17 A Perspective on Hillslope Hydrology in the Context of PUB

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INTRODUCTION

The IAHS Predictions in Ungauged Basins (PUB) initiative offers an unprecedented opportunity for process hydrologists, modellers and theoreticians to work together on a common problem: reduction of predictive uncertainty. While this topic has been addressed in recent years in the watershed modelling literature (see review by Beven, 2001), only recently has the process literature begun to explore how conceptual understanding of basin behaviour may be used to structure new models (Montanari & Uhlenbrook, 2004), be used as soft data in multicriteria model calibration (Seibert & McDonnell, 2002), be used to narrow model parameter ranges (Freer *et al.*, 2004) and to define new model structures (McDonnell & Vache, 2004). This chapter presents a "perspective" on the role of process knowledge within the PUB framework and how studies in hillslope hydrology may contribute to Target 2 of the PUB Implementation Plan (Sivapalan *et al.*, 2003): *Shifting from models that rely heavily on calibration to models that are based on extraction of first order process controls and more complete understanding of flow pathways and flow sources at the basin scale.*

What follows are some ideas that we think may accelerate advancements within PUB from a process perspective. This short distillation of key concepts focuses on the whittling-down of process descriptions toward defining emergent properties at the basin scale. Furthermore, these new data sources and process ideas may form new measures of model acceptability, as the community moves away from calibration-reliant model schemes to more process-based descriptions (as defined recently by Soulsby *et al.*, 2004, and Quinn, 2004). Our thoughts are grouped into three sections: streamflow, storm hydrograph composition and baseflow mean residence time. We argue that together, these measures of water flowpath, source and age may help to constrain a conceptualization of runoff generation in gauged and ungauged basins and be a way forward to reducing predictive uncertainty with respect to our conceptualization of key processes operating in catchments.

THE NATURE OF HILLSLOPE HYDROLOGY

Hillslopes are often a basic building block of our catchment models (Sivapalan, 2003). Hillslope hydrology, as a field of study, is defined essentially by three questions: Where does water go when it rains? What flowpath does it take to the stream? How long does that water reside in the catchment (Kirkby, 1978; Bonell, 1998). Great strides have been made in recent decades in defining fast runoff producing zones in watersheds associated with overland flow: infiltration excess overland flow and saturation excess overland flow. For many events, these zones are the hot spots that are responsible for the delivery of water and sediment to the stream. Kinematic wave approaches have proved effective in terms of routing this water to the channel (Singh, 2002). The vast majority of most watershed areas is made up of land that does not produce overland flow. Zones producing infiltration excess overland flow are usually restricted to defined areas of reduced infiltrability like roads, compacted ground, crusted surfaces (Smith & Goodrich, 2005). Similarly, saturation overland flow producing zones are usually limited in space: around channel margins, in swales and hollows, channel heads and areas of limited soil depth. As Ambroise (2004) notes, if these zones are to be active contributing areas, then they must be somehow connected to the channel.

Our understanding of runoff generation in-between the extremes of infiltration excess and saturation excess overland flow is much more rudimentary. Subsurface flow is a difficult process to see and measure. Lateral flow in the subsurface during rainfall and snowmelt events (variously called subsurface stormflow, interflow, lateral flow) is highly complex and involves conversion from vertical to lateral flow, partitioning of fast flow in large partially connected pore space (Noguchi *et al.*, 1999) and slower flow in other parts of the domain.

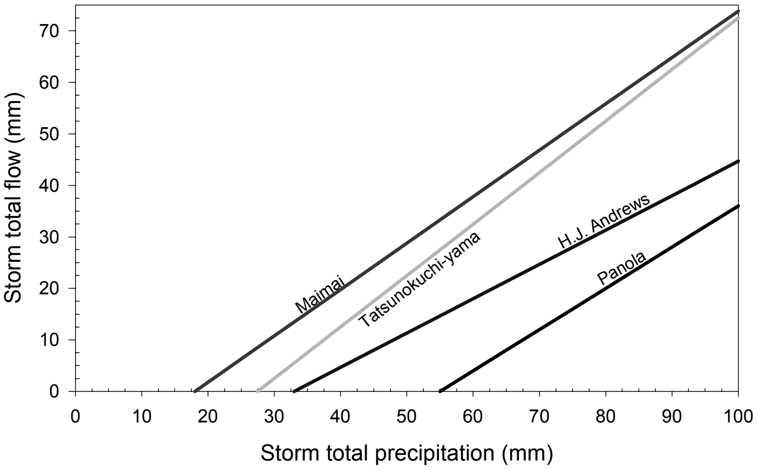
While often highly threshold-like (Buttle *et al.*, 2004; Tromp-van Meerveld & McDonnell, 2005a,b) and perhaps only delivering water to the channel during larger storms, subsurface stormflow has been implicated in a number of studies as being a large source of stormflow in large events (Mosley, 1979); as a key control on the spatial distribution and timing of deep groundwater recharge (Torres *et al.*, 1998); and as a key control on the flushing of labile nutrients to the stream (Boyer *et al.*, 1999). Despite this importance, subsurface stormflow is not well described by simple kinematic wave theory when one considers both the quantity and quality of water routed downslope.

STREAMFLOW GENERATION PROCESSES

The past two decades of streamflow process research has shown that the dominant runoff processes change with changing scale. At the scale of a soil core, “runoff processes” might be conditioned most by the nature of the moisture release curve. At the plot scale, the first order controls on water movement may be the partitioning into preferential and non-preferential flow as controlled by soil structure and rain intensity (Weiler *et al.*, 2004). At the hillslope scale, many studies observe that the spatial variation in soil depth is the first order control on lateral mobile flow in highly transient subsurface saturated areas (Freer *et al.*, 2002). Finally, at the catchment scale, the first order control on stream hydrograph behaviour and tracer composition of streamwater may be the relative amounts of water delivered from different catchment geomorphic units (e.g. hillslopes, riparian zones, bedrock outcrops, etc.) (Burns *et al.*, 2001). McDonnell (2003) argues that these cryptic reservoirs that connect and disconnect may be one of the dominant processes at the catchment scale. Indeed, process representation is the most fundamental problem of scaling. As Quinn (2004) notes, it is only by defining and showing the processes at each scale that we can define appropriate model structures.

In most catchment-scale Variable Source Area (VSA)-based conceptual runoff models, an unambiguous, monotonic function between the groundwater storage and runoff is implemented. Consequently, the dynamics of the simulated runoff from the groundwater zone always follows the simulated rise and fall in groundwater levels. Increasingly, field evidence is challenging this notion. Seibert *et al.* (2003) showed that water table response in the riparian zone is often separate and independent from those positions farther upslope. Flux from the riparian zone often leads the hydrograph in a hysteretic way, with the hillslope input (on those storms when it is activated) dominating the recession limb after the threshold for its activation is exceeded (McGlynn & McDonnell, 2003).

So how does this relate to PUB? These process studies are often replete with complex, yet qualitative descriptions of many mechanisms and feedbacks. One of the more promising findings from intercomparison of watersheds where we have worked is that each seems to show threshold-like behaviour in terms of when hillslopes connect to the riparian zone and the stream channel. Threshold descriptions of hillslopes may be a pathway forward for distilling the myriad complexities of hillslopes into a function based on precipitation amount and subsurface flow per unit water applied (Fig. 17.1). The work of Tromp-van Meerveld (2004) suggests that defining these thresholds for different landscapes may be a way to bring the experimentalist's perspective to ungauged systems. Figure 17.1 shows this threshold behaviour (based simply on rainfall amount) at sites in Japan, Georgia, New Zealand and Oregon. Recent studies have suggested that a decision tree (Scherrer & Naef, 2003) approach may be a pathway to indicate dominant flow pathways in ungauged catchments. We would advocate a similar position based on our threshold findings. Our take-home message in the context of PUB is that: *catchments appear to operate like a series of cryptic*



Panola, Georgia, USA (Tromp-van Meerveld & McDonnell, 2005a)
Maimai, New Zealand (Mosley, 1979)
Tatsunokuchi-yama expt forest, Honsyu Island, Japan (Tani, 1997)
H. J. Andrews expt forest, Oregon, USA (McGuire, unpublished data)

Fig. 17.1 *Schematic representation of the threshold-like relationship between total storm precipitation and storm total flow under wet antecedent conditions. Data extracted from literature values and our own experimental data. The lines represent the best fit lines through data points, as produced by Tromp-van Meerveld & McDonnell (2005a) and cited in Weiler & McDonnell (2005). Data for H. J. Andrews is from Kevin McGuire's unpublished data.*

reservoirs that connect and disconnect. Looking for this "threshold" and "post-threshold rainfall–runoff relation" may be a way forward to collapse hillslope complexity into a simple measure of emergent behaviour at the watershed scale.

STORM HYDROGRAPH TIME SOURCE AND GEOGRAPHIC SOURCE COMPOSITION

The cryptic units expressed in flow relations at the catchment scale are often also expressed geochemically in the stream. Many recent studies have reported end-member mixing results (e.g. Burns *et al.*, 2001) that have shown how hillslope waters are chemically and isotopically distinct from riparian zone waters. The degree of expression of hillslope water in the stream is often minimal, or varies along a riparian aquifer volume gradient from watershed to watershed. Similarly, time source hydrograph separation using stable isotope tracers and simple two-component mixing models have shown gross differences for watersheds dominated by infiltration excess runoff production (i.e. Horton overland flow) *vs* saturation excess runoff environments (i.e. saturation overland flow and subsurface stormflow) (see review by Buttle & McDonnell, 2004). Perhaps 100–150 hydrograph separation studies have been published to date (Agarwaal, 2002); these works indicate collectively that infiltration excess overland flow environments have storm hydrographs comprised largely of event water (i.e. that water associated with the storm rainfall) and saturation excess environments have storm hydrographs largely comprised of pre-event water (i.e. that water stored in the watershed prior to the rainfall or snowmelt event (Buttle, 2004).

So how does this relate to PUB? These often fuzzy estimates of hydrograph composition based on an experimentalist's assessment of a given watershed (either geographical source estimates of catchment units like hillslopes and riparian zones or time source estimates of event and pre-event water) provide criteria for assessing model acceptability. In ungauged basins, these tracer-based studies have matured to the point where they may be used in an expert system-like manner. For predictions in ungauged basins then, soft hydrograph separation may help to differentiate behavioural from non-behavioural simulations.

Figure 17.2 shows runoff simulated over a three day period, 28–30 May 2001 at a poorly gauged basin in Chile (see Vache, 2003 for details). While minimal measurements exist in the basin (other than discharge that the model is calibrated on), the basin is known to produce infiltration excess overland flow from the nature of the soils, geomorphology and semiarid climate. The details of the model are not important for this discussion—what is important is that maximum model efficiencies shown in Fig. 17.2 are for simulations with >0.85 Nash-Sutcliffe efficiency. Since infiltration excess overland flow is the dominant component of storm runoff in the channel (with commensurate flashy, seasonally ephemeral hydrographs and very low soil hydraulic conductivity measurements (Dave Rupp, personal communication, unpublished data), the infiltration excess overland flow can be assumed to produce high new water contributions to storm hydrographs. Nevertheless, we are very uncertain as to what number or range these values should take. One therefore might reasonably make the assumption that the percentage of event water is greater than 50% of the total. In all likelihood, the value could be much higher, but in this instance, we treat the 50% as a conservative value. Figure 17.2 shows how this fuzzy hydrograph compositional information may help to reject "nonsense dots" from the dotty plot (for dotty plot

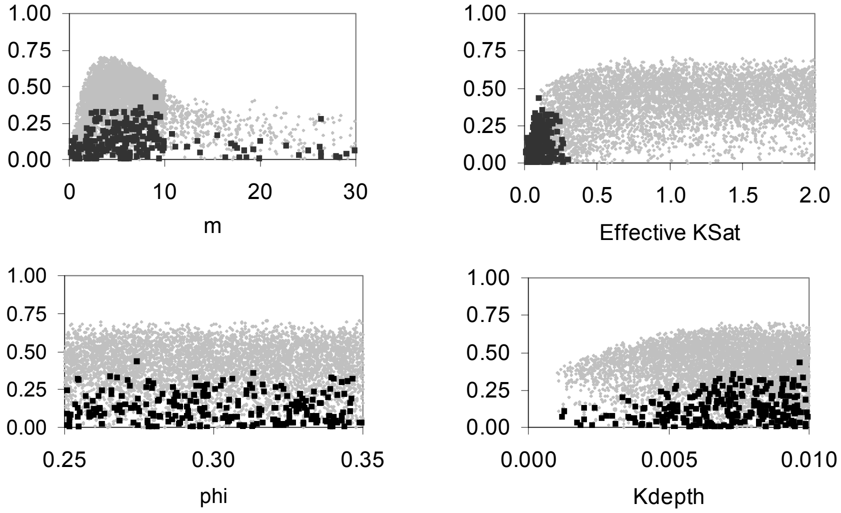


***Fig. 17.2** Parameter values versus model efficiency in the San Jose catchment, Chile. Simulations are classified further by those simulating >50% old water and those simulating <50% old water. See text for further description. Y-axis is the efficiency measure and the x-axis represents four parameters in the model (m is a shape parameter for hydraulic conductivity decline with depth; phi is soil porosity; Ksat is the effective hydraulic conductivity; and Kdepth is the groundwater recharge rate. Further details can be found in Vache (2003) and Vache et al. (2004).*

discussion, see Beven, 2001): grey dots represent % event water <50; black dots represent % pre-event water >50.

Our take-home message in the context of PUB is that: *time source components can be estimated for broad classes of catchment behaviour (saturation excess environments would produce <50% event water; infiltration excess environments would produce >50% event water). This simple time source partitioning may identify parameter sets that produce "efficient" results for the wrong reasons.* Considering these soft data, while highly uncertain, may be a way to bring a *collective field intelligence* to ungauged areas and transfer valuable process knowledge from gauged to ungauged basins, and in turn, key model calibration criteria.

MEAN RESIDENCE TIME

Arguably, one fundamental question of the PUB initiative is: what observations or analysis can be made from readily available data to elucidate emergent properties at the basin scale and across scales? Closely related are the key questions: How long does water reside in the catchment? What are the first-order controls on water residence time? How does this vary with catchment scale? We suggest that mean residence time (MRT) of stream baseflow is an integrative measure of catchment hydrological processes. MRT is the mean residence time of water molecules in a catchment from rainfall to runoff and represents the mean of a distribution of water ages (Maloszewski & Zuber, 1996).

With these questions in mind, we calculated the MRT of stream baseflow to examine how baseflow MRT might scale with basin area and other measurable catchment attributes (Fig. 17.3). We used a tritium-based approach to quantify stream

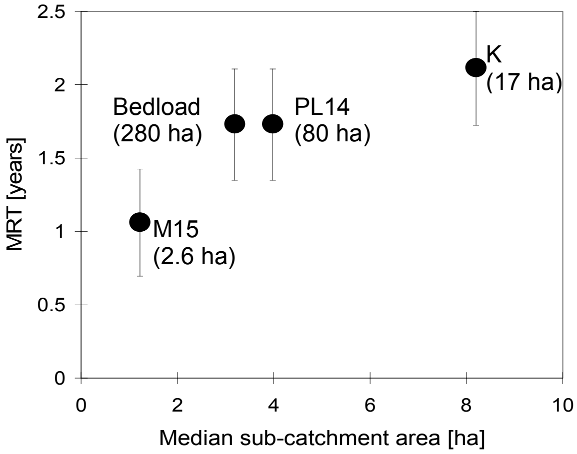


Fig. 17.3 *Mean streamwater age sampled at each catchment outlet on 30 April 1999 vs median sub-catchment size for each sampled catchment. Mean ages reported here are based on the average annual tritium input (McGlynn & Seibert, 2003).*

MRT in four nested catchments draining the Maimai Valley, New Zealand. We did not find a relationship between MRT and absolute catchment size. However, median catchment area, computed based on landscape analysis, showed a strong trend with MRT. MRT increased with increasing median sub-catchment size for each sampled catchment (McGlynn & Seibert, 2003). Streamwater sampled at the outlet of each gauged catchment was an admixture of streamwater from each of its tributaries; therefore the composition of streamwater at each sampled catchment outlet was controlled by the distribution of tributaries, related sub-catchment area, and the associated MRT of each.

These results suggest that, in this case, total catchment area is a poor measure of watershed function and that *landscape organization* is a first-order control on streamwater age. These results suggested a previously unrecognized linkage between landscape organization and catchment hydrology (McGlynn & Seibert, 2003). The implications include: sub-catchment size distribution might be a more suitable measure of watershed form and function than total catchment area since it reflects catchment hillslope and channel network structure, and landscape organization principles might provide a framework for up-scaling (aggregation), down-scaling (disaggregation), and transfer of emergent patterns in streamwater MRT.

We have recently developed a new topographically derived index that quantifies topographically-driven flowpaths and relates them to travel time (water age) distributions. In our approach, the distance-to-creek divided by gradient-to-creek measure is the combination of the flowpath lengths of every cell in the catchment to the stream channel divided by the gradient over that flowpath (McGlynn & Seibert, 2003).

The index can be viewed as a first approximation of Darcy's law assuming transmissivity is constant throughout the watershed:

$$\overline{V} = T \times I \quad \rightarrow \quad T = \text{a constant} \quad \rightarrow \quad \overline{V} = I \quad \rightarrow \quad TT_{Distribution} = \int \frac{D}{\overline{V}}$$

where: $\overline{V}$ is the average velocity, T is the transmissivity, I is the gradient (slope) along the flowpath to the stream, D is the flowpath distance to the stream, and TT is the travel time from each grid cell to the stream following the topographically driven flow routing algorithm. Assuming the first-order approximation that transmissivity is constant, this TT index is a rough measure of the distribution of runoff travel times in the catchment. In Fig. 17.4, we compare the $TT_{Distributions}$ (our RTD surrogate) for four diverse catchments from Maimai, New Zealand, to HJ Andrews, Oregon, to Mineral Creek, Montana, to Svartberget, Sweden, and find that the computed $TT_{Distributions}$ provide insight into catchment structure and highlight potential first-order differences in catchment water residence times and hydrological processes.

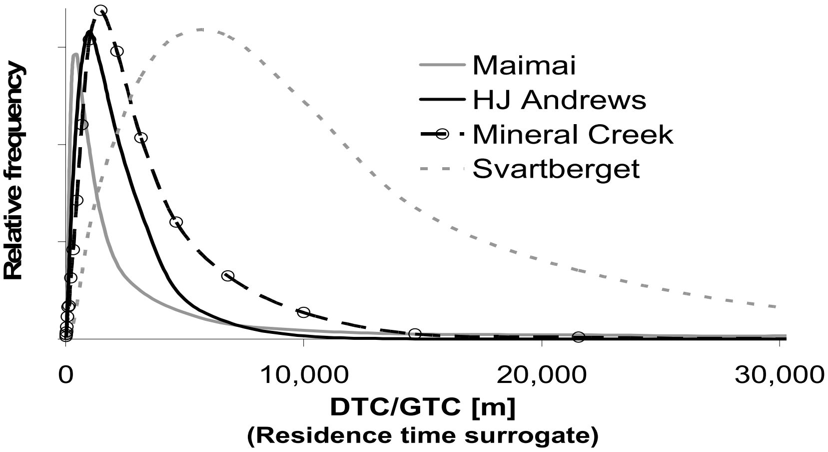


***Fig. 17.4** The integration of all the individual catchment flowpath lengths divided by the gradient along each individual flowpath. This measure represents the physical characteristics of the catchments, comparable to residence time distributions (water age) that represent the hydrological transport time in the catchment (Seibert & McGlynn, 2003).*

Simple landscape metrics appear to provide useful insight into ungauged basins and perhaps provide a way forward for ungauged catchment assessment and classification. Our results point to the role of topography, topology, and landscape organization as a template for hydrological processes. *Mean residence time–terrain/ landscape organization relationships could inform PUB by elucidating fundamental properties of basins that provide a first-order control on water age and hydrological processes.*

CONCLUSIONS

This paper has presented some ideas that we think may accelerate advancements within PUB from a process perspective. We argue that these new data sources and process ideas may form new measures of model acceptability, as the community moves away from calibration-reliant model schemes to more process-based descriptions. We argue that together, measures of water flowpath, source and age may help to constrain a conceptualization of runoff generation in gauged and ungauged basins and be a way forward to reducing predictive uncertainty with respect to our conceptualization of processes operating in catchments. Our key findings include:

1. Catchments appear to operate like a series of cryptic reservoirs that connect and disconnect. Looking for process thresholds may be a way forward to collapse hillslope complexity into a simple measure of emergent behaviour at the watershed scale.
2. Time source components estimated for broad classes of catchment behaviour may be used to identify parameter sets in our models that produce "efficient" results for the wrong reasons. Considering these soft data may be a way to bring a collective field intelligence to ungauged areas and transfer valuable process knowledge from gauged to ungauged basins, and in turn, key model calibration criteria.
3. Simple landscape metrics may provide a way forward for ungauged catchment assessment and classification. Our results point to the role of topography, topology, and landscape organization as a template for hydrological processes. Mean residence time–terrain/landscape organization relationships could inform PUB by elucidating fundamental properties of basins that provide a first-order control on water age and hydrological processes.

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