scotland, in 2007 (http://www.abdn.ac.uk/~wpg027/w_shop.php), will succinctly highlight some emerging issues on how new approaches to data collection aid process conceptualization, particularly in relation to runoff processes.

Evolution of Data Collection in Catchment Studies

In many ways, long-term catchment studies have been the bedrock of process understanding and conceptualization in hydrology. Long-established sites such as Plynlimon, Wales (McCulloch, 2007); Babinda, Australia (e.g. Bonell *et al.*, 1998); Maimai, New Zealand (McGlynn *et al.*, 2002); Panola, USA (Burns *et al.*, 2001) and the Allt a' Mharcaidh, Scotland (Soulsby *et al.*, 2000) have been the foci for evolutionary advances in process investigations and the integration of field and modelling perspectives. Traditionally, such experimental sites were relatively small catchments and the focus was on physical hydrology, although at sites like Plynlimon, Panola and the Allt a' Mharcaidh, biogeochemical studies were also important and indeed have provided invaluable insight into hydrological processes (e.g. Neal *et al.*, 2004a). The requirements of environmental managers have shifted the need for monitoring and investigation to larger spatial scales, and thus, in many instances, recent work has involved upscaling from small experimental catchments to the larger mesoscale (Shaman *et al.*, 2004). A major step forward was the proposal for a nested basin approach for the Large-Scale Biosphere–Atmosphere Experiment in Amazonia (LBA, 1996). This concept was later facilitated in the UK, in the Catchment Hydrology And Sustainable Management (CHASM) and LOwland Catchment Research (LOCAR) initiatives that have advanced upscaling work in several UK catchments including the Feshie (Soulsby *et al.*, 2004, 2006), Eden (O'Connell *et al.*, 2007), Oona (Jordan *et al.*, 2007) and Thames (Neal *et al.*, 2004b; Wheater *et al.*, 2007). Similar initiatives have advanced this agenda in other countries (Woods *et al.*, 2001).

These advances in upscaling are timely, as water management legislation in many parts of the world requires a more integrated, holistic understanding of larger catchment systems and thus presents new challenges to hydrological data collection. An example is the EU Water Framework Directive that places hydrological research in a wider context, using criteria such as 'good ecological status' as a benchmark for sustainable water management (Dorge and Windolf, 2003). Thus, the need to understand the hydrological characteristics of high quality ecological habitats in rivers is forcing experimental catchment studies to become even more integrated, with sites such as Krycklan (Sweden) and the Girnock (Scotland) being the ones where ecological monitoring and assessment are explicitly integrated with hydrological process studies (e.g. Petrin *et al.*, 2007; Tetzlaff *et al.*, 2007b). This is a healthy development within catchment science and hydrology and can only benefit from more interdisciplinary approaches (Neal and Clarke, 2007). Such studies are also providing the basis for more robust, systematic inter-catchment comparisons that will clarify the role of geographical variability in governing hydrological behaviour (Wagener *et al.*, 2007) and the wider biogeochemical and ecological implications (Figure 1).

In addition to upscaling and wider, more interdisciplinary studies experimental catchments are invaluable in understanding the 'transient' nature of catchment function, in the aspect of both longer-term landscape evolution and short-term land management changes (Aylwood, 2005). Increasingly, as is evidenced by the UNESCO Hydrology, Environment, Life and Policy (HELP) programme (Bonell *et al.*, 2006) and similar initiatives, this latter point is involving stakeholders in catchment science and data collection programmes, in order to ensure that information is provided that addresses the needs of different interest groups concerned with catchment management (Grayson, 2005).

Recent Developments in Data Collection

Within this evolving framework of catchment studies, a number of recent technological developments are facilitating significant progress in process understanding and conceptualization. In terms of runoff processes, for example, weather radar is beginning to realize more of its potential in terms of real-time characterization of inputs at a range of catchment scales (e.g. Woods *et al.*, 2001; Creutin and Borga, 2003). Other methods of remote sensing are also allowing improved characterization of other large-scale fluxes between the atmosphere and terrestrial surfaces, though uncertainties and ground-truthing remain limiting factors (e.g. Young, 2006).

At the scale of individual hill slopes and catchments, light detecting and ranging (LiDAR) is now becoming increasingly available and has the ability to resolve catchment land surfaces to the scale of a few centimetres in DTMs. Although still relatively expensive, the approach is becoming increasing flexible and already many applications are helping, among other things, in conceptualizing the connectivity of hill slope flow paths (Lane *et al.*, 2004), in the spatial arrangements

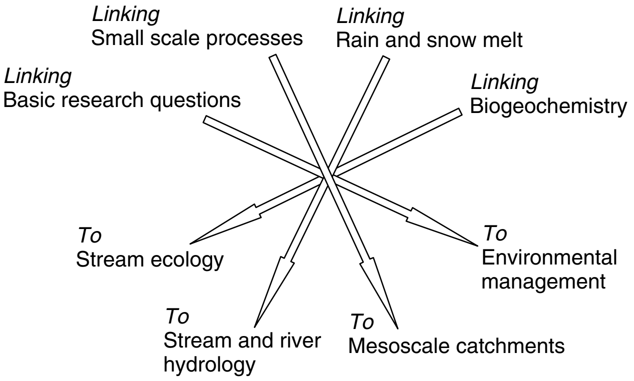

Figure 1. Evolving research agendas at the Krycklan catchment study, Sweden; moving to larger scales, more interdisciplinary approaches and more applied research questions

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of soil moisture field (Tenenbaum *et al.*, 2006) and patterns of flood plain inundation (Bates, 2004) in ways that can inform modelling studies. Likewise, improvements and reduced costs of geophysical surveys have made characterization of sub-surface hydrology possible, at least at the hill slope scale (Wenninger *et al.*, 2008).

Recent developments in wireless network technology have enabled monitoring networks for standard hydrological parameters (e.g. precipitation, soil moisture, groundwater levels and stream stage) to become increasingly spatially distributed and with the facility for fine temporal resolution (e.g. Bogena *et al.*, 2007). Although the technology is in its early phase, it has the potential to revolutionize data collection at least at the experimental catchment scale. Likewise, developments in fibre optic technology have been used innovatively to facilitate highly resolved, spatially distributed temperature measurements to infer groundwater–surface water interactions (Selker *et al.*, 2006). Possibilities for soil moisture monitoring and boundary layer hydroclimatology are also being explored.

Tracer hydrology has aided conceptualization, particularly in relation to upscaling studies, because of the ability of tracers to reflect smaller scale processes (e.g. Uchida *et al.*, 2005). Recent developments of water quality probes capable of continuous data collection are becoming cheaper, more reliable and are able to measure accurately a greater number of parameters, thus aiding conceptualization of groundwater–surface water interactions (Malcolm *et al.*, 2006), nested runoff processes (Tetzlaff *et al.*, 2007a) and the dynamics of diffuse pollution (Jordan *et al.*, 2007). Related to this, new laser spectrometers provide the potential for increasing numbers of samples being analysed on-line at experimental sites (Lis *et al.*, 2008). This offers tremendous potential in isotope hydrology in terms of fine temporal resolution of stable isotope behaviour in rainfall-runoff studies.

Model-Guided Data Collection

The increasing integration of field and modelling investigations in hydrology is revolutionizing experimental design within which such new technologies can be deployed (e.g. Seibert and McDonnell, 2002). For example, models can guide the instrumentation of catchments by helping to design optimal sampling strategies that are technically and economically feasible, while maximizing the probable information content of the collected data (Kirchner, 2006). Given the improved potential for high-resolution data collection in space and time, it is essential for this research frontier to be advanced. Most hydrologists increasingly experience the feeling of 'drowning' in too much data: closely coupled modelling and field investigations can approach monitoring as an exercise in hypothesis testing. Such changes in methodological approaches have recently been cited as an urgent need to advance the hydrology as a science, which has often relied on simply monitoring rather than being hypothesis driven (McDonnell *et al.*, 2007). There are obvious advantages in getting 'more' valuable information from gathering 'less' data, so long as the data have the maximum possible information content for the study in hand, and clearly modelling has much to offer in this respect.

Mining Existing Data Sets

In the same vein, analysis of hydrological data, although effective, has often been based on relatively simple approaches. Now many tools are available from other disciplines, such as systems analysis, which offer significant potential in the analysis of existing data sets to 'squeeze' greater information from them (Babovic, 2005). Examples include spectral analysis, use of self-organizing maps and isometric feature mapping (e.g. Kirchner *et al.*, 2000; Lischeid *et al.*, 2007). In many cases such an analysis has remarkably insightful process implications. However, application of such techniques often involves making data more accessible, and it has recently been noted that there is a need to integrate larger publicly available data repositories and archives with those of individual researchers to best facilitate progress (Torgersen, 2006).

Future Prospects

It is an exciting time in catchment hydrology, where new technologies and new experimental designs in fieldwork offer tremendous potential in developing new approaches to process conceptualizations based on improved data streams. The increasingly fertile common ground between field hydrology and modelling is likely to drive this agenda and develop new learning frameworks for understanding the function of hydrological systems (see Dunn *et al.*, 2008). Increasingly, however, this will be framed within interdisciplinary studies and influenced by a wider community of stakeholders and users of hydrological information. It is important therefore that more sophisticated and flexible approaches of data archiving are developed, which facilitate data sharing and provide a basis for analysis and inter-catchment comparisons and improvement of process conceptualization.

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