

When interflow also percolates: downslope travel distances and hillslope process zones

C. Rhett Jackson,^{1*}
Menberu Bitew¹ and Enhao Du²

¹ Warnell School of Forestry and
Natural Resources, University of
Georgia, GA 30602, Athens, USA

² Climate Science Department,
Lawrence Berkeley National
Laboratory, CA 94720, Berkeley, USA

*Correspondence to: C. Rhett Jackson,
Warnell School of Forestry and Natural
Resources, University of Georgia, Athens,
GA 30602, USA.
E-mail: rjackson@warnell.uga.edu

Introduction

In hillslopes with soils characterized by deep regoliths, such as Ultisols, Oxisols, and Alfisols, interflow occurs episodically over impeding layers near and parallel to the soil surface such as low-conductivity B horizons (e.g. Newman *et al.*, 1998; Buttle and McDonald, 2002; Du *et al.*, In Review), till layers (McGlynn *et al.*, 1999; Bishop *et al.*, 2004), hardpans (McDaniel *et al.*, 2008), C horizons (Detty and McGuire, 2010), and permeable bedrock (Tromp van Meerveld *et al.*, 2007). As perched saturation develops within and above these impeding but permeable horizons, flow moves laterally downslope, but the perched water also continues to percolate through the impeding horizon to the unsaturated soils and saprolite below. Perched water and solutes will eventually traverse the zone of perched saturation above the impeding horizon and then enter and percolate through the impeding horizon. In such flow situations, only lower hillslope segments with sufficient downslope travel distance will deliver water to the riparian zone within the time scale of a storm. Farther up the slope, lateral flow within the zone of perched saturation will act mainly to shift the point of percolation (location where a water packet leaves the downslope flow zone in the upper soil layer and enters the impeding layer) down the hillslope from the point of infiltration. In flatter parts of the hillslope or in areas with little contrast between the conductivities of the upper and impeding soil layers, lateral flow distances will be negligible.

From Darcy's law, we can estimate the downslope travel distance for quasi-steady-state conditions within the saturated layer assuming Boussinesq (slope parallel) flow above the restrictive layer and normal flow (perpendicular to the slope) through the restrictive layer to unsaturated soils below (Figure 1). Using a downslope flow vector, we must employ an orthogonal normal vector and avoid Harr's (1977) mistake of adding non-orthogonal and non-independent gradient vectors in calculating flow directions. We assume that each layer is isotropic, and the impeding layer is saturated or nearly so and drains freely to an unsaturated layer below (pressure head equals zero at the base of the impeding layer). We assume diffuse porosity within the impeding layer so percolation is not restricted to randomly spaced discontinuities. With these assumptions generally applicable to hillslopes with deep regoliths and a low conductivity layer paralleling the soil surface, we will calculate downslope travel distances for reasonable combinations of slopes, conductivities, and impeding layer thicknesses; evaluate these distances with respect to typical slope lengths; map the downslope travel distances on watersheds with soil and slope conditions matching these assumptions; and discuss how coupling Boussinesq downslope flow and percolation affect our understanding of the potential zonation of lateral flow processes.

Received 21 January 2014

Accepted 23 January 2014

INVITED COMMENTARY

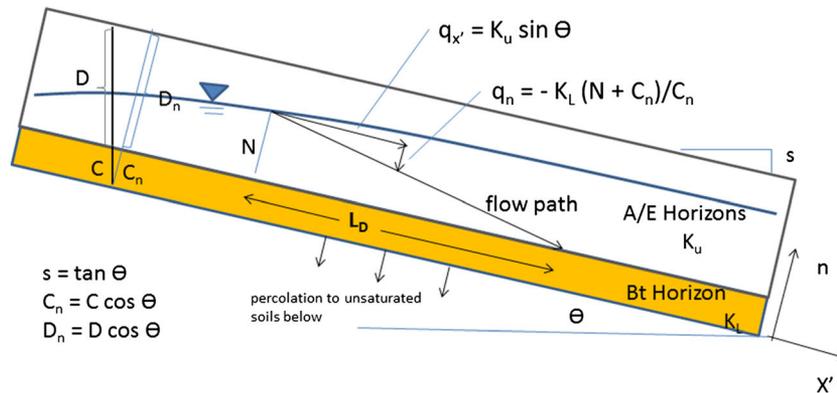


Figure 1. Hillslope flow components and soil characteristics used to calculate downslope travel distance, L_D , for perched Boussinesq (slope parallel) flow with percolation. Gradients and flow vectors are calculated for downslope and normal coordinates

Calculation of Downslope Travel Distances

The downslope travel distance of a water parcel infiltrating to the top of the saturated lens is simply the time it takes to cross the saturated lens (via the normal flow component) multiplied by the magnitude of the downslope flow component. An equivalent result is achieved using either Darcy or pore velocities as both the normal and downslope flow components that would be scaled by the same upper layer porosity. We will consider the Darcy velocities here, and we will assume that the hydraulic gradient in the downslope direction $\delta H/\delta x'$ can be closely approximated as $\sin \Theta$ (ignoring the effect of variation in the thickness of the saturated lens) (Figure 1). Assuming pressure head of zero at the bottom of the impeding layer, the absolute value of the hydraulic gradient in the normal direction across the impeding layer can be approximated as the sum of the normal thicknesses of the saturated lens above the impeding layer, N , and the impeding horizon, C_n , divided by the impeding horizon thickness, C_n :

$$q_{x'} = K_u \sin \Theta \text{ and} \quad (1)$$

$$q_n = -K_L(N + C_n)/C_n \quad (2)$$

$q_{x'}$ and q_n are the lateral and normal components of Darcy's velocity; K_u and K_L are the hydraulic conductivity of upper and impeding (lower) layers. The resultant is the sum of these orthogonal Darcy velocities. After infiltrating to the top of the saturated lens, the time for a water molecule to traverse the saturated zone above the impeding layer is equal to the normal thickness of the saturated zone above the impeding layer divided by the normal Darcy velocity:

$$T, \text{ transit time across the upper soil} \\ = N/(K_L(N + C_n)/C_n) \quad (3)$$

The downslope travel distance, L_D , is then the transit time multiplied by the downslope velocity:

$$L_D = K_u(\sin \Theta) N/(K_L(N + C_n)/C_n) \quad (4)$$

rearranging, $L_D = (K_u/K_L) (\sin \Theta/[(N + C_n)/C_n])N$ (5)

Therefore, the downslope travel distance is simply the product of the normal thickness of the saturated zone above the impeding layer and the ratios of the conductivities and the hydraulic gradients:

$$L_D = K \text{ ratio} * \text{Gradient ratio} * N \quad (6)$$

The conductivity ratio and the hydraulic gradient ratio are equally important, and their product is the downslope travel distance for a saturated lens with a normal thickness of 1 m. Downslope travel distances are driven by the conductivity ratio, not the absolute value of the impeding layer conductivity. Subsurface storage as a result of impeding layer concavities (Buttle *et al.*, 2004; Tromp van Meerveld HJ and McDonnell, 2006) is ignored. Including subsurface topography would change the threshold for interflow initiation in a dynamic analysis and also lead to spatial variability in the normal gradient, with higher gradients in the concavities. Nevertheless, as long as the slope of the saturated lens can be reasonably approximated, this estimation of average downslope travel distance is still valid for perched saturated flow situations over impeding layers with irregular surfaces.

Downslope Travel Distances Over the Range of Likely Conductivity and Gradient Ratios

With Equations (5) or (6), downslope travel distances can easily be calculated for all likely combinations of conductivity and gradient ratios. Because the downslope travel distance scales linearly with the normal thickness of

the saturated layer above the impeding zone, N , we have calculated travel distances for $N=1$ m. Maximum values of downslope travel distances can be estimated by setting N equal to the normal thickness of the topsoil. The high end of reported ranges for average forested topsoil conductivities is about 2000 mm/h, and the lower range of average conductivities for B horizons is around 1 mm/h, so we used conductivity ratios ranging from 1 (no layering and no saturated interflow) to 2000 (very high contrast between the topsoil and the impeding layer). The minimum value of the normal gradient is 1 (a thin saturated lens and a very thick impeding horizon), and an extremely high value would be around 9 ($N=2$ m and $C_n=0.25$ m). We have used slopes ranging from 1 (0.57°) to 100% (45°), and $\sin \Theta$ thus ranges from 0.0099 to 0.71. For these ranges of downslope and normal gradients, possible gradient ratios range from 0.001 (1% slope with a very thin impeding layer) to 0.7 (100% slope with a normal gradient of 1). Within the resulting field of possibilities, downslope travel distances are small relative to hillslope lengths except for combinations of very high conductivity and gradient ratios (Figure 2). At the hillslope that we are studying at the Savannah River Site in the Sandhills of South Carolina (Du *et al.*, In Review), the maximum downslope travel distance is about 29 m (maximum surface conductivity of 2000 mm/h, clay conductivity of 5 mm/h, surface slope of 11%, normal clay thickness of about 2 m, and a maximum saturated zone of 1-m normal thickness above the impeding layer), meaning that interflow on this slope does not deliver water to streams or valleys but simply shifts the percolation of infiltrated water, at most, 30-m downslope. Many

interflow studies have been conducted in steep terrain underlain by low permeability rock and therefore feature high conductivity and gradient ratios and, thus, long interflow travel distances. In such cases, interflow travel distances can exceed 1000 m (Figure 2).

Implications and Considerations

In rolling, highly weathered terrain where water perches upon a porous B horizon, downslope travel distance estimation predicts that interflow delivers water to the valleys from only the lower reaches of the slope and suggests zonation of the dominant hydrologic processes from ridgetop to stream. In such terrain, we can envision four dominant process zones (Figure 3). On the relatively flat ridgetops and intermediate benches, interflow is an unimportant process, and vadose zone hydrology is largely vertical. Over most of the slope, interflow acts to redistribute percolation of water and solutes, shifting the point of infiltration by the travel distance. Of course, the movement of solutes is complicated by dispersion, mixing with old water, sorption, and desorption, so this calculation addresses only the net movement of solutes. Only rainfall that falls on the lower slopes within the downslope travel distance of the valley may be delivered to the valley as saturated interflow. In this lower region of the slope, interflow may deliver water directly to the stream if the channel is cut to the base of the slope, but it is more likely that interflow acts to subsidize valley hydrologic processes (e.g. McGlynn and McDonnell, 2003; Jencso *et al.*, 2010). Interflow from the lower portions of valley-adjacent hillslopes can be considered an extension of the variable source area. Groundwater mounding in the alluvial aquifer or toe slope (Ragan, 1968; Sklash and Farvolden, 1979, Abdul and Gillham 1989) has been attributed to the proximity of the water table to the ground surface and the relative wetness of the soils there, but interflow contribution from the lower slopes can also contribute to the formation of groundwater mounds (Figure 3). The degree to which interflow subsidizes groundwater mounding *versus* saturation excess flow depends on the valley topography, particularly the existence and thickness of a terrace deposit above the floodplain. This process zonation exists even when the saturated lens is continuous from the ridgetop to the stream as observed by Detty and McGuire (2010).

To illustrate the variation of downslope travel distances over first-order watersheds with soils and topography matching the assumptions herein, we estimated and mapped the downslope travel distances on three first-order watersheds in the Sandhills of South Carolina located within the Savannah River Site and

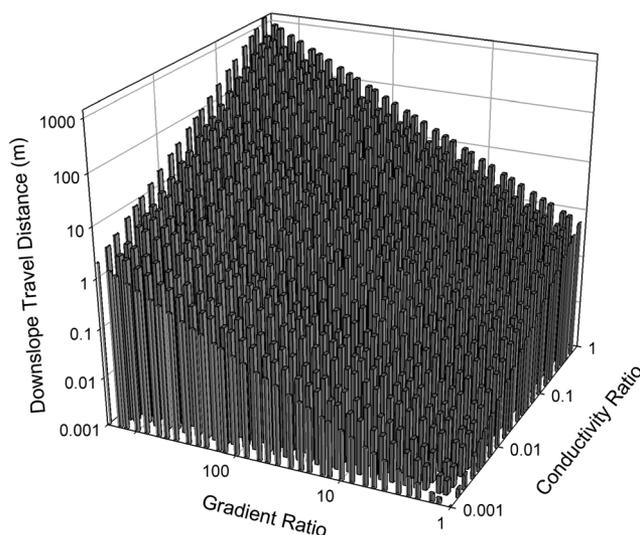


Figure 2. Downslope travel distances (metres) for all likely combinations of gradient and conductivity ratios. Calculated for a 1-m thick saturated layer above the impeding horizon ($N=1$ m). Travel distances scale linearly with N

INVITED COMMENTARY

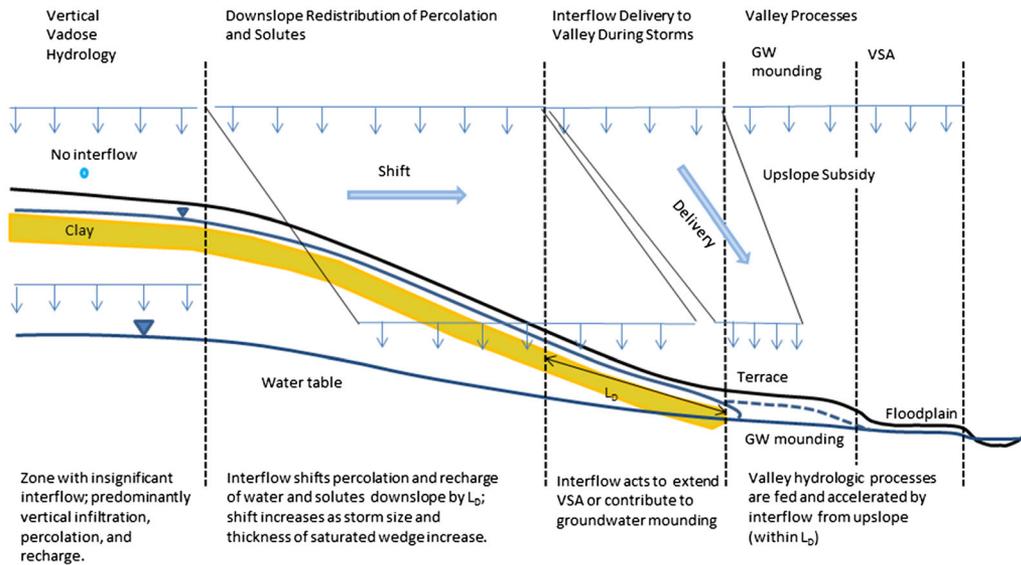


Figure 3. Implications of saturated interflow travel distance for the zonation of hillslope flow processes

described in Du *et al.* (In Review). Slopes were calculated based on the elevation difference and distance to the nearest stream cell generated from 10-m digital elevation model. Normal thickness of the impeding layer and conductivities was estimated from auger investigations and compact constant head permeameter measurements. Within these watersheds, maximum downslope travel distances are 36 m, and these higher values are generally located on steeper slopes directly adjacent to the stream valleys (Figure 4). Over most of the watersheds, downslope travel distances are quite short, less than 15 m. The travel distance maps also reveal the very low slopes within the riparian valleys

and wetlands where the valley hydrologic processes of saturation excess flow and groundwater mounding are dominant.

Travel distances scale directly with the thickness of the perched saturated zone above the impeding layer. While others have demonstrated the existence of rainfall/soil moisture thresholds for the initiation of interflow (e.g. Uchida *et al.*, 2005, Lehmann *et al.*, 2007), this analysis also shows that the upslope interflow contributing length to the stream valley increases with the thickness of the saturated layer, so the cumulative interflow contribution to the valley during a storm should increase nearly linearly with the size of the storm

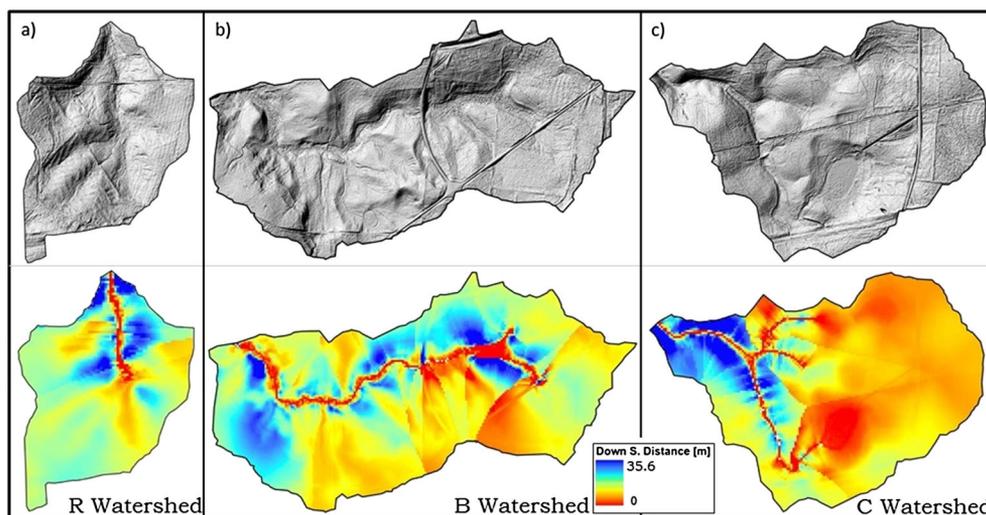


Figure 4. Map of downslope travel distances for three first-order watersheds in the Sandhills of South Carolina (Du *et al.*, In Review) based on average slope from each 10 × 10-m digital elevation model pixel and the nearest stream cell. A hillshade map based on light detection and ranging of each watershed is shown above the travel distance map. The C watershed features several Carolina Bay depositional wetlands in the upper part of the watershed, and these appear as circular or elliptical red areas

minus the threshold. While not a surprising result, this analysis clearly demonstrates that the relative importance of interflow on hillslopes falls on a continuum, leaving hydrologists with somewhat subjective decisions about when interflow must be considered and when it can be safely ignored. This analysis strongly suggests that many process-based models need to be modified to account for the longitudinal zonation of flow processes in hillslopes where such zonation is likely. The results also indicate that slope-parallel flow with negligible percolation is the dominant process in steep hillslopes with high conductivity contrasts between the topsoil and the impeding layer. In such cases, interflow models that ignore percolation (e.g. Troch *et al.*, 2003; Jackson and Cundy, 1992) are appropriate.

The limitations of our observational systems make it difficult to put interflow into context with other hillslope processes. Piezometer networks inform little about how far interflow moves. Because interflow often mixes with riparian water before entering streams, end-member mixing analysis cannot tell us how much of the 'old' riparian water arrived via interflow. Interception trenches measure only what is passing a given contour and impose flow-altering boundary effects. Tensiometers are temperamental and difficult to manage deeper in the soil profile. Given the variation of hillslope characteristics and the difficulties of monitoring interflow, generalizing the interpretation of results from different hillslope process studies is difficult. Consideration and mapping of downslope travel distances may be a tool for understanding and synthesizing results of interflow studies in different hillslope environments. Explicitly considering the normal flow component (percolation) as well as the downslope flow component allows the relatively easy identification and mapping of likely dominant process zones or hydrologic response units over entire watersheds (*sensu stricto* Devito *et al.*, 2005) based on soil characteristics and local topography. The resulting process zonation can be applied to water quality management issues and used to help define spatially variable riparian buffer widths as suggested by Dosskey *et al.* (2002 and 2013) and Rivenbark and Jackson (2004). However, as with most distributed modelling concepts, only the topography variables are easy to measure and map. Calculating downslope travel distances for perched interflow still requires knowledge of soil hydraulic conductivities and depths (e.g. Buttle *et al.*, 2004).

In summary, by considering percolation simultaneously occurring with saturated interflow, we can easily estimate the likely downslope travel distances of water and solutes before reaching the impeding layer and percolating through it. For many hillslope environments, particularly for rolling topography underlain by porous but impeding soil horizons, these downslope travel

distances are much shorter than slope lengths and suggest zonation of the importance and relevance of interflow along hillslope catenas. Interflow only contributes to and subsidizes valley hydrologic processes from the lower slopes, within the downslope travel distance from the riparian valley.

Acknowledgements

This idea was spawned from a large-scale collaborative investigation of dominant hydrologic processes within small watersheds of the Sandhills of South Carolina within the Savannah River Site. Collaborators who have contributed substantially to thinking about interflow processes in this environment and their implications for water quality management include Jeff McDonnell, Luisa Hopp, Kellie Vache, Julian Klaus, Natalie Griffiths, James Greco, and John Blake (project manager for the USDA Forest Service). Benjamin Morris collected much of the field data from which our observational database was created. The research on which this was based was supported by grants from the US Department of Energy's Bioenergy Technology Office and the USDA Forest Service. Pondering of hydrologic observations made as part of the Coweeta LTER (DEB-0823923) also influenced this analysis.

References

- Abdul AS, Gillham R. 1989. Field studies of the effects of the capillary fringe on streamflow generation. *Journal of Hydrology* 112: 1–18.
- Bishop K, Seibert J, Kohler S, Laudon H. 2004. Resolving the double paradox of rapidly mobilized old water with highly variable responses in runoff chemistry. *Hydrological Processes* 18: 185–189.
- Buttle JM, McDonald DJ. 2002. Coupled vertical and lateral preferential flow on a forested slope. *Water Resources Research* 38: 18–1.
- Buttle JM, Dillon PJ, Eerkes GR. 2004. Hydrologic coupling of slopes, riparian zones and streams: an example from the Canadian Shield. *Journal of Hydrology* 287: 161–177.
- Detty JM, McGuire KJ. 2010. Topographic controls on shallow groundwater dynamics: implications of hydrologic connectivity between hillslopes and riparian zones in a till mantled catchment. *Hydrological Processes* 24: 2222–2236.
- Devito K, Creed I, Gan T, Mendoza C, Petrone R, Silins U, Smerdon B. 2005. A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider? *Hydrological Processes* 19: 1705–1714.
- Dosskey MG, Helmers MJ, Eisenhauer DE, Franti TG, Hoagland KD. 2002. Assessment of concentrated flow through riparian buffers. *Journal of Soil and Water Conservation* 57: 336–343.
- Dosskey MG, Qiu Z, Kang Y. 2013. A comparison of DEM-based indices for targeting the placement of vegetative buffers in agricultural watersheds. *Journal of the American Water Resources Association* 49: 1270–1283.
- Du E, Jackson CR, Klaus J, McDonnell JJ, Griffiths NA, Williamson MF, Greco JM, Bitew M. In review. More fill, less spill: interflow behavior over a low-angle argillic layer. Submitted to *Hydrological Processes*.
- Harr RD. 1977. Water flux in soil and subsoil on a steep forested slope. *Journal of hydrology* 33: 37–58.

- Jackson CR, Cundy T. 1992. A model of transient, topographically-driven, saturated subsurface hillslope flow. *Water Resources Research* 28: 1417–1427.
- Jencso KG, McGlynn BL, Gooseff MN, Bencala KE, Wondzell SM. 2010. Hillslope hydrologic connectivity controls riparian groundwater turnover: Implications of catchment structure for riparian buffering and stream water sources. *Water Resources Research* 46: W10524.
- Lehmann P, Hinz C, McGrath G, Tromp - van Meerveld HJ, McDonnell JJ. 2007. Rain Threshold for hillslope outflow: an emergent property of flow path connectivity. *Hydrology and Earth System Science* 11: 1047–1063.
- McDaniel PA, Regan MP, Brooks E, Boll J, Barndt S, Falen A, Young SK, Hammel JE. 2008. Linking fragipans, perched water tables, and catchment-scale hydrological processes. *Catena* 73: 166–173.
- McGlynn BL, McDonnell JJ. 2003. Quantifying the relative contributions of riparian and hillslope zones to catchment runoff. *Water Resources Research* 39: 1310.
- McGlynn BL, McDonnell JJ, Shanley JB, Kendall C. 1999. Riparian zone flowpath dynamics during snowmelt in a small headwater catchment. *Journal of Hydrology* 222: 75–92.
- T van Meerveld HJ, McDonnell JJ. 2006. Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. *Water Resources Research* 42: W02411.
- Newman BD, Campbell AR, Wilcox BP. 1998. Lateral subsurface flow pathways in a semiarid ponderosa pine hillslope. *Water Resources Research* 34: 3485–3496.
- Ragan RM. 1968. An experimental investigation of partial area contributions. *IAHS Publ* 76: 241–251.
- Rivenbark BL, Jackson CR. 2004. Concentrated flow breakthroughs moving through silvicultural streamside management zones: southeastern Piedmont, USA. *Journal of the American Water Resources Association* 40: 1043–1052.
- Sklash MG, Farvolden RN. 1979. The role of groundwater in storm runoff. *Journal of Hydrology* 43: 45–65.
- Troch PA, Paniconi C, van Loon EE. 2003. Hillslope-storage Boussinesq model for subsurface flow and variable source areas along complex hillslopes: 1. Formulation and characteristic response. *Water Resources Research* 39: 316.
- Tromp van Meerveld HJ, Peters NE, McDonnell JJ. 2007. Effect of bedrock permeability on subsurface stormflow and the water balance of a trenched hillslope at the Panola Mountain Research Watershed, Georgia, USA. *Hydrological Processes* 21: 750–769.
- Uchida TI, T-v Meerveld, McDonnell JJ. 2005. The role of lateral pipe flow in hillslope runoff response: an intercomparison of non-linear hillslope response. *Journal of Hydrology* 311: 117–133.