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Discussion

Reply to comment by Tromp van Meerveld and McDonnell on Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes

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We thank Tromp van Meerveld and McDonnell (this issue) for their comment on our paper. They raise important issues about catchment response and the role of soil moisture. It is clearly important to reconcile different sources of field evidence.

Tromp van Meerveld and McDonnell argue that at the Panola research hillslope, transient subsurface saturation rather than root-zone soil moisture is the causative mechanism of subsurface stormflow. They then generalise this finding in two ways: (a) that it not only applies to event scale subsurface stormflow but to longer time scale subsurface flow, and (b) that it not only applies to Panola but also to most other catchments of the world including the Tarrawarra et al. catchments. While we fully agree with the Panola results we believe that the two generalisations need to be treated with caution. We wish to respond to these generalisations in a process context but first we wish to comment on the interpretation of soil moisture patterns and its causative role in lateral subsurface flow.

We agree that saturation is important for generating significant lateral subsurface flow because of the nonlinearity of the hydraulic conductivity (including macropore effects, etc.)—soil moisture relationship. Essentially the hydraulic conductivity reduces so quickly as the soil desaturates that water will only move over significant (e.g. hillslope) distances if at least part of the soil profile is saturated. Whether or not there is a link between the root-zone soil moisture and the occurrence of saturated subsurface lateral flow depends on where the lateral flow is occurring, which is essentially dependent on the soil profile characteristics. When interpreting soil moisture patterns, we argue that the soil moisture is the cumulative result of the fluxes of water into and out of a volume of soil. Thus if lateral flow is important in either directly draining or contributing to water in the root zone, then the root-zone soil moisture will be an indicator of those processes, although the soil moisture pattern clearly needs to be interpreted in the context of properties of the soil profile. We have perhaps not made clearly enough the distinction between the indirect role of

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soil moisture in the causality of lateral flow and the use of soil moisture as an indicator of lateral flow (in certain circumstances).

It is important to recognize that rainfall-runoff processes vary between landscapes and that these different processes will have different signatures when examined through similar measurement paradigms, at least where the measurements provide a critical test of the process hypotheses. Catchments are often categorised in terms of the dominant rainfall-runoff processes into infiltration excess, saturation excess and subsurface stormflow dominated regimes. Soil moisture, saturation and subsurface lateral flow play different roles in each of these. The results discussed by Tromp van Meerveld and McDonnell relate to catchments where subsurface stormflow dominates. The landscapes we have studied vary to some extent in their runoff processes but are mostly dominated by saturation excess processes. Infiltration excess runoff is not important in any of the landscapes considered here and is not discussed further.

Subsurface lateral flow is important in both subsurface storm flow and saturation excess, the key distinction is the timescale over which the hillslope drains and this is controlled by the saturated hydraulic conductivity and its spatial variability (i.e. presence, density and connectivity of preferred flow paths, macropores and soil pipe networks), the drainable porosity and soil depth and profile characteristics. Where the time taken to drain the hillslope is of the same order of magnitude or less than the typical storm duration, subsurface stormflow will dominate. Where the time taken to drain the hillslope is similar to or longer than the inter-storm period, water will tend to accumulate on the hillslope during wet periods (i.e. where rainfall exceeds potential evapotranspiration), profile saturation will occur for long periods of time and saturation excess runoff will be important.

In the case of subsurface stormflow, Tromp van Meerveld and McDonnell are correct in arguing that the antecedent soil moisture pattern is not closely linked to the pattern of transient saturation and subsurface flow. The observation that transient subsurface saturation at Panola does not correspond well with areas of high antecedent soil moisture fits into the understanding of the processes there. Transient saturation occurs mainly where soils are shallow, where bedrock contributing area is high or where there is an impediment to lateral drainage. In other words saturation occurs where there is limited storage available in the soil profile due to shallow depth or where water concentrates due to either convergence or a drainage constraint. Shallow soils are also likely to be associated with low antecedent moisture contents due to more rapid drying of the profile by both drainage and evapotranspiration (at least in terms of moisture content rather than profile water storage). Also because drainage is rapid and saturation transient at the inter-storm time scale in such catchments, the spatial root zone or profile soil moisture pattern is likely to rapidly become controlled by the soil water retention properties, namely field capacity. Thus, there may also be soil property (e.g. field capacity) variations that could contribute to the observations at Panola. Thus Panola and catchments dominated by subsurface stormflow in general represent situations where antecedent root-zone soil moisture is likely to be a poor indicator of subsurface lateral flow.

Saturation excess runoff processes are also influenced by subsurface lateral flow. However, the lateral flow processes occur at timescales significantly longer than the storm duration due to slow drainage rates. Lateral flow in these catchments also tends to be a more constant process so saturation in the profile exists for long periods. Piezometer records show this to be the situation at Tarrawarra. We do not have piezometer readings from the New Zealand catchments but 30–60 cm soil moisture time series indicates that it is also the case there. These catchments also have a drainage impediment near the bottom of the root zone, so saturation in the root zone is strongly correlated with root zone (0–30 cm) soil moisture in these cases. This means that here it is reasonable to use the soil moisture pattern as an indicator of the occurrence (and rate) of subsurface lateral flow.

In the context of this debate it is also worth remembering that it is common in discussions of hillslope hydrology to give the role of topography a high prominence, often without justification (Grayson and Western, 2001). It is important to recognise that topography is only one element in controlling the lateral flow, soil moisture and runoff response of a catchment. Our data clearly illustrate that lateral flow processes are only important in some landscapes (Western et al., 2004; Wilson et al., 2004) and at some times (Grayson et al., 1997; Western et al., 1999). Other spatially varying properties (e.g. soil properties) and processes (e.g. spatially varying evaporative forcing) also influence the soil moisture pattern (Western et al., 2004; Wilson et al., 2004). Where there are different processes dominating behaviour in different landscapes, we should be incorporating this knowledge into our models, as is well argued by Tromp van Meerveld and McDonnell (this issue). While there are a variety of sources of spatial variability in catchments, topography often has some useful but limited predictive power. However, as Tromp van Meerveld and McDonnell note, the proliferation of models relying on the topographic wetness index without information on whether this represents the dominant processes, is worrying.

In summary, we agree with Tromp van Meerveld and McDonnell that saturation at some point in the profile is required for significant subsurface lateral flow. In some cases, notably where saturation and lateral drainage occurs over relatively long time scales, the soil moisture pattern is likely to be a reliable indicator of the occurrence of lateral subsurface flow. In others where drainage is rapid and the runoff response is dominated by subsurface storm flow, the antecedent soil moisture is not likely to be a good indicator of transient saturation and lateral subsurface flow. In these cases the antecedent soil moisture pattern is more likely to reflect soil property and soil depth patterns.

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