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Discussion

Comment to "Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes, Journal of Hydrology 286: 113–134"

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The recent paper by Western et al. (2004) is another in a series of papers by the Melbourne Group that explore the spatial patterns of soil moisture in small catchments and their perceived relationship to defined dominant spatial hydrological processes. These papers have influenced the field greatly and forced new examination of spatial patterns in catchment hydrology and how they can be used to better define process understanding. While we appreciate these important and influential works, and this latest paper in particular that presents results from a number of catchments in Australia and New Zealand, we worry about the implicit message in this and their other published papers on this topic: that indices of mapped soil moisture in the upper decimeters of the soil profile represent causally, topographically driven lateral subsurface flow. We argue that the finding that discharge varies in a strongly nonlinear way with soil moisture is a non-sequitur. In this comment we argue that soil moisture can be a passive signal between that of rainfall input and the subsurface stormflow output that drives streamflow response. In other words, while soil moisture may co-vary with streamflow, it is often transient saturation in the profile, at the soil–bedrock interface, or at a zone of reduced permeability in a duplex or layered soil environment, that is usually the causal mechanism for lateral discharge of mobile water to the riparian zone and/or directly to the channel. This is counter to the Western et al. (2004) main assertion that indices of soil moisture represent topographically driven subsurface lateral flow. Our motivation for writing this comment is that several recent studies have taken up the Western et al., results and begun using the soil moisture—flow path linkage as axiomatic of how hillslopes work (e.g. Meyles et al., 2003). Even more worrying is that these concepts are becoming codified into our watershed models without critical assessment of whether or not these spatial patterns make functional sense.

In this comment we offer a counter argument aided with data from one of our study sites that shows how soil moisture, despite it strong correlation to flow in the stream, is of little direct importance in the generation of lateral subsurface flow. While soil moisture may define and control near stream saturated areas that produce saturation excess overland flow, we argue that spatial patterns of soild moisture may have little bearing on lateral subsurface

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flow during events. The main tenant of our argument comes from three main points that we make below: (1) that the relation between hillslope average soil moisture and subsurface flow or stream discharge is often strong and highly nonlinear, but that (2) the relation between soil moisture development in time and space is not related to the development of transient saturation on the hillslope, and that (3) this transient saturation is often the causal mechanism for subsurface lateral flow to the channel. While we do not claim that our data presented in this note are representative of all areas of the world, they are representative of various catchments, where we have worked, directly or indirectly, in North America, New Zealand, Japan and northern Europe.

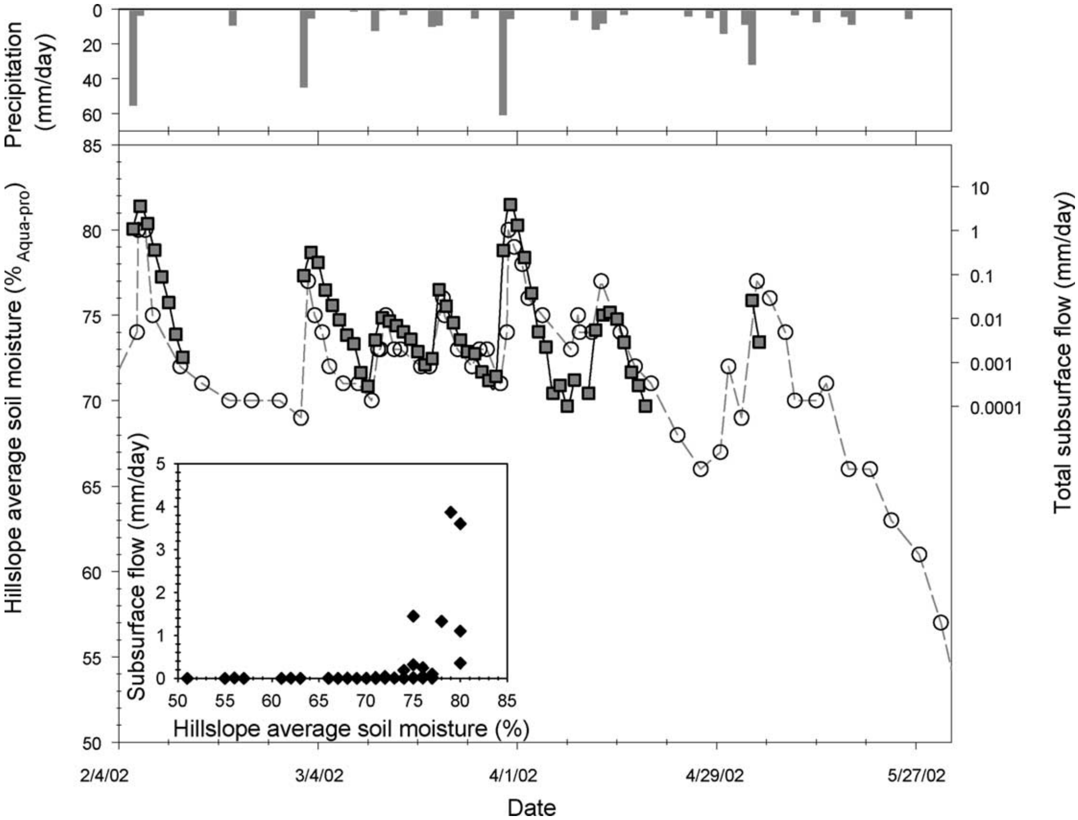

Fig. 1. Relation between subsurface flow and hillslope average soil moisture. Soil moisture was measured at 64 locations on the hillslope using the Aqua-pro sensor (Aqua-pro Sensors, Reno NV) in polycarbonate access tubes that were installed to the soil–bedrock interface. The Aqua-pro sensor is a capacitance sensor (radio frequency) that measures soil moisture on a percent scale between 0 (in air or air dried soil) and 100 (in saturated soil or water). Soil moisture was measured at 0.05 m increments to 0.3 m below the soil surface and at 0.1 m increments between 0.3 m and the soil–bedrock interface. Profile average soil moisture at a measurement location was calculated by multiplying the Aqua-pro soil moisture measurements at specific depths by the distance between the soil moisture measurements and dividing by the total soil depth at that measurement location. Hillslope average soil moisture was calculated by averaging the profile average soil moisture values from all measurement locations. Flow from the base of the hillslope was measured via a 20-m long trench excavated normal to the fall line of the slope down to bedrock at a midslope position approximately 30 m upslope from an ephemeral stream. Discharge was measured by routing flow through tipping-bucket gages. The number of tips was recorded every minute. When no subsurface flow is shown on the graph, there was no measurable subsurface flow (<0.0001 mm/day).

1. The relation between hillslope average soil moisture and subsurface flow or stream discharge is often strong and highly nonlinear

We find that flow in the stream, or in our case, flow from a hillslope is a nonlinear function of hillslope average soil moisture (see Fig. 1 for our observations during the winter and early spring period at the Panola Mountain Research Watershed (PMRW) near Atlanta Georgia, USA). Subsurface flow occurs only when hillslope average soil moisture is greater than $\sim 72\%_{\text{Aqua-pro}}$. The relation between soil moisture and subsurface flow at Panola is strikingly similar to the relation between soil moisture and streamflow at Tarrawara (Fig. 3, p. 2767 in Western and Grayson, 1998). Where Tarawarra is influenced by duplex soils, Panola has a saprolitic impeding layer at <1 m depth. Fig. 1 shows how the hillslope remains relatively wet throughout the winter and spring period (until mid April) and dries quickly thereafter, similar to the two states described by Grayson et al. (1997). Soil moisture responses to precipitation are clear. During the February to early April period the hillslope drained to the same moisture level ($70\%_{\text{Aqua-pro}}$, $\sim$field capacity) while it dried to lower soil moisture levels after mid April. This change corresponds at our forested site to the beginning of leaf out. While we acknowledge that the relation between hillslope average soil moisture and subsurface flow or stream discharge is often strong and highly nonlinear, we take exception to the general assumption that the relation between soil moisture development in time and space is representative of mobile water movement during an event.

2. The relation between soil moisture development in time and space is often not related to the development of transient saturation on the hillslope

At Panola, the correlation lengths for both subsurface saturation and soil moisture appear to be very short (Fig. 2). We admit that our grid setup at Panola for the soil moisture and subsurface saturation measurements (Fig. 3) and the small absolute number of soil moisture measurements (compared to Western et al. (1998, 1999, 2004)) does not allow a very precise determination of the correlation length. These comments notwithstanding, during the wet period, the locations with higher than median profile average pre-event soil moisture were relatively stable (Fig. 3a). Pre-event soil moisture for these events was relatively similar (varying between $68–72\%_{\text{Aqua-pro}}$, see Fig. 1). The spatial extent of subsurface saturation, however, changed with increasing storm size (Fig. 3b). Only during the largest storms was the subsurface saturated area connected to the trench face. Clearly

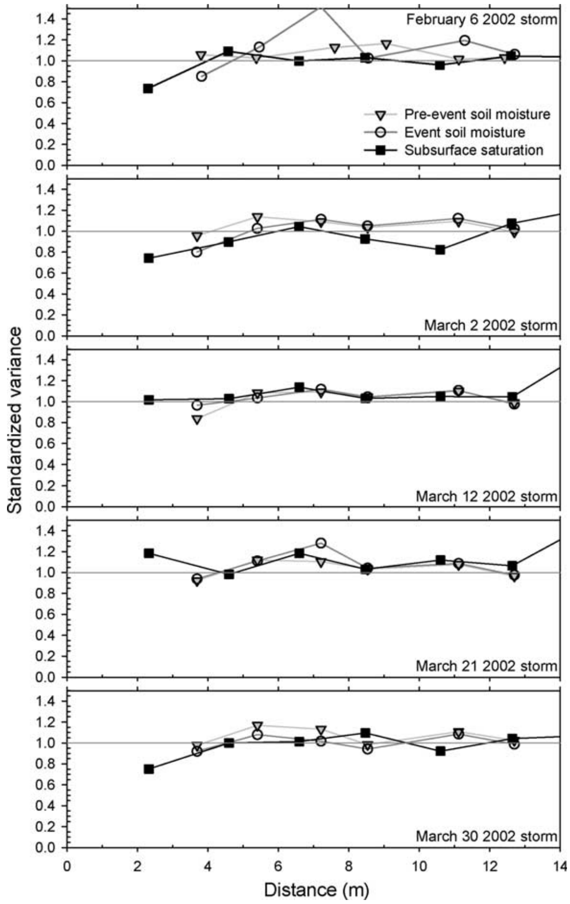

Fig. 2. Standardized omni-directional semi-variograms of pre-event soil moisture (triangles), event soil moisture (open circles) and subsurface saturation (closed squares) for five storms during the 2002 study period. The delineation of the subsurface saturated areas was made via 135 crest stage gauges filled with cork dust spatially distributed across the hillslope. These 19 mm diameter PVC wells were screened over the lower 0.2 m and installed on the soil–bedrock contact. The maximum water level rise was measured after each storm during the January–August 2002 period.

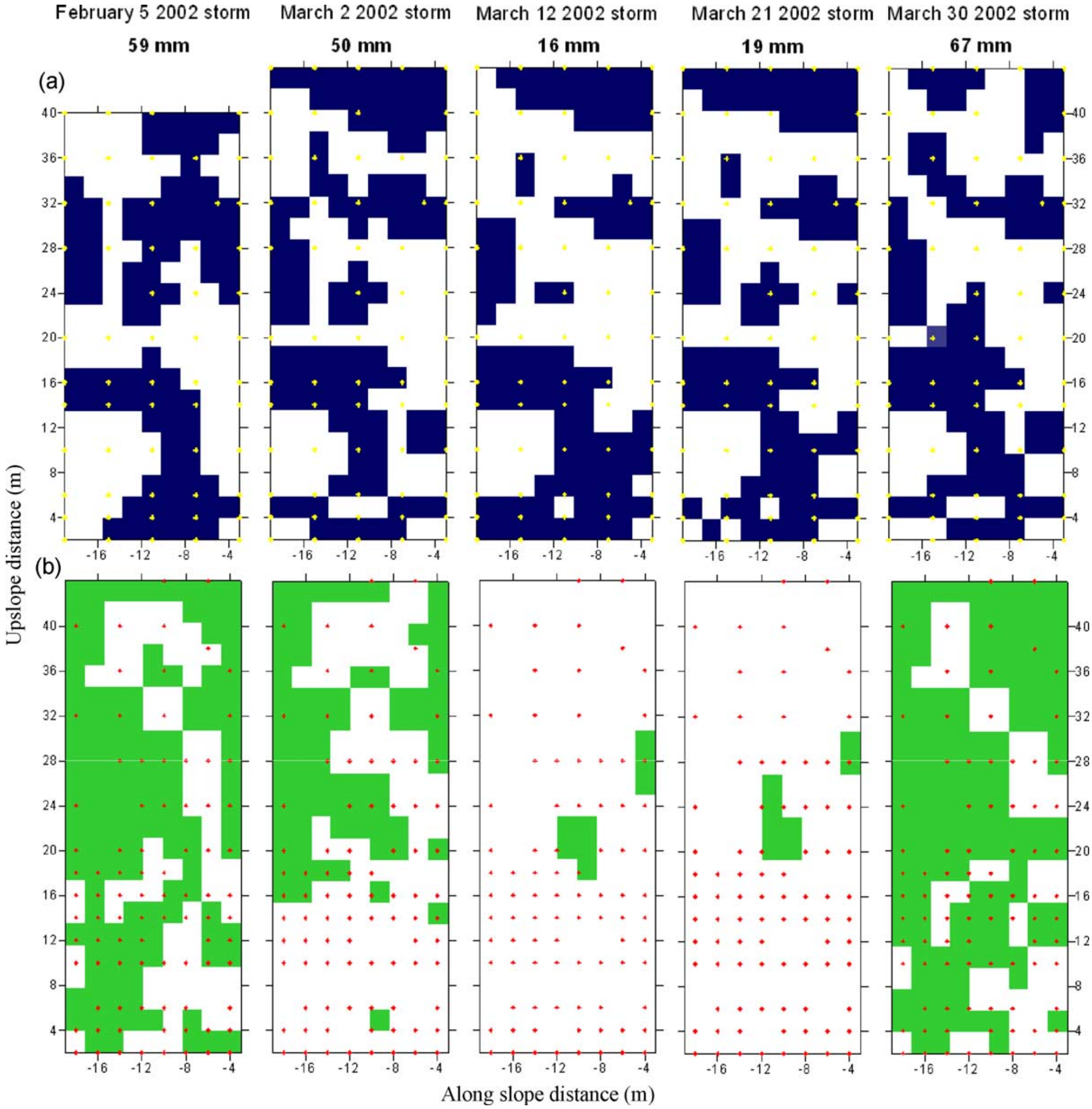

Fig. 3. Locations of above median soil moisture (blue shaded area) (a) and the locations of subsurface saturation (green shaded area) for five storms during the wet state during the 2002 study period (b). The standardized semi-variograms of soil moisture and subsurface saturation for these storms are shown in Fig. 2. Yellow dots in (a) represent soil moisture measurement locations using an Aqua-pro device; red dots in (b) represent maximum-rise wells for water table detection.

the locations of higher than median soil moisture and subsurface saturation did not correspond well to each other. Subsurface saturation occurred mainly at locations with shallow soils (on the upslope) and in areas with both high bedrock contributing area and high impedance to downslope drainage near the midslope (i.e. high downslope index values) (see Freer et al., (1997, 2002); Burns et al., 1998 for details), not in areas with larger than average pre-event soil moisture.

To quantify the (lack of) correlation between pre-storm soil moisture and subsurface saturation, the soil

Table 1
The logistic R^2 between pre-event soil moisture at different depths below the surface and the occurrence of subsurface saturation for the February 6, March 2 and March 2002 storms

Logistic R^2	February 6 2002	March 2 2002	March 30 2002
0.05 m	0.01	0.05	0.01
0.15 m	0.00	0.00	0.00
0.30 m	0.03	0.00	0.02
0.50 m	0.02	0.06	0.03
0.70 m	0.01	0.03	0.01
At soil–bed-rock contact	0.06	0.00	0.02
Profile average	0.00	0.03	0.00

The small spatial extent of subsurface saturated area during the March 12 and 21 2002 storms (Fig. 3) did not allow for an accurate determination of the logistic R^2 between soil moisture and the occurrence of subsurface saturation.

moisture measurements were re-interpolated to a new 2×2 m grid using linear triangulation. The logistic correlation coefficients between pre-storm soil moisture at different depths and the occurrence of subsurface saturation were very low (Table 1). This means that despite the strong, nonlinear relation between hillslope average soil moisture and subsurface flow, the relation between soil moisture development in time and space is often not related to the development of transient saturation on the hillslope. This is significant because this transient saturation is the causal mechanism for hillslope and stream response. Panola is not unique in this sense; numerous studies in many different hydrogeologic and climate environments have shown that transient saturation is the causal mechanism for lateral flow of mobile water on the time scale of an event (Peters et al., 1995 at Plastic Lake in Canada; Tani, 1997 at the Minamitani hillslope in Japan; McGlynn et al., 2002 for the Maimai catchment in New Zealand, to name a few).

3. Transient saturation is often the causal mechanism for subsurface lateral flow to the channel

The storms during the winter period (wet state) all had similar pre-event soil moisture conditions (∼field

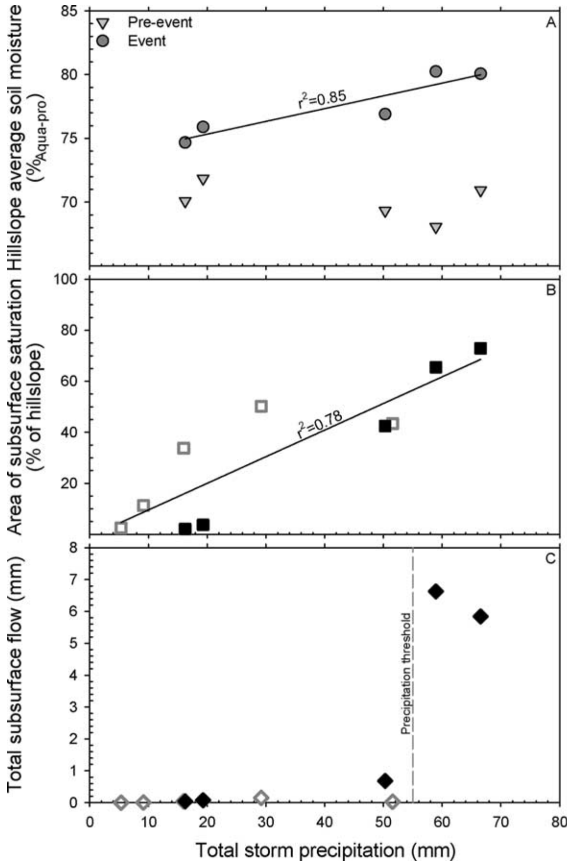

Fig. 4. Hillslope average pre-event (triangles) and event soil moisture (circles) (a), the maximum area of transient saturation (b) and storm total subsurface flow as a function of storm total precipitation for the five storms shown in Fig. 3(c). The dark closed symbols in (b) and (c) represent the storms shown in Fig. 3. The light colored open symbols in (b) and (c) represent other storms between January and March 2002.The 55 mm precipitation threshold shown in (c) is from Tromp van Meerveld and McDonnell (submitted).

capacity). The measured maximum hillslope average soil moisture during the storm period was a linear function of total storm precipitation (Fig. 4a). The area of transient saturation also increased linearly with increasing precipitation. The relation between storm total precipitation and storm total subsurface flow, however, was highly nonlinear (Tromp van Meerveld and McDonnell, 2004; and Fig. 4c) because connectivity between the subsurface saturated area to the trench occurred only during the largest storms (Fig. 3).

4. Summary

While hillslope average soil moisture is strongly correlated to subsurface flow and the correlation length of both subsurface saturation and pre-event soil moisture is very short, there is a lack of correlation between the soil moisture pattern and the pattern of subsurface saturation. We observed, like may other hillslope hydrological studies, that subsurface saturation is the causal mechanism for production of lateral subsurface flow. Our data show that subsurface saturation is related to soil depth and bedrock micro-topography, not to soil moisture patterns. Thus at this planar hillslope, where lateral subsurface flow is the dominant runoff mechanism and the occurrence of subsurface saturation at an impeding layer is most important for the subsurface flow generation process, the soil moisture pattern is a passive pattern, not one that actively controls flow. Subsurface flow is a due to the connection of subsurface saturated areas, which is influenced by the bedrock micro topography not pre-event soil moisture. Thus it is not the spatial soil moisture pattern or the connection of areas with high soil moisture but the connection of areas of transient saturation, which is controlled by the bedrock topography that is responsible for the occurrence of significant subsurface flow. While soil moisture is important in that the soil on the hillslope needs to be wet enough for subsurface saturation at the soil–bedrock interface to occur, its pattern is not a first order control on the generation of lateral subsurface flow.

Acknowledgements

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