INVITED COMMENTARY

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Are all runoff processes the same?

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Introduction

Research on runoff processes to date has focused on the differences between the main divisions of runoff partitioning. Indeed, our major advancements in runoff theory have come with new differentiations of different forms of overland flow and subsurface stormflow. These studies of 'how runoff processes are different' have resulted in our current summaries of runoff regimes conceptually [e.g. the variable source area (VSA) concept] and codified in our models (e.g. TOPMODEL and its derivatives). Such summaries are captured in iconic figures in textbooks that we teach new generations of hydrologists – the most popular of which is shown in Figure 1, from Dunne (1983) and reproduced more recently in Wagener *et al.* (2007) and Mirus and Loague (2013).

Although such process differentiation was useful as new dominant forms of runoff were 'discovered' in different climates with different soils, slope morphologies and vegetation cover, continued differentiation does not appear helpful for improved understanding of runoff dynamics and streamflow generation. We seem to have exhausted the main list of runoff classes (infiltration excess overland flow, saturation excess overland flow and subsurface stormflow) some decades ago, with perhaps the last wave of minor updates to these processes coming in the 1980s and early 1990s in response to isotope tracing demonstration of the importance of stored water and clarification of differences between hydrologic and hydraulic time scales (see reviews by Bonell, 1993, 1998 and in Bachmair and Weiler, 2011).*

In the spirit of Sivapalan (2009), I wonder if it is more useful now to change our organizing question from 'how are runoff processes different?' to 'how are runoff processes similar'? In many ways, I am simply building upon and restating what others have said in recent, useful statements; on the importance of boundary conditions and flux closures (Beven, 2006), the need for new theory (e.g. Troch *et al.*, 2008) and new ways of considering runoff systems (Spence, 2010). Asking if all runoff processes are the same, conceptually, is a possible new way to come at runoff process research to aid improved process measurement, understanding and prediction (through new, flexible model structural approaches similar to Fenicia *et al.*, 2011) across diverse regions. It opens up new research questions such as: What can we learn about subsurface stormflow from overland flow (and vice versa)? Can we recognize things on the surface (where boundary conditions are visible) that may help guide new theory for the subsurface where such boundary controls are hidden?

Here, I present a simple analogical reasoning that shows how all runoff processes are similar. This comes following the viewing of many dozens of hillslopes and catchment sites across the world for 25 years, especially

*Although I do note that pioneering work in the 1990s in deglaciated landscapes particularly in Canada has shown new behaviours outside of these three classes, largely linked to groundwater and wetland processes (see Branfireun and Roulet, 1998; Peters *et al.*, 1995 and others).

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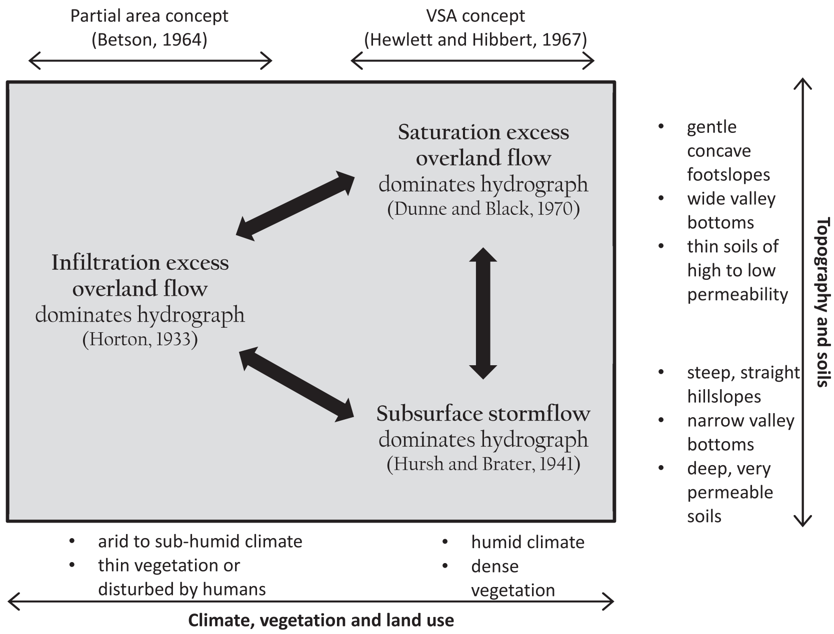

Figure 1. The three runoff classes based on discovery of overland flow from early descriptions of surface runoff due to infiltration excess overland flow (Horton, 1933) to partial area restriction of where infiltration excess can occur (Betson, 1964); to subsurface stormflow controls where all water is assumed to infiltrate to then form lateral flow contribution to channel stormflow (Hursh and Brater, 1941)) to saturation excess overland flow (Dunne and Black, 1970), the latter two in the context of variable source area theory. Modified from the original diagram by Dunne (1983)

diverse slopes from the tropics to subarctic and from mountains to plains in the past year. Indeed, a hallmark of science is seeing how seemingly odd things fit together. So, motivated simply by science for science sake and not model development, parameterization or calibration or pressing applied questions, I present some thoughts that I hope might spark new discussion within the hydrological community.

Overland flow and subsurface flow: two sides of the same coin?

On the face of it, Figure 1 does indeed classify three very different forms of runoff behaviour. However, at the heart of runoff initiation and activation for each lies similarities. If we have learned anything since the diagram's creation, it is that all runoff initiation is threshold-like and that boundary conditions control this to a very large extent. Indeed, it is the recognition of the primacy of boundary conditions that opens up new pathways of understanding of runoff partitioning in the environment. Perhaps the greatest boundary control is on partitioning of overland flow. If rainfall intensity exceeds soil infiltrability, then infiltration excess overland will occur. If not, then overland flow will only occur when groundwater rises to intersect the soil surface to produce saturation excess overland flow.

For years, I have excavated hillslope trenches and attempted to link subsurface stormflow response to streamflow response and chemistry. At some hillslope sites, filling and spilling of depressions at the soil-bedrock interface (i.e. perching of transient groundwater) were key to lateral flow generation, where connectivity of a thin transient saturated zone was a precondition for lateral flow generation at the hillslope scale (e.g. Tromp-van Meerveld and McDonnell, 2006a, b). At other sites, deeper (and sometimes more permanent) water tables rise from below into shallower, more transmissive layers or up through weathered rock or poorly permeable till into mineral soil, providing the pathway for rapid lateral hillslope release (e.g. Kendall *et al.*, 1999; Gabrielli *et al.*, 2012). Of course, others have seen these same behaviours before and after my observations, and I make no claim to the originality of these observations (e.g. Spence and Woo, 2003; Bishop *et al.*, 2004; Torres *et al.*, 1998). My thesis now, though, is that these two broad classes of subsurface stormflow parallel the two broad classes of overland flow at the land surface. Perhaps, in fact, they are effectively the same?

Consider Figure 2. This is a photo of patches of surface ponding produced during a rain event onto a poorly permeable soil. Even with ponding at the surface, there is loss to the unsaturated soil profile below as the patches of surface saturation expand. As

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Figure 2. Fill and spill behaviour from an agricultural field in North Dakota. Ponding produced by infiltration excess with growth and later connectivity of surface-saturated patches resulting in threshold runoff behaviour at the slope base. This behaviour appears common across all runoff types – surface and subsurface – where filling and spilling of microscale to mesoscale depressions lead to connectivity and emergent behaviour. Here, I define microscale as small depressions with correlation length scales on the order of centimetres to decimeters (within and between the tilled rows); mesoscale with correlation length scales of decimeters to metres (as shown in the patches circled in blue) and macrotopography as the general slope of the larger hillslope, in this photo on the order of 3–5 degrees. Photo: Michael Chu, North Dakota State University; used with permission

the event progresses, the ponded areas grow in size, connect to other downslope ponded patches until there is hillslope scale 'connectivity' and lateral flow at the slope base is produced. Like all runoff processes, this is very scale-dependent. However, if we restrict ourselves to the 'hillslope scale' – the scale at which we often consider fundamentally, the runoff generation process – the hillslope flow initiation 'threshold' is directly related to whole-slope connectivity of the ponded patches (although certainly other locations in the catchment may be linked to the stream before such widespread connectivity develops). This emergent behaviour is linked to microtopography, mesotopography and macrotopography on and of the slope (where microtopography refers to small depressions with correlation length scales on the order of centimetres to decimeters, mesotopography with correlation length scales of decimeters to metres and macrotopography as the overall slope angle). Such behaviour is three dimensional as there is topographic convergence into mesoscale hollows. A single infiltration measurement on the slope would not explain hillslope runoff behaviour because it is the *pattern* and *connectivity* of the saturation, and not the saturation at any one point position on the slope, that determines the flow threshold (and connected flowpath) at the hillslope scale.

Now imagine Figure 2 as a representation of the soil-bedrock interface. This is a challenging proposition because we are not used to seeing such things (again, in the spirit of seeing how seemingly odd things fit together). Challenging also because our current measurement technology limits our ability to characterize regularly such zones. Nevertheless, the aforementioned description of surface ponding is precisely what happens at depth at many subsurface stormflow generating sites. Graham *et al.* (2010) have stripped away soil from the Maimai hillslope to expose the partitioning 'surface'. This 'subsurface partitioning surface' or interface, has the same depressional filling, growth and connectivity behaviour of surface-saturated ponded patches in Figure 2, with coalescence of flow; 'loss' to deeper percolation along the flowpath; and ultimate connectivity of the ponded patches – only, obscured by soil – soil that, at the end of the day, matters little to the lateral flow transmission downslope (albeit with differences in the velocity of the water particles). Figure 3 illustrates this 'subsurface infiltration excess'.[†]

[†]This can also occur at horizontal boundaries as noted early on by Weyman (1973) and as shown in Figure 1.4 of Beven (2001).

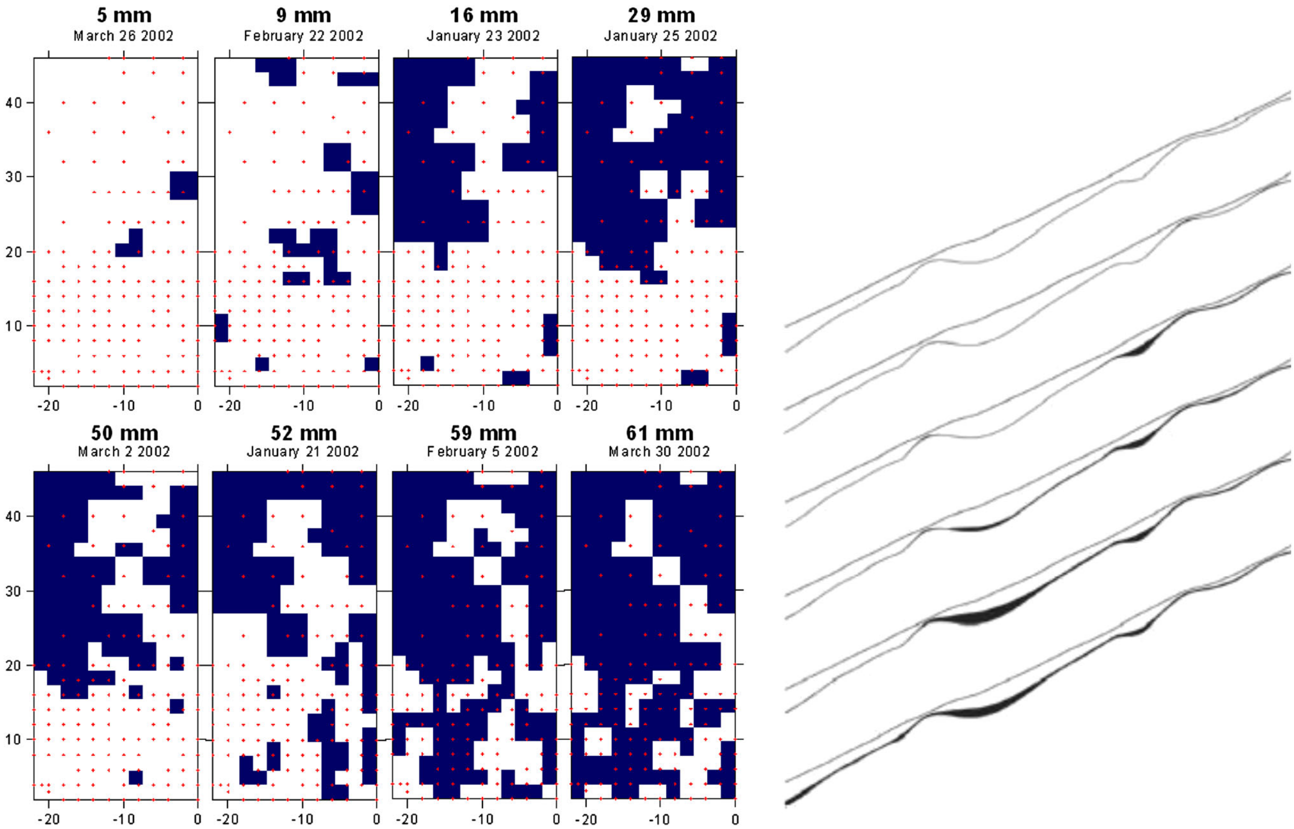

Figure 3. Fill and spill behaviour from a forested hillslope in Georgia, USA. Ponding produced by infiltration excess at the soil-bedrock interface with growth and later connectivity of saturated patches resulting in threshold runoff behaviour at the slope base. The right-hand side illustrates the same behaviour for a 2D cross section of the slope, showing that such runoff may be produced from the top-down; or from upper soil sections to lower slope sections. Modified from Tromp-van Meerveld and McDonnell (2006b)

To say that soil means little to the lateral downslope transmission, I mean that soil is mainly a delay or a filter to the development of 'ponding' at the subsurface boundary. Once ponding occurs and once the patch size of the saturated zones expands and coalesces, connectivity drives rapid lateral, downslope translation. Now, one might argue on theoretical grounds that response times are quite different in the case of overland flow with a free water surface and subsurface ponded flow at an interface associated with flow through a porous medium. However, on most slopes where I have worked that produce significant subsurface infiltration excess, extreme anisotropy (where lateral hydraulic conductivity is many times greater than vertical hydraulic conductivity) is the norm; where regular saturation (usually less than 0.25 the soil depth) at this soil-'rock' interface may drive eluviation and opening-up of larger interfacial flow gaps or macroporosity (see Uchida *et al.*, 2001 for review). Perhaps more importantly, many studies have shown, and Beven (2001) has summarized, that celerities in wet soils (with an effective porosity of ~0.01) can be of same order of magnitude as for overland flow (with an effective porosity of ~1). This means that subsurface water speeds can approximate overland flow – something many forest hydrologists have noted at steep, wet forest hillslopes with runoff ratios that compare to suburban catchments but with runoff comprised of mostly – or in some cases entirely – old water (as shown by Berman *et al.*, 2009).

The parallel between infiltration excess overland flow and infiltration excess subsurface stormflow is comparable to parallels between saturation excess overland flow and its mirrored subsurface counterpart. Saturation excess overland flow occurs, of course, when water tables rise from below and create zones of exfiltration or saturated areas, where return flow of groundwater and direct precipitation onto saturated areas mix to form rapid overland runoff (Dunne and Black, 1970). This can be due to the rise of permanent water table or due to a perched, more transient water table (as seen in Figure 4a). Consistent with the premise that all runoff is the same, my argument is that many seemingly disparate forms of subsurface stormflow can be collapsed into a similar subsurface form of this saturation excess overland flow

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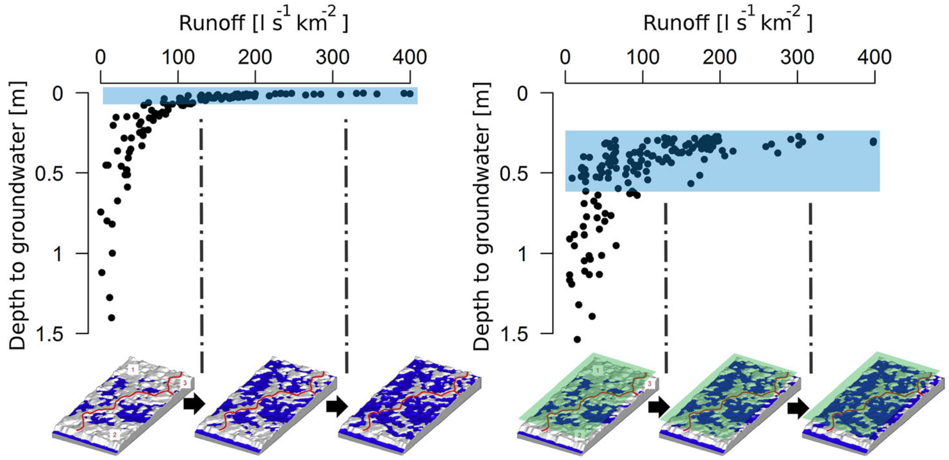

Figure 4. Conceptual rendering of saturation excess overland flow (a) and its subsurface counterpart (b) with data modified from Seibert *et al.* (2003). The time series of saturated patch connectivity is from the modeling of Frei *et al.* (2010), who showed striking similar behaviour for saturation excess as seen earlier by Tromp-van Meerveld and McDonnell (2006a) and shown in Figure 3

mechanism – where everything is the same, except that there is no manifestation of water at the soil surface; but where the process operates in a very similar fashion at depth.‡ This subsurface saturation excess – although not called that or recognized as such – has been shown regularly in till-mantled terrain, where water tables rise from till into transmissive mineral soil, where lateral flux rates can be very high, owing to higher saturated hydraulic conductivities as one rises up through the soil profile (as shown in Figure 4b). This transmissivity feedback (noted early on by Rodhe, 1981) occurs across a spectrum of conditions; from lateral flow induced by saturation excess in steep, wet, saprolitic soils (Torres *et al.*, 1998; Muñoz-Villers and McDonnell, 2012; Gabrielli *et al.*, 2012) to lower angled, till-mantled terrain where nonlinear increases in lateral flow occur within mineral soil above glacial till (Bishop *et al.*, 2004). Again, water tables rise – very much like saturation excess overland flow – up into zones of higher conductivity with extreme lateral anisotropy (see the extreme nonlinear relation between groundwater and streamflow in Seibert *et al.* (2003) as a vivid example of this nonlinearity).

Similar to the distinction between infiltration excess and saturation excess at the surface – one driven by saturation from above and one driven by saturation from below – the two broad classes of subsurface stormflow appear to share remarkable similarities to their overland flow counterparts. Subsurface infiltration excess is ponding at an interface from above whereas subsurface saturation excess is ponding above a higher transmissivity interface from below. Indeed, Frei *et al.* (2010) have shown a beautiful model-based illustration of the microtopographic and mesotopographic controls on saturated patches in a surface saturation excess overland flow environment (Figure 4). These are strikingly similar to what we might imagine for infiltration excess at the surface, fill and spill behaviour in the subsurface and, of course, subsurface saturation excess. All are controlled by a partitioning surface; however, for water tables that rise up into the partitioning surface (i.e. the zone of increased transmissivity) there may be a smearing of the contrast between fast and flow. Meaning that for infiltration excess and its subsurface counterpart, the sharpness of the boundary generates a more defined interfacial flow. In contrast, for saturation excess and its subsurface counterpart, this lateral flow region is thicker and smeared across the inflection of the saturated hydraulic conductivity with depth curve (again, see Figure 4 for a diagrammatic depiction of this). Despite this, all runoff forms do indeed display commonality of storage and release. New work by Appels (2013) suggests that infiltration excess may also be more sensitive to microtopographic relief of the surface topography – something I would expect would extend to its subsurface counterpart.

Figure 5 outlines a sequencing (from the lower panel to the upper panel) that I believe is common across all four of the response types discussed earlier. These same fundamental controls for all runoff types lead to emergent behaviour at the hillslope scale as depicted in Figure 5. If moving from the soil surface downwards, then the sequence is filling and spilling of small depressions, continued loss to the subsurface, connec-

‡Of course, this ignores the role of soil in modifying the timing and location of water delivery to the impermeable surface (e.g. vertical macropores—see Buttle and McDonald (2002) for an example). This is unlike the situation for overland flow, where we often assume that inputs of rain or snowmelt are spatially uniform at the hillslope scale.

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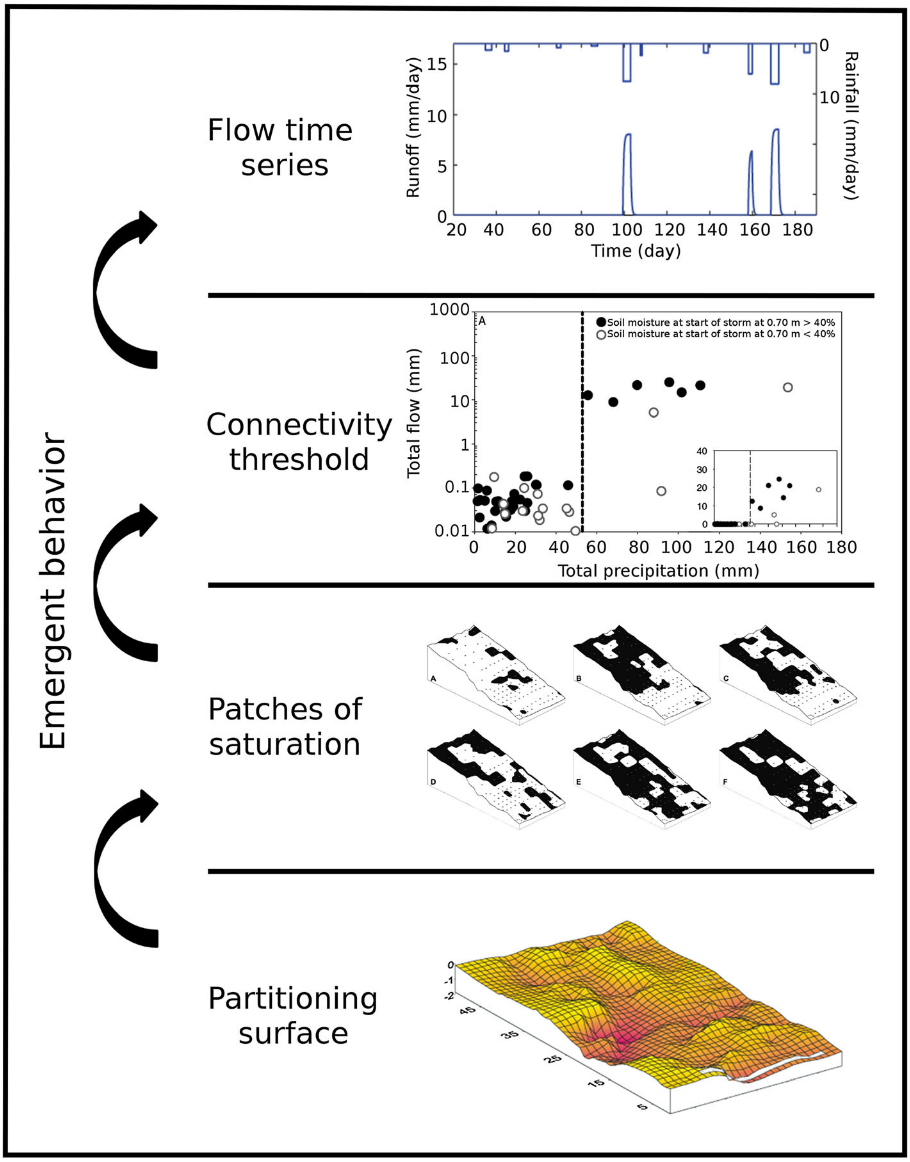

Figure 5. Emergent behaviour from a partitioning surface. The 'surface' may be the soil surface or the soil-bedrock interface or some other subsoil interface. Connectivity may be patches of saturation that are generated at the soil surface or in the subsurface at a subsurface interface by infiltration excess or saturation excess. In addition to all runoff process being the same, all runoff processes have filling, spilling, transmission losses, connectivity and thresholds at their core. Modified from the original diagram developed by Ciaran Harman, Johns Hopkins University, with his figure based on plots from Freer *et al*. (2002) and Tromp-van Meerveld and McDonnell (2006a,b) and modified from its use in Troch *et al*. (2009)

tivity of expanded saturated patches, threshold response at the base of the hillslope and ultimate filtering in a watershed comprised of multiple hillslope sections. If moving from the deeper subsurface upwards, then filling and spilling of small depressions in the partitioning surface is also generated, in this case from below and rising upwards. Irrespective of the direction of saturation development at the interface, the next phases are then the following: connectivity of expanded saturated patches followed by threshold response at the base of the hillslope, followed ultimately by the watershed's filtering of inputs from multiple hillslope sections. Now of course, as one moves beyond the single hillslope to make the conceptual jump to the watershed, other landscape elements come into play – perhaps riparian zones or colluvial filled hollows, or wetlands or talus slopes, etc. The point here is that for runoff generation at the scale of the basic watershed building block – the hillslope – all runoff generation processes share the conceptual sequencing of Figure 5

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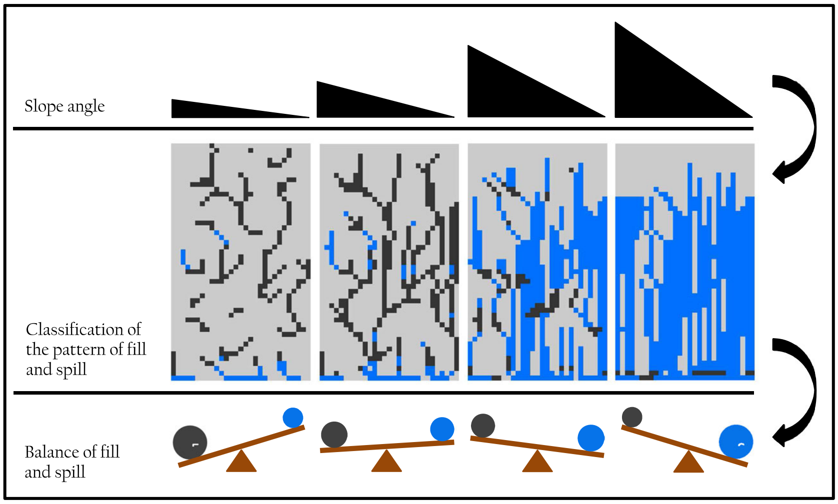

Figure 6. A classification of fill and spill from the surface in Figures 3 and 5. Lateral connectivity can be conceptualized as a balance of upslope accumulated area (black pixels) and downslope drainage efficiency (denoted by blue pixels). Where the slope is low, the accumulated patches of saturation are large but poorly connected as fill (F) dominates spill (S). As the macroscale slope steepens to the right-hand side, spill dominates over fill and water streams down the 'surface'; micro and mesotopography become less significant. Modified from Hopp and McDonnell (2009)

with patches of saturation and lateral connectivity and driven from above or below.

Does not variable source area theory explain all this?

So how does all of this relate to our existing runoff concepts? VSA theory is still the most durable runoff concept and many have argued that it can indeed accommodate all forms of runoff generation (Pearce *et al*., 1986). Despite being a student of Hewlett and trying to honor his VSA legacy (McDonnell, 2009), VSA has distinct limitations in this regard and scrutiny of Figure 1 shows quickly that VSA is not a home for all runoff types. Beyond the issues outlined in McDonnell (2003), VSA has further shortcomings that restrict its use as a platform for improved understanding of runoff generation: it does not deal with infiltration excess overland flow, it assumes that subsurface contributing areas grow upslope from the slope base, it does not apply in semi-arid and arid areas, and it does not apply to low relief wetland-dominated, peatland-dominated and lake-dominated watersheds. The upshot of all this is that no overarching theory currently exists for runoff generation across all climates, geology and topography (although Spence and Woo, 2006 have shown one nicely for subarctic basins). This is a problem – both for the experimentalist knowing how to approach a new area and wondering how to diagnose the dominant processes governing water flow and mixing en route to the stream, and for modellers who wish to capture the key aspects of runoff behaviour at a site, rather than simply imposing a one-size-fits-all model structure at the site. Although a one-size-fits-all theory may be just as problematic as a one-size-fits-all model structure (!), the recognition of the sameness of dominant controls of the many manifestations of runoff generation may be a way to interpreting and diagnosing runoff generation at 'ungauged' field sites.

So how might one implement such an approach? One way could be to consider the effects on filling and spilling at a partitioning surface. Figure 6 shows a possible simple metric that captures the main elements of fill and spill from the 'surface' in Figure 5. Although not a theory per se, it illustrates one possible framework that may help lead to new theory linked to the sameness of runoff processes: the force balance of upslope contributing area at a pixel on a hillslope and that pixel's downslope drainage efficiency (as defined by a metric like that of Hjerdt *et al*., 2004). Figure 6 illustrates four hillslopes with increasing (macroscale) steepness (and assumes for simplicity that variations in relief of the surface of the impeding layer stay the same in all cases). Lateral connectivity can be conceptualized as a balance of upslope accumulated area in the black pixels and downslope drainage efficiency as denoted by blue pixels. Where the macroscale slope is low, the accumulated patches of saturation are large but poorly connected as fill (F) dominates spill (S). As the macroscale slope steepens to the right-hand side, spill dominates over fill and water streams down the 'surface'; micro and mesotopography become less significant.

At the very least, the approach shown in Figure 6 immediately helps shift the measurement strategy from

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a few detailed point scale observations towards characterization and understanding of patterns of connectivity and how microscale, mesoscale and macroscale topography of the portioning surface may control it. Indeed, it can provide something of a roadmap for diagnosing catchment function in ungauged catchments – where knowing *a priori* that filling and spilling, connectivity and thresholds are the drivers of runoff production, then the quest is to find, map and describe these relations for any given site. In some ways, I see this as perhaps a field-based approach to the 'closure relation as holy grail' discussion ongoing in our science (Beven, 2006). What I am proposing here is a closure relation; that is, the precipitation – runoff threshold as closure. Of course, the closure problem is more than this. It is defining the fluxes to include in the balance equations (whether mass, energy or momentum). So getting the precipitation-runoff threshold is only a start and only a part of defining the storage-flow hysteresis as discussed by Beven (2006) and Spence (2010) and others. Not all precipitation above that threshold becomes runoff – how much becomes runoff and its timing as a boundary flux will depend on antecedent states, pattern of intensities, size of area being considered and other factors.

Conclusions and vision for the future

The question 'are all runoff processes the same' appears to have value beyond simple rhetoric. Overland flow and subsurface stormflow do appear to be two sides of the same coin. Although not throwing out any detailed soil physics fundamentals, I think that the evidence is clear that continued emphasis on point scale observations is futile unless aimed squarely at larger scale connectivity pattern development. Or, as stated in McDonnell (2003), the hillslope is not a linear superposition of soil patches or cores; rather there is structure, architecture and pattern that controls how the system connects up and activates. New levels of hydrological abstraction (conceptually, not in terms of withdrawals!) are needed. What has stymied me for years is the constraint that VSA theory places on runoff process conceptualization. Although I have not offered a thoroughgoing analysis of runoff generation in this short commentary, the simple premise that all runoff processes are the same opens up new avenues to explore: Is there common emergent behaviour across all runoff types? How can this recognition guide field diagnosis, namely what to measure in what order and why? Are there simple threshold metrics that might collapse process heterogeneity and pesky point scale details into a single function for hillslope flow initiation?

Although not addressing scale issues in this commentary, new work is providing exciting and provocative new observations (e.g. Shaw *et al*., 2012) that may suggest that such surface fill and spill behaviour (from above and below) may occur writ large across the landscape with new storage-discharge theory across scales that could ultimately shape a formalization of threshold-connectivity elements within a storage excess framework (Sayama *et al*., 2011). Such a framework could, at last, link flow and transport and provide a pathway to linking storage excess in the landscape to fundamental transport metrics like streamwater mean residence time.

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