Spatial Scaling of Soil Moisture: A Review and Some Recent Results

A. W. Western[a], **R. B. Grayson**[a], **G. Blöschl**[b]

[a] *CRC for Catchment Hydrology, Department of Civil and Environmental Engineering, University of Melbourne, Australia (a.western@civag.unimelb.edu.au)*

[b] *Institut für Hydraulik, Gewässerkunde und Wasserwirtschaft, Technische Universität Wien, Austria*

Abstract: We review the literature on the spatial scaling of soil moisture. Much progress is being made in this field, particularly in response to the need for improved understanding of land-atmosphere interaction. New measurement techniques have enabled advances in data collection but further work is required before operational soil moisture remote sensing systems produce reliable estimates of root zone soil moisture for large areas. Particular aspects of soil moisture scaling considered include the spatial probability distribution function (pdf) of soil moisture, spatial correlation of soil moisture and correlation of soil moisture with surrogate variables including terrain indices. We have analysed the statistical characteristics of thirteen spatial soil moisture data sets from around the world. Systematic changes in variance and skewness can be identified from these data. Variance tends to peak at moderate spatial average soil moisture levels, while there is positive skewness for low spatial average soil moisture and a symmetric pdf for moderate and high spatial average soil moisture levels. While the soil moisture pdf is non-normal at times, the departures from normality are relatively small compared with other hydrologic parameters.

Keywords: Soil moisture; Scale; Probability Distribution

1. INTRODUCTION

Soil moisture is a key variable characterising the state of the land component of the hydrologic system. It is important in rainfall-runoff response and land-atmosphere interactions, as well as influencing a variety of plant and soil processes.

Soil moisture varies in space and time and many processes depend on soil moisture in a non-linear manner. Scale effects result as a consequence and these need to be better understood for making accurate predictions of hydrologic behaviour, especially where a change of scale is necessary. Other fields, including soils, topography, vegetation and meteorology, that influence soil moisture and other hydrologic responses are also variable, which leads to complicated scale effects and makes prediction very challenging.

There are many examples of scale effects involving soil moisture in the literature. The sensitivity of rainfall-runoff response to spatial variability of soil moisture has been demonstrated in model studies [Merz and Plate, 1997; Western et al., 2001]. Not only is the amount of variability important, but also the characteristics of the spatial patterns, particularly the degree of spatial organization of the soil moisture by the topography. Atmospheric circulation (convection, cloud formation and precipitation) at meso and continental scales has been shown to be sensitive to heterogeneity in the surface sensible and latent heat fluxes, which are partly determined by soil moisture [Entekhabi et al., 1996; Weaver and Avissar, 2001].

In this paper we first provide a review of soil moisture scaling and then we present some recent results and their implications for scaling analyses. The review provides a brief overview of the controls on soil moisture variability and then concentrates on behavioural (usually statistical) scaling techniques and results relevant thereto. Then results of analyses of the statistical distribution of soil moisture based on a database of thirteen data sets from around the world are presented. A more comprehensive version of this review of available [Western et al., in press] and other reviews also provide useful insight in scaling in hydrology and related fields [Blöschl and Sivapalan, 1995; Dunne et al., 1975; Entekhabi, 1995; Giorgi and Avissar, 1997; Koltermann and Gorelick, 1996].

2. SCALING OF SOIL MOISTURE

2.1 Scale and the Scale Problem

The concept of scale applies to data, models and processes. It can be thought of as consisting of three components: spacing, extent and support [Blöschl and Sivapalan, 1995]. Spacing is the characteristic separation between measurements or computational nodes, extent is the size of the overall measurement or model domain, and support is the size of the area represented (averaged over) by each measurement or model element. Scaling involves using information from one scale at another. Practical scale problems are challenging because they involve using information from one scale at a scale with a greater information requirement. This can be interpolating intervening values from sparse data, extrapolating from small to larger extents or disaggregating spatial averages.

2.2 Soil Moisture Controls

Soil moisture varies in space and time in response to a variety of fluxes including rainfall (and snowmelt), infiltration, evapotranspiration, lateral flow, and interaction with the groundwater. These fluxes are modulated by meteorological conditions, soil characteristics, the vegetation cover and topography. All of these fields are spatially and temporally variable. In time topography is the slowest to vary, followed by soils and vegetation, and the weather varies most rapidly. In space it is less clear which of these fields varies most rapidly and there is a tendency for some correlation between the variation (eg. topography, rainfall and temperature). The space-time variability of the soil moisture field is determined by the net effect of all these influences and by interactions between the soil moisture field and the other fields.

2.3 Measurement of Soil Moisture

Measurement is important from a scaling perspective because available measurement techniques impose very different scale characteristics. Soil moisture can be measured using a range of ground-based techniques including thermogravimetric, neutron scattering and dielectric techniques (eg. Time Domain Reflectometry (TDR)). All of these techniques are essentially point based, with typical supports varying between 1 and 10cm. Dielectric sensors can be easily logged, providing continuous records in time. Modern positioning technology (the Global Positioning System) and sensor design allows roving systems that can collect highly detailed temporal and spatial data sets [Western and Grayson, 1998; Woods et al., 2001] but logistical considerations mean that it is only possible to study small areas (typically < 1km^2).

Efforts in remote sensing of soil moisture have concentrated on the microwave wavelengths [Dobson and Ulaby, 1998; Engman, 2000; Jackson et al., 1996], since these are sensitive to the dielectric constant, hence soil moisture, in the top few cm of the soil profile, provided the vegetation canopy is not too dense [Du et al., 2000]. Remote sensing provides data that is essentially continuous in space, over very large extents, at a point in time. Passive microwave systems have very large supports or footprints (10-100 km from space or 100-1000m from aircraft) and daily repeat coverage (from space). Active or Synthetic Aperture Radar (SAR) systems have higher spatial resolution (typically 10-100m) but less frequent (about 2 weeks) repeat coverage.

There are some pressing issues that need to be addressed before well validated remotely sensed soil moisture data is operationally available. These include interpretation of the near surface soil moisture measurements in terms of the root zone and complete soil profile and addressing the impact of vegetation canopies and surface roughness (mainly for SAR systems). It is likely that complementary use of ground measurement and remote sensing could provide valuable improvements.

2.4 Scaling Methods

Where quantities vary in space or time, the variation can be quantified with a number of different characteristics. One possible classification is given below, roughly in order of increasing detail. The objectives of our analysis determine how far we need to progress down this list.

- Central tendency (mean, median)
- Spread (variance, interquartile range)
- Extremes (threshold values, high percentiles)
- Probability Density Function (pdf)
- Spatial relationships (correlation function, cross correlation with say terrain)
- The actual pattern

Western et al. [in press] give examples of applications of each of these, including the use of spatial mean moisture in water balance studies and using the pdf to parameterise sub-grid variability in hydrologic models. All but the first of these characteristics are scale dependent. The key to scaling within a behavioural framework is predicting this scale dependence and then using the scale dependent statistics as input to other (eg. hydrologic process) analyses. For example one may use the scale dependent pdf of soil moisture in a calculation of latent heat flux that accounts for subgrid variation in moisture availability. Distributed models can be used for scaling [Western et al., in press]; however, their use is not considered here. While the above characterise statistical behaviour, an understanding of physical processes is invaluable when interpreting and using these statistical approaches.

2.5 Spatial Scaling of Soil Moisture

In this section we consider the statistical distribution of spatial soil moisture, spatial correlation of soil moisture, and relationships between soil moisture and surrogate variables.

The statistical distribution, or pdf, of spatial soil moisture under field conditions is bounded between wilting point (usually) and porosity. These limits arise from the ability of plants to extract water and the pore space available to hold water, respectively.

Bouding tends to result in pdfs that become skewed and less variable as the mean approaches the boundary. Positive skew results near the lower boundary and negative near the upper boundary. It must of course be recognised that for soil moisture both of these boundaries are likely to be spatially variable due to variations in soils and that the properties of these distributions could affect the pdf of soil moisture under extreme dry and wet conditions.

The pdf of soil moisture has been examined in a number of studies [eg. Bell et al., 1980; Famiglietti et al., 1999]. Often the normality of the sample has been tested. The results have been equivocal, with a tendency for a greater proportion of large samples to be significantly non-normal due to increased statistical power. Where a large number of sampling occasions have been analysed, between 50 and 80% of the sampling occasions have statistically normal pdfs. Decreases in the coefficient of variation with increasing wetness are typically observed due to the increasing mean. Some studies have found increasing variance with increasing wetness [Bell et al., 1980] and others have found decreasing variance [Famiglietti et al., 1999]. Famiglietti et al. [1999] found a systematic change in skew from positive to negative as mean moisture increased.

Pdfs can be used as the basis for representing subgrid variability in models, as outlined by Beven [1995]. Models such as Topmodel and the Xinanjiang or VIC model use this approach to represent the distribution of saturation deficit and hence estimate saturation excess runoff. Topmodel uses a terrain-based pdf while VIC uses a theoretical pdf. There are significant differences between the two pdfs used in these models and also between observed and assumed pdfs [Kalma et al., 1995; Western et al., 1999a; Western et al., 1999b]. Topmodel and VIC have often been successfully applied to predict runoff. However they do not necessarily represent the pdf of moisture well.

In addition to the pdf, the spatial arrangement of soil moisture is also important for many applications. The relationship between soil moisture at different points in space can be characterised using the correlation function or variogram [Western et al., 1998]. The variogram can be used both to make inferences about processes [Western et al., 2002] and as a tool in spatial interpolation [Bárdossy and Lehmann, 1998], stochastic simulation and regularisation (predicting the effect of scale change on statistical properties) [Western and Blöschl, 1999].

The most important parameter characterising the spatial correlation is the correlation length. Most analysis of the spatial correlation of soil moisture has been at small scales (up to ~1km) (see Western et al. [1998] for a summary). Typically it is found that the spatial soil moisture field is stationary with a correlation length in the range 20 to 300m. At large scales (50-1000s km), the spatial soil moisture field has also been found to be stationary, but with a correlation length of about 400-800km [Entin et al., 2000; Robock et al., 1998]. One data set at intermediate scales has been analysed for the Washita, OK, catchment. Unlike other studies, this was remotely sensed data that averages moisture over 200m pixels and only represents the top few cm of the soil profile. These studies found that the soil moisture field was fractal (therefore nonstationary) [Rodríguez-Iturbe et al., 1995] over scales between 30m and 10km, with a transition from simple- to multi-fractal during dry downs [Hu et al., 1997; Peters-Lidard et al., 2001].

Some of the differences in observed behaviour are likely to be related to sampling effects [Western and Blöschl, 1999] and some are related to differences in process controls. Robock et al. [1998] and Entin et al. [2000] have proposed that spatial soil moisture is controlled by meteorological processes at large scales and catchment processes at small scales. In this conceptualisation there is a wide separation in scales that needs to be confirmed with more data from intermediate scales. One would also expect that soil properties and vegetation may play a significant role at these intermediate scales.

The relationship between soil moisture and other characteristics of the landscape can also provide useful information for scaling, including interpolation and disaggregation. The most common surrogate variables are terrain indices [Wilson and Gallant, 2000]. This is due to both the availability of digital terrain data and a perception that terrain is a dominant influence on the spatial variability of soil moisture. Terrain indices are often derived by considering physical processes such as lateral flow [eg. Beven and Kirkby, 1979] and, provided that the assumptions made are correct, they allow a consideration of physical processes within a behavioural analysis.

Where terrain indices have been compared with soil moisture data, up to 81% of the spatial variability in soil moisture has been accounted for [Zavlasky and Sinai, 1981]. However, it is rare to find more than 50% of the variation being accounted for and often much poorer results are obtained [Western et al., 1999a]. This spread in results is partially due to incorrect assumptions about dominant processes in particular landscapes. Indices also assume that terrain is dominant in determining variation, whereas soils and vegetation also play a role.

Key applications of terrain indices include interpolation, disaggregation and prediction of the pdf of soil moisture or saturation deficit in distribution function models. The results described above are relevant to the first two but for the third, comparing the model assumptions with observed pdfs is more relevant. Western et al. [1999a] performed such a comparison and found that the moisture pdf was poorly predicted by a range of topographic indices. The remainder of this paper presents some recent results relating to the pdf of soil moisture and its behaviour in relation to catchment wetness.

3. THE SOIL MOISTURE PDF

We have analysed the spatial soil moisture pdf from thirteen study areas around the world. These study areas cover climates ranging from semi-arid to humid, soils ranging from sands to clays, vegetation ranging from sparse rangelands to tall wet Eucalypt forests and topography from gently undulating to steep. The soil moisture is measured over different (and sometimes multiple) depths at each site, but is always sufficiently deep to be representative of at least a significant proportion of the root zone. At least fifteen samples (up to ~600) in space were measured on each occasion and at least four sampling occasions (up to ~280) are included for each site.

Our analysis has concentrated on characterising the pdf by plotting histograms and calculating a range of summary statistics including the number of samples, mean, variance, skew and kurtosis. For skewness and kurtosis, we used L-moments, which are more robust to outliers [Stedinger et al., 1992]. Here we summarise the overall behaviour of the data sets, as a function of catchment wetness.

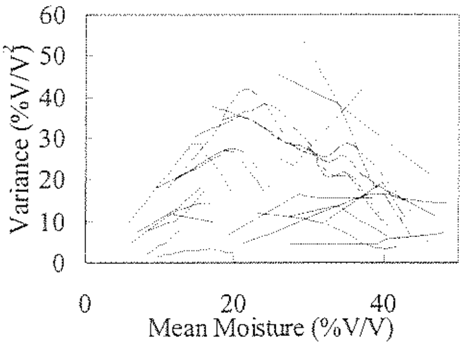

Figure 1: Changes in soil moisture variance with catchment wetness for each of the catchment/depth combinations.

Figure 1 shows plots of variance against mean moisture. Smoothed relationships calculated using LOWESS [Cleveland, 1979] have been fitted through the data points, which have been omitted for clarity. For dry catchments, a pattern of increasing variance as average moisture increases is evident. For wet catchments a pattern of decreasing variance with increasing moisture is evident. Where the spatial mean moisture has a sufficiently large range over time, the variance peaks at intermediate values. The location of the peak in variance and the magnitude of that peak change between catchments and further analysis is required to understand why this is so. Where multiple depths have been measured at a particular catchment, depth appears to have only a small effect on the relationship.

Figure 2 shows a plot of L-skewness against mean moisture content. Again smoothed relationships are plotted. The numerical values of L-skew are typically about 1/5 of the values of the product moment skewness. There is a general pattern of skewness being positive for low moisture contents and near zero for moderate and higher soil moisture. Individual catchments exhibit differences from this general behaviour.

One way to compare data with theoretical probability distribution functions is to use L moment diagrams [Stedinger et al., 1992]. On the L-skewness, L-kurtosis diagram, two parameter distributions (eg the normal distribution) plot as a point and three parameter distributions (eg the generalised extreme value distribution) plot as a line. Figure 3 shows the behaviour of soil moisture in L-skew, L-kurtosis space. The three parameter gamma (thick line) and normal (diamond) pdfs are also shown. For these data sets, the typical L-skew and L-kurtosis are quite close to the normal distribution. The range of variation in L-skew is well represented on this diagram but the range in L-kurtosis is somewhat compressed by the LOWESS fitting. However scatter plots indicate a similar general pattern. Minimal changes in kurtosis are evident in moving from negative to positive skewness. Of the three parameter distributions considered, the Gamma distribution most closely matches this behaviour, together with the average relationship between L-skewness and L-kurtosis.

The ultimate aim of this work is to develop a generalised description of the statistical distribution of soil moisture. These can then be used in applications such as parameterising sub-grid soil moisture variability in large-scale models.

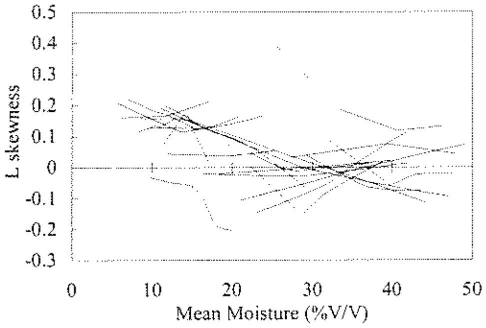

Figure 2: The relationship between L-skewness and spatial average soil moisture.

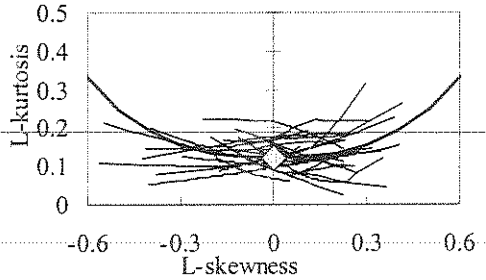

Figure 3: L moment diagram for spatial soil moisture. The heavy line shows the three parameter gamma distribution and the diamond shows the normal distribution

4. CONCLUSIONS

We have reviewed a range of different approaches to soil moisture scaling. Much progress is being made in this field, particularly in response to the need for improved understanding of land-atmosphere interaction. New measurement techniques have enabled advances in data collection but further work is required before operational soil moisture remote sensing systems produce reliable estimates of root zone soil moisture.

We have analysed the statistical characteristics of thirteen spatial soil moisture data sets from around the world. Systematic changes in variance and skewness can be identified from these data. Variance tends to peak at moderate soil moisture levels, while there is positive skewness for low soil moisture and a symmetric pdf for moderate and high soil moisture levels. While the soil moisture pdf is non-normal at times, the departures from normality are relatively small, compared with other hydrologic parameters. Further analysis of this data set is required to establish the role of various catchment characteristics on soil moisture variability.

5. REFERENCES

Bárdossy, A., and W. Lehmann, Spatial distribution of soil moisture in a small catchment. Part 1: geostatistical analysis, *Journal of Hydrology, 206*, 1-15, 1998.

Bell, K. R., B. J. Blanchard, T. J. Schmugge, and M. W. Witczak, Analysis of surface moisture variations within large-field sites, *Water Resources Research, 16*(4), 796-810, 1980.

Beven, K., Linking Parameters Across Scales: Subgrid Parameterizations and Scale Dependent Hydrological Models, *Hydrological Processes, 9*, 507-525, 1995.

Beven, K. J., and M. J. Kirkby, A physically-based variable contributing area model of basin hydrology, *Hydrological Sciences Bulletin, 24*, 43-69, 1979.

Blöschl, G., and M. Sivapalan, Scale issues in hydrological modelling: A review, *Hydrological Processes, 9*(3/4), 251-290, 1995.

Cleveland, W. S., Robust locally weighted regression and smoothing scatterplots, *Journal of the American Statistical Association, 74*(368), 829-836, 1979.

Dobson, M. C., and F. T. Ulaby, Mapping soil moisture distribution with imaging radar, in *Principles and applications of imaging radar*, vol. 2, edited by F. M. Henderson and A. J. Lewis, pp. 407-433, John Wiley & Sons/American Society for Photogrammetry and Remote Sensing, New York, 1998.

Du, Y., F. T. Ulaby, and M. C. Dobson, Sensitivity to soil moisture by active and passive microwave sensors, *Ieee transactions on geoscience and remote sensing, 38*(1), 105-114, 2000.

Dunne, T., T. R. Moore, and C. H. Taylor, Recognition and prediction of runoff-producing zones in humid regions, *Hydrological Sciences Bulletin, 20*, 305-327, 1975.

Engman, E. T., Soil moisture, in *Remote sensing in hydrology and water management*, edited by G. A. Schultz and E. T. Engman, pp. 197-216, Springer, Berlin, 2000.

Entekhabi, D., Recent Advances in Land-Atmosphere Interaction Research, *Reviews of geophysics, 33*, 995-1003, 1995.

Entekhabi, D., I. Rodriguez-Iturbe, and F. Castelli, Mutual interaction of soil moisture state and atmospheric processes, *Journal of Hydrology, 184*, 3-17, 1996.

Entin, J. K., A. Robock, K. Y. Vinnikov, S. E. Hollinger, S. X. Liu, and A. Namkhai, Temporal and spatial scales of observed soil moisture variations in the extratropics, *Journal of Geophysical Research-Atmospheres, 105*(D9), 11865-11877, 2000.

Famiglietti, J. S., J. A. Devereaux, C. A. Laymon, T. Tsegaye, P. R. Houser, T. J. Jackson, S. T. Graham, M. Rodell, and P. J. van Oevelen, Ground-based investigation of soil moisture variability within remote sensing footprints during the Southern Great Plains 1997 (SGP97) Hydrology Experiment, *Water Resources Research, 35*(6), 1839-1851, 1999.

Giorgi, F., and R. Avissar, Representation of heterogeneity effects in earth system modelling: experience from land surface modeling, *Reviews of Geophysics, 35*(4), 413-438, 1997.

Hu, Z., S. Islam, and Y. Cheng, Statistical characteriszation of remotely sensed soil moisture images, *Remote Sensing of the Environment, 61*, 310-318, 1997.

Jackson, T. J., J. Schmugge, and E. T. Engman, Remote sensing applications to hydrology: soil moisture, *Hydrological Sciences Journal, 41*(4), 517-530, 1996.

Kalma, J. D., B. C. Bates, and R. A. Woods, Predicting catchment-scale soil moisture status with limited field measurements, *Hydrological Processes, 9*, 445-467, 1995.

Koltermann, C. E., and S. M. Gorelick, Heterogeneity in sedimentary deposits: A review of structure-imitating, process-imitating and descriptive approaches, *Water Resources Research, 32*(9), 2617-2658, 1996.

Merz, B., and E. J. Plate, An analysis of the effects of spatial variability of soil and soil moisture on runoff, *Water Resources Research, 33*(12), 2909-2922, 1997.

Peters-Lidard, C. D., F. Pan, and E. F. Wood, A re-examination of modeled and measured soil moisture spatial variability and its implications for land surface modeling, *Advances in Water Resources*, in press, 2001.

Robock, A., C. A. Schlosser, K. Y. Vinnikov, N. A. Speranskaya, J. K. Entin, and S. Qiu, Evaluation of the AMIP soil moisture simulations, *Global and Planetary Change, 19*(1-4), 181-208, 1998.

Rodriguez-Iturbe, I., G. K. Vogel, R. Rigon, D. Entekhabi, F. Castelli, and A. Rinaldo, On the spatial organization of soil moisture fields, *Geophysical Research Letters, 22*, 2757-2760, 1995.

Stedinger, J. R., R. M. Vogel, and E. Foufoula-Georgiou, Frequency analysis of extreme events, in *Handbook of Hydrology*, edited by D. R. Maidment, pp. 18.1-18.66, McGraw Hill, New York, 1992.

Weaver, C. P., and R. Avissar, Atmospheric disturbances caused by human modification of the landscape, *Bulletin of the American Meteorological Society, 82*(2), 269-281, 2001.

Western, A. W., and G. Blöschl, On the spatial scaling of soil moisture, *Journal of Hydrology, 217*, 203-224, 1999.

Western, A. W., G. Blöschl, and R. B. Grayson, Geostatistical characterisation of soil moisture patterns in the Tarrawarra Catchment, *Journal of Hydrology, 205*, 20-37, 1998.

Western, A. W., G. Blöschl, and R. B. Grayson, Towards capturing hydrologically significant connectivity in spatial patterns, *Water Resources Research, 37*(1), 83-97, 2001.

Western, A. W., and R. B. Grayson, The Tarrawarra data set: Soil moisture patterns, soil characteristics and hydrological flux measurements, *Water Resources Research, 34*(10), 2765-2768, 1998.

Western, A. W., R. B. Grayson, and G. Blöschl, Scaling of Soil Moisture: a hydrologic perspective, *Annual Review of Earth and Planetary Sciences, 30*, in press.

Western, A. W., R. B. Grayson, G. Blöschl, G. R. Willgoose, and T. A. McMahon, Observed spatial organisation of soil moisture and its relation to terrain indices, *Water Resources Research, 35*(3), 797-810, 1999a.

Western, A. W., R. B. Grayson, and T. R. Green, The Tarrawarra Project: High resolution spatial measurement, modelling and analysis of soil moisture and hydrological response, *Hydrological Processes, 13*, 633-652, 1999b.

Wilson, J. P., and J. C. Gallant, Terrain analysis: principles and applications, John Wiley, New York, 2000.

Woods, R. A., R. B. Grayson, A. W. Western, M. J. Duncan, D. J. Wilson, R. I. Young, R. P. Ibbitt, R. D. Henderson, and T. A. McMahon, Experimental Design and Initial Results from the Mahurangi River Variability Experiment: MARVEX, in *Observations and Modeling of Land Surface Hydrological Processes*, edited by V. Lakshmi, J. D. Albertson and J. Schaake, American Geophysical Union, 2001.

Zavlasky, D., and G. Sinai, Surface Hydrology: I - Explanation of phenomena, *Journal of the Hydraulics Division, Proceedingsof the American Society of Civil Engineers, 107*(HY1), 1-16, 1981.