The effect of topography, subsurface strata and land-use on observed distributions of soil moisture within a sub-catchment of the River Eden, Cumbria

Mary Ockenden[1,2] and Nick A. Chappell[1]

[1] *Lancaster University;* [1,2]*Centre for Ecology and Hydrology*

Abstract

The location of saturated areas, generating saturation overland flow by return-flow and direct rainfall, affects the rates and pathways of nutrients and sediment moving into streams, thereby having implications for river water quality. The prediction of saturated areas is difficult as it depends on many factors such as topography, subsurface strata, land-use and aspect. This study, in the Blind Beck sub-catchment of the Eden River (Cumbria), investigates how these factors affect soil moisture patterns. Intensive spatial measurements of soil moisture are made during different seasons across research plots affected by different contributing factors. Geostatistical analysis is used to quantify differences in spatial patterns observed. Measured soil moisture distributions are to be compared to spatial distributions of relative wetness predicted by existing topography-only indices. This paper presents the results of a preliminary set of soil moisture plots.

Introduction

Accurate representation of the processes of overland and subsurface flow in numerical models requires an understanding of the hillslope hydrology, in particular the soil moisture patterns. Understanding soil moisture dynamics is important as it has implications for management of water resources, movement of chemicals and irrigation planning (Liu and Zhang, 2007). Soil moisture plays an important role in the formation of clouds through evapotranspiration (Famiglietti *et al*., 1998) and, as such, contributes to the energy changes between the soil and the atmosphere (Ridolfi *et al*., 2003) and the resulting weather patterns (Bardossy and Lehmann, 1998). The importance of soil moisture heterogeneity in Global Climate Models (GCMs) has been highlighted by Gedney and Cox (2003).

Beven and Kirkby (1979) recognised that improved representation of soil moisture was needed for better hydrological modelling and formulated the idea of a topographic index, based only on topographic data, to predict the likely distribution of variable source areas of saturation overland flow. O'Loughlin (1981) developed a Wetness Index on similar lines. Because of the increasing availability and ease of use of digital terrain data, the topographic index idea has gained a lot of interest in modelling. However, the algorithms used for calculation of the indices introduce additional uncertainties into the modelling (Quinn *et al.,* 1995; Pan *et al*., 2004). There are already many sources of uncertainty in modelling (Beven and Binley, 1992; Beven, 2000), including observational data (measurement errors or temporal and spatial averaging), input parameters, initial and boundary conditions and errors in the model structure (simplification or incorrect assumptions). It is important for modellers to evaluate the uncertainty in the model to be able to defend it (Beven, 2000). Several researchers have compared the topographic index of Beven and Kirkby (1979) with field measurements of soil moisture. In some cases, particularly for areas of topographic convergence (such as gullies) in wet conditions, the agreement has been reasonable (Grayson *et al*., 1997; Western *et al*., 1999b), with up to 61% of the soil moisture variance explained by the terrain. However, in other cases (particularly for drier conditions or fast-draining soils), the variance in moisture content is poorly explained by the topographic index (Burt and Butcher, 1985; Crave and Gascuel-Odoux, 1997; Blyth e*t al.,* 2004). In general, for a range of landscapes and climates, less than 50% of the variability in soil moisture is explained by the terrain (Western *et al*., 1999a; Wilson *et al.,* 2004). Nevertheless, topographic indices have been used in the Meteorological Office Surface Exchange Scheme (MOSES) and coupled to a global climate model (Gedney and Cox, 2003). Grayson and Western (1998) identified GCMs as an area which could be improved by a better understanding of the spatial distribution of soil moisture.

The idea that only localised areas of hillslopes contribute saturation overland flow to streams is well documented (e.g. Dunne and Black, 1970; Anderson and

Burt, 1990) but the accurate representation of such saturated areas is difficult as it depends on many factors (including for example topography, soil type and texture, geology, land use) which vary between and within catchments. However, the location of these saturated areas affects the likelihood of nutrients and sediment reaching the stream and therefore has implications for protection zone design (Chappell *et al.*, 2006). Land management practices such as riparian buffer zones along river banks are one way of addressing the problem. However, such protection zones are not always designed with an understanding of the hydrology (Bren, 2000; Buttle, 2002). As a result, they can be inefficient or ineffective, not protecting the most vulnerable areas or not reducing pollutants reaching the waterways. In addition, they can be wasteful of agricultural land which does not need the protection. Bren (2000) has identified the need for water quality protection zones that are hydrologically defined. This project seeks to determine what features of the landscape at Blind Beck catchment can be used to predict soil moisture patterns, including an evaluation of topographic indices. The particular features of interest are the topography, sub-surface strata and land use.

Study area

The field study site is Blind Beck (near Little Musgrave, grid ref: NY 753130), a tributary of the River Eden, Cumbria. The catchment area is 8.8 km^2. The catchment spans a typical range of geologies for the Upper Eden, with Carboniferous limestone (Alston Group) in the upland areas and Lower Permian Penrith sandstone in the 'lowland' flood plain of the Upper Eden Valley. The steeper upland slopes (maximum altitude 400 m) are mainly unimproved pasture, grazed by sheep; the gentler lower slopes and valley bottom (minimum altitude 125 m) are mostly improved pasture with sheep and dairy herds. Figure 1 shows the location, topography and underlying geology of the Blind Beck subcatchment, with the measurement sites marked.

Method

Spatial measurements of soil moisture were made at several sites within the Blind Beck basin. The observed patterns were analysed using geostatistical methods. To assess the relative contribution of certain features of the landscape on soil moisture, several pairs of sites within the Blind Beck catchment were identified where only one main feature was different (e.g. landuse, geology, aspect). For instance, to look at the effect of land use, sites with the same (or as similar as possible) geology and topography were selected. So far, eight sites have been selected; the locations are shown in Figure 1b and the differing features at each site are described in Table 1.

Soil moisture measurements in the top 6 cm of the soil were made with a ThetaProbe (Delta-T Devices Ltd., Cambridge, UK). This uses a form of time-domain reflectometry (TDR) as described by Whalley (1993), but in a manner which allows many measurements to be made simply and cheaply (Gaskin and Miller 1996). The ThetaProbe method was chosen as no fixed installation is required and measurements can be made quickly at many different sites. This was necessary for the subsequent geostatistical analysis.

At each site a small plot of approximately 50 m × 50 m was measured out with tapes and measurements of soil moisture were made on a grid pattern with a resolution of 2

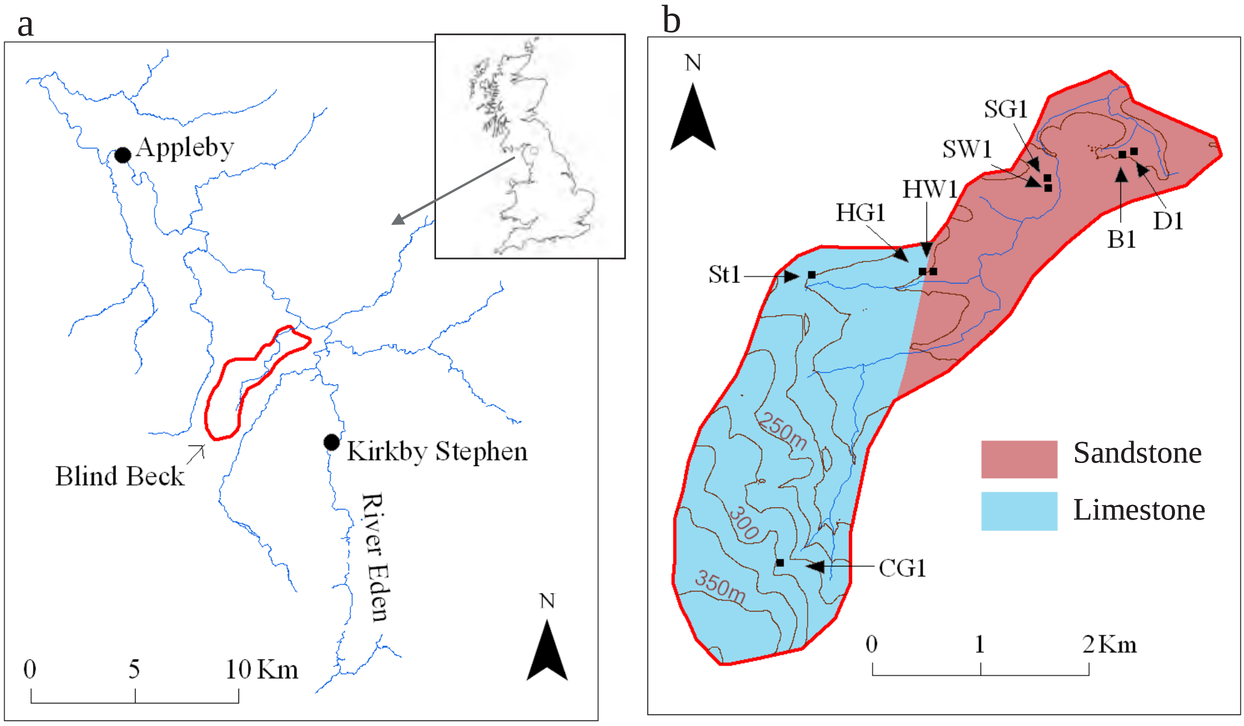

Figure 1 *(a) Location of Blind Beck study area ; (b) Topography and underlying geology of Blind Beck catchment, showing sites of soil moisture measurements (see Table 1).*

Table 1 *Description of soil moisture measurement sites within the Blind Beck basin (Figure 1b)*

Site ref.	*Land use*	*Geology*	*Slope aspect*
CG1	Unimproved pasture	Limestone	E
B1	Improved pasture	Sandstone	Flat
D1	Improved pasture	Sandstone	Flat
HG1	Improved pasture	Limestone/sandstone	S
HW1	Woodland	Limestone/sandstone	S
SW1	Woodland	Sandstone	E
SG1	Improved pasture	Sandstone	E
St1	Improved pasture	Limestone	S

to 5 m. Typically, a small grid of fine resolution (<2.5 m) was measured within a bigger grid of larger resolution (3–5 m), giving a total of 100–200 soil moisture measurements at each plot (nested sampling). A large number of observations, as recommended by Webster and Oliver (1992), was required for the geostatistical analysis. For each site, the values of soil moisture at every point of the grid were plotted as a contour map. The mean and variance of the data were calculated. A histogram of the data was plotted to see if the data followed a normal distribution. Geostatistical analysis was performed using the software packages EasyKrig (The MathWorks Inc., Natick, MA, USA) and VARIOWIN 2.2 (Pannatier, 1996). With geostatistical analysis, in addition to the descriptive statistics of mean and variance, additional information is gained from the spatial locations of the data. A semivariogram, relating the semivariance $^{3}(\mathbf{h})$ to the lag **h**, was calculated for each site. The semivariance $^{3}(\mathbf{h})$ is defined as half the expected squared difference between values at locations separated by the lag **h**, i.e.

$$\gamma(\mathbf{h}) = \frac{1}{2m}\sum_{i}^{m}\{z(\mathbf{x}_i) - z(\mathbf{x}_i + \mathbf{h})\}^2 \qquad (1)$$

where **x** and **h** are vectors.

The shape of the semivariogram depends on the spatial variability, but also on the scaling effects of the number and spacing of the observations, as investigated by Western and Bloschl (1999). The semivariogram can be approximated by several different models, and described by the terms nugget, sill and range. The nugget is the variance at **h** = 0, and should theoretically be zero. However, in practice it can be greater than zero due to spatially dependent variation over distances smaller than the sampling interval or measurement errors. The sill is the maximum value of the semivariance and the range is a measure of the spatial dependence of the data, i.e. the distance over which pairs of observations remain correlated.

Results

The plot sizes, measurement spacing, mean and variance of soil moisture are given for all plots in Table 2.

Most of the sites had an arithmetic mean soil moisture content greater than 0.5 $m^3 m^{-3}$ (i.e., close to saturation). Highest values were recorded in the improved pasture, which tends to be on flat or gently sloping areas. The woodland sites had a lower mean moisture content, but a larger variance in the measurements. The unimproved pasture site had the lowest mean soil moisture content and the highest variance. This site had the steepest slopes and could be expected to drain faster than some of the other sites. The coefficient of variation, defined as the standard deviation divided by the arithmetic mean, expressed as a percentage, is also given in Table 2. This varies from around 5% for the improved pasture sites to 24% for one of the woodland sites and 35% for the unimproved pasture site. Compared with a value of 26% measured for the Slapton Wood catchment in Devon (Chappell and Franks 1996) or 21% measured for the Baru tropical forest catchment (Chappell *et al.*, 2006), the small values measured for the improved pasture in Blind Beck indicate

Table 2 *Descriptive statistics for soil moisture plots in Blind Beck basin (Figure 1b). The coefficient of variation is the standard deviation divided by the arithmetic mean, expressed as a percentage.*

Date	*Plot ref*	*Plot size (m)*	*Measurement spacing (m)*	*Arithmetic Mean (m^3m^{-3})*	*Variance*	*Coefficient of Variation (%)*
07.09.07	*CG1*	*80 x 50*	*2m – 4m*	*0.30*	*0.0110*	*35*
05.10.07	*B1*	*30 x 20*	*2m – 5m*	*0.54*	*0.0008*	*5*
05.10.07	*D1*	*50 x 50*	*5m*	*0.53*	*0.0008*	*5*
09.11.07	*HG1*	*30 x 40*	*2m – 4m*	*0.54*	*0.0012*	*6*
09.11.07	*HW1*	*30 x 40*	*2m – 4m*	*0.41*	*0.0098*	*24*
13.02.08	*SW1*	*50 x 30*	*2.5m – 5m*	*0.49*	*0.0028*	*11*
13.02.08	*SG1*	*50 x 50*	*2.5m – 5m*	*0.55*	*0.0007*	*5*
04.04.08	*St1*	*50 x 50*	*2.5m – 5m*	*0.56*	*0.0005*	*4*

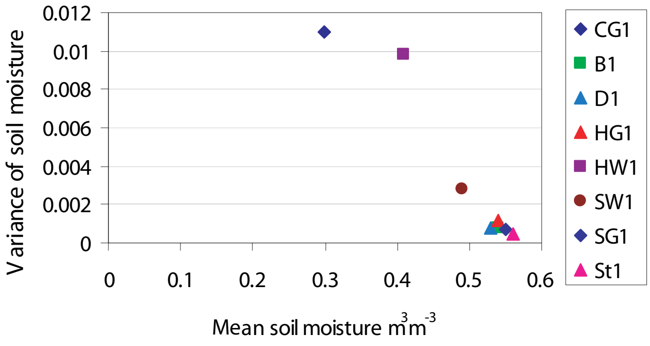

Figure 2 *Mean and variance of soil moisture at sites in Blind Beck basin (Figure 1b).*

a particularly low variability in soil moisture at these sites. The decrease in soil moisture variance with increase in mean soil moisture is shown in Figure 2.

The most marked difference is between the paired sites comparing woodland with improved grassland. The contour maps for grassland site HG1 and woodland site HW1 are shown in Figure 3.

The larger variance of soil moisture is visible in the woodland site, which also shows patterns of connectivity. These are mainly due to small topographic features which were also perhaps once present in the improved grassland but have been removed by ploughing and cultivation. These small topographic features are not represented in 5 m resolution topographic data. In general, the spatial resolution in numerical models is coarser than this, so the small topographic features, which are important for determining the surface flow pathways, are not adequately represented.

Numerical models which calculate a soil moisture distribution based on topography alone typically assume that the topography has a more significant effect than the geology, soil type or other features and that the spatial soil moisture distribution is linearly related to the spatial distribution of a topographic index. The topographic index (») of Beven and Kirkby (1979) can be expressed as

$$\lambda_i = \ln\left(\frac{a_i}{\tan \beta_i}\right) \qquad (2)$$

where λ_i is the topographic index for area *i*, a_i is the upslope contributing area to *i* and β_i is the surface slope angle for area *i*. For adjacent paired sites HG1 and HW1, on the same south facing slope, with a similar upslope contributory area which is large relative to the size of the plot, the topographic indices calculated for sites HG1 and HW1 from Equation 2 would be approximately the same. However, the observations of soil moisture reported here indicate that land use is an important influence.

The semivariogram for each site is shown in Figure 4. In all cases, the structure of the semivariogram is broadly

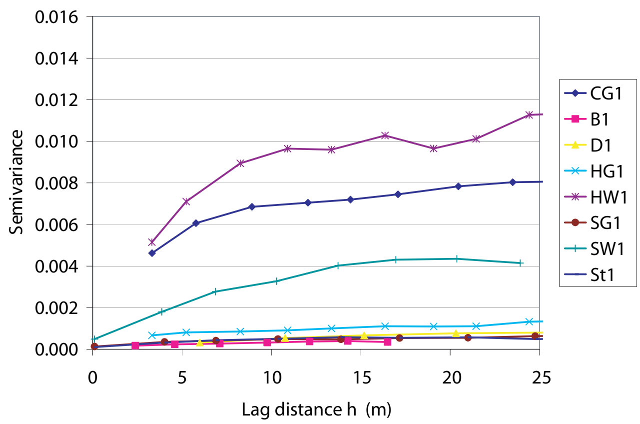

Figure 4 *Semivariogram for each soil moisture plot in Blind Beck basin (Figure 1b), showing increasing semivariance with lag distance h.*

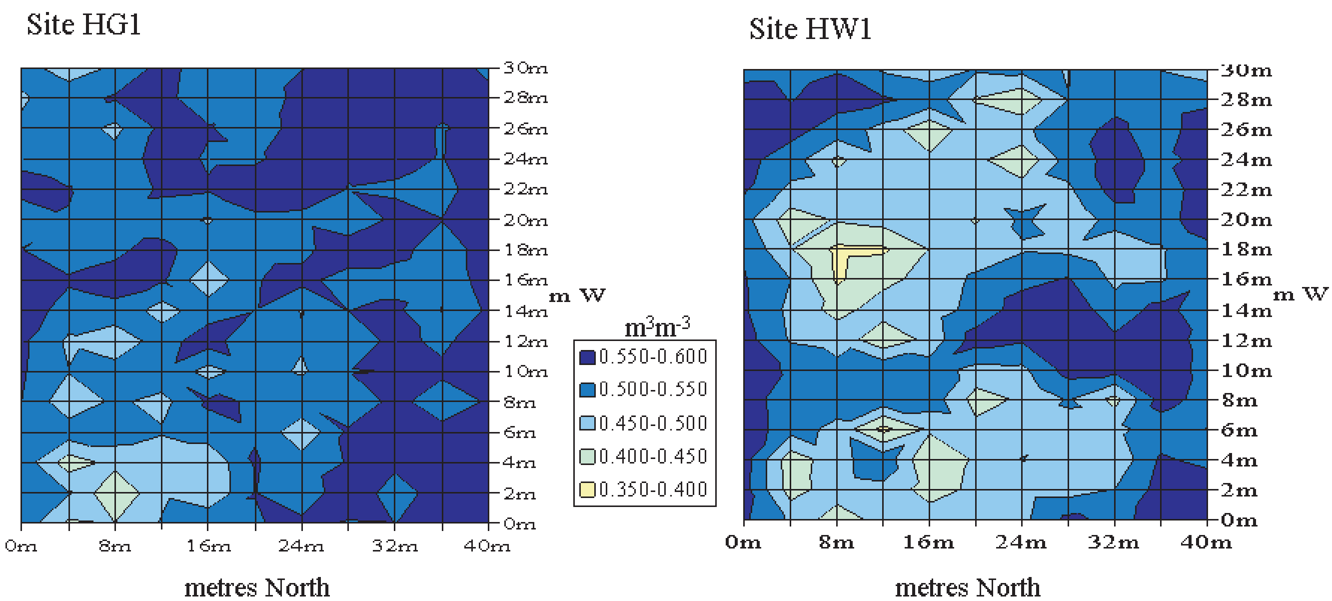

Figure 3 *Soil moisture distributions at sites HG1 and HW1. Soil moisture is measured in m^3m^{-3}.*

similar; the semivariance generally increases with increasing lag distance. This is most obvious for the woodland sites HW1 and SW1 and the upland site CG1, where the semivariances are larger. There is little difference between the wettest sites, in either the shape of the semivariogram or the sill reached. Sites HG1 and St1, which are both improved pasture on a south facing slope, have different underlying solid geologies, but there is little difference between the semivariograms. Differences in drift geology still need to be investigated.

In general, the semivariograms show most spatial dependence at small lag distances (< 10 m), and tend towards an upper bound (sill) for *h* greater than around 15–20 m. This structure can be modelled by a theoretical semivariogram defined by the nugget, range and sill. In this case, the model which best fits all the sites was found to be an exponential model, defined by

$$\gamma(h) = C\left[1 - \exp\left(-3h/a\right)\right] \qquad h \geq 0 \qquad (3)$$

where *C* is the sill, a is the range and *h* is the lag distance. In this case the nugget is zero and the sill is approached as *h* approaches *a*.

Table 3 gives the sill and range for the theoretical semivariogram (exponential model) fitted to the data at each site. Over the lag distance for which the model was fitted, the sites with the highest semivariances generally showed lower ranges, indicating that the soil moisture at pairs of points remains correlated over a shorter distance at these sites.

Table 3 *Sill (C) and range (a) for the exponential semivariograms fitted to the data at each site in Blind Beck basin (Figure 1b).*

Plot ref	C	a (metres)
CG1	0.0078	12
B1	0.0004	15
D1	0.0008	26
HG1	0.0012	20
HW1	0.0105	14
SG1	0.0006	17
SW1	0.0045	20
St1	0.0006	15

This paper reports work in progress, so more systematic analysis of many plot-based datasets are required to produce more robust interpretations. Many additional sites will be investigated and detailed topographic measurements will be made to compare topographic indices calculated from the detailed measurements with topographic indices calculated from coarser resolution data. At some sites, soil moisture will be measured during different seasons to assess the temporal variation.

Conclusions

Initial findings suggest that land use may have an important influence on soil moisture distributions, whereas the underlying geology has much less impact at the local scale. Soil moisture distributions calculated from the topography alone will not take this difference into account. Further work is necessary to provide more evidence and compare observed soil moisture distributions with those calculated from topographic indices.

Acknowledgements

This work is funded by NERC Award NER/S/A/2006/14326. Field support was provided by the Centre for Ecology and Hydrology.

References

Anderson, M.G. and Burt, T.P., 1990. Subsurface runoff. In: *Process Studies in Hillslope Hydrology*. M.G. Anderson and T.P. Burt (eds), John Wiley & Sons.

Bardossy, A. and Lehmann, W., 1998. Spatial distribution of soil moisture in a small catchment. Part 1: Geostatistical analysis. *J Hydrol.,* **206**, 1–15.

Beven, K., 2000. On model uncertainty, risk and decision making. *Hydrol. Process.,* **14**, 2605–2606.

Beven, K. and Binley, A., 1992. The future of distributed models - model calibration and uncertainty prediction. *Hydrol. Process.,* **6**, 279–298.

Beven, K.J. and Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology. *Hydrol. Sci. Bull.,* **24**, 43–69.

Blyth, E.M., Finch, J., Robinson, M. and Rosier, P., 2004. Can soil moisture be mapped onto the terrain? *Hydrol. Earth Syst. Sci.,* **8**, 923–-930.

Bren, L.J., 2000. A case study in the use of threshold measures of hydrologic loading in the design of stream buffer strips. *For. Ecol. Manage,m* **132**, 243–257.

Burt, T.P. and Butcher, D.P., 1985. Topographic controls of soil-moisture distributions. *J. Soil Sci.,* **36**, 469–486.

Buttle, J.M., 2002. Rethinking the donut: the case for hydrologically relevant buffer zones. *Hydrol. Proces.* **16**, 3093–3096.

Chappell, N.A. and Franks, S.W., 1996. Property distributions and flow structure in the Slapton Wood catchment. *Field Studies* **8**, 559–575.

Chappell, N.A., Vongtanaboon, S., Jiang, Y. and Tangtham, N., 2006. Return-flow prediction and buffer designation in two rainforest headwaters. *For. Ecol. Manage.,* **224**, 131–146.

Crave, A. and Gascuel-Odoux, C., 1997. The influence of topography on time and space distribution of soil surface water content. *Hydrol. Process.,* **11**, 203–210.

Dunne, T. and Black, R.D., 1970. An experimental investigation of runoff production in permeable soils. *Water Resour. Res.* **6**, 478–490.

Famiglietti, J.S., Rudnicki, J.W. and Rodell, M., 1998. Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas. *J. Hydrol.,* **210**, 259–281.

Gaskin, G.J. and Miller, J.D., 1996. Measurement of soil water content using a simplified impedance measuring technique. *J. Agric. Eng. Res.,* **63**, 153–159.

Gedney, N. and Cox, P.M., 2003. The sensitivity of global climate model simulations to the representation of soil moisture heterogeneity. *J. Hydrometeorol.,* **4**, 1265–1275.

Grayson, R.B. and Western, A.W., 1998. Towards areal estimation of soil water content from point measurements: time and space stability of mean response. *J. Hydrol.,* **207**., 68–82.

Grayson, R.B., Western, A.W., Chiew, F.H.S. and Bloschl, G., 1997. Preferred states in spatial soil moisture patterns: Local and nonlocal controls. *Water Resour. Res.* **33**, 2897–2908.

Liu, G. and Zhang, J., 2007. Spatial and temporal dynamics of soil moisture after rainfall events along a slope in Regosols of southwest China. *Hydrol. Process*., **21**, 2778–2784.

O'Loughlin, E.M., 1981. Saturation regions in catchments and their relations to soil and topographic properties. *J. Hydrol.,* **53**, 229–246.

Pan, F.F., Peters-Lidard, C.D., Sale, M.J. and King, A.W., 2004. A comparison of geographical information systems-based algorithms for computing the TOPMODEL topographic index. *Water Resour. Res.,* **40**(6): W06303, doi:10.1029/2004WR003069.

Pannatier, Y., 1996. *VARIOWIN: Software for spatial data analysis in 2D*. Springer-Verlag New York, Inc.

Quinn, P.F., Beven, K.J. and Lamb, R., 1995. The ln(a/tan-beta) index - How to calculate it and how to use it within the TOPMODEL framework. *Hydrol. Process.* **9**, 161–182.

Ridolfi, L., D'Odorico, P., Porporato, A. and Rodriguez-Iturbe, I., 2003. Stochastic soil moisture dynamics along a hillslope. *J. Hydrol.,* **272**, 264–275.

Webster, R. and Oliver, M.A., 1992. Sample adequately to wstimate variograms of soil properties. *J. Soil Sci.,***43**, 177–192.

Western, A.W. and Bloschl, G., 1999. On the spatial scaling of soil moisture. *J. Hydrol.,* **217**, 203–224.

Western, A.W., Grayson, R.B., Bloschl, G., Willgoose, G. R. and McMahon, T.A., 1999a. Observed spatial organization of soil moisture and its relation to terrain indices. *Water Resour. Res.,* **35**, 797–810.

Western, A.W., Grayson, R.B. and Green, T.R., 1999b. The Tarrawarra project: high resolution spatial measurement, modelling and analysis of soil moisture and hydrological response. *Hydrol. Process.,* **13**, 633–652.

Whalley, W.R., 1993. Considerations on the use of time-domain reflectometry (TDR) for measuring soil-water content. *J. Soil Sci.,* **44**, 1–9.

Wilson, D.J., Western, A.W. and Grayson, R.B., 2004. Identifying and quantifying sources of variability in temporal and spatial soil moisture observations. *Water Resour. Res.,* **40**(2): W02507,doi:10.1029/2003WR002306.