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# DEALING WITH SOIL VARIABILITY: SOME INSIGHTS FROM LAND DEGRADATION RESEARCH IN CENTRAL SPAIN

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## ABSTRACT

Soil variability is often seen as problematic in land degradation studies in terms of sampling effort, data interpretation and for the extrapolation of results to other areas or time periods. Examples are given from land degradation research undertaken in central Spain which demonstrate some of these problems associated with soil variability. Geostatistics is presented as a useful tool for quantifying soil variability and in particular the variogram for interpreting and understanding spatial patterns. Soil variability is also seen to complicate the issues surrounding management strategies and makes monospecific management strategies less likely to be successful. In recent years several studies have suggested that variability in soil properties and vegetation cover may reduce the risk of land degradation by minimizing the spatial extent of runoff and erosion. These studies suggest that increasing soil variability may prove to be an effective strategy for reducing the runoff and erosion risk. This paper discusses these ideas and highlights the importance of increasing thresholds above which runoff and erosion occurs for the success of such strategies. This in particular applies to many semiarid environments where thresholds are deemed to be extremely low. Finally, these concepts are placed in the context of scale where soil variability may be viewed as existing at a multitude of nested levels varying from the micro- to the macro-scale. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: soil variability; geostatistics; thresholds; scale; land management; sustainability

## INTRODUCTION

Soil variability occurs due to changes in properties over space and time as a result of continuous interactions between the lithosphere, biosphere and atmosphere (Rowell, 1994). In arid and semi-arid regions variability in soil properties is often high due to the complex geology, sediments, terrain and heterogeneity in vegetation cover encountered (Yair and Lavee, 1985; Berndtsson and Larson, 1987). This ‘natural’ variability can be further increased by human disturbance, in particular through the onset of degradational geomorphic processes such as soil erosion and gullying which can increase soil variability through the re-mixing of sediments and exposure of underlying sediments by gully dissection (Beckett and Webster, 1971). For these regions in particular, soil variability is often seen as being problematic for scientific research (McBratney, 1992). In terms of sampling effort the more variability that is encountered the greater the number of samples needed to unravel the complexity. In addition the quality of information obtained and its ease of interpretation will also be dependent to some degree on the extent of soil variability encountered by the investigation. Since most scientific research is constrained by a budget and a time period, the degree of variability encountered can determine the nature of the sampling strategy used and the scale at which the study is undertaken. Variability is also problematic when trying to transfer research

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findings and ideas to areas and time periods other than those in which the study took place. Shakesby *et al.* (this volume) give an example where temporal variability in degradational processes can mislead interpretations of erosion hazard when the research is constrained by a limited time period. Soil variability also has implications for land management and the success of implemented management strategies. The more uniform a soil is, the easier it is to manage and the less complex the management strategy needs to be (McBratney, 1992). Where soil variability is complex, a single monospecific management strategy is likely to have limited success. It is therefore becoming increasingly recognized that in environments exhibiting high soil variability that land managers need to adopt a management approach which is soil specific or spatially sensitive (Robert, 1993). The spatially sensitive management concept, however, requires newer and higher levels of technology as well as new management skills, both of which are costly to obtain (Robert, 1993).

From an ecological point of view soil variability may be seen as beneficial. Distinct soil variations will support a diversity of ecosystems, increasing the ecological value of a region (Ibanez *et al.*, 1995). Furthermore, such diversity is considered beneficial in that it promotes stability and resilience within the environment (McBratney, 1992). In recent years several authors have shown that variability in soil properties or vegetation cover may be beneficial for runoff and erosion control (Sharma *et al.*, 1987; Cerdà, 1995; Bergkamp *et al.*, 1996; Fitzjohn *et al.*, 1998). Both Cerdà (1995) and Bergkamp *et al.* (1996) have shown how a patchiness in vegetation cover can reduce the amount of runoff and sediment reaching the base of slopes and channels. Fitzjohn *et al.* (1998) have suggested that spatial variability in soil properties may create a mosaic pattern of areas with contrasting hydrological properties, thus promoting a self-regulating system for runoff and erosion control.

In land degradation research soil variability can be clearly seen to be both problematic in terms of assessing degradation and formulating management strategies and beneficial in terms of creating a 'natural' mechanism for runoff and erosion control and enhancing biodiversity. Using case studies of land degradation research undertaken in central Spain, this paper gives some examples of the problems associated with soil variability as well as some methods for quantifying variability, in particular geostatistical analysis. The paper also examines the concepts behind promoting soil variability as a strategy for runoff and erosion control.

## EXAMPLES OF SOIL VARIABILITY

Located 70 km to the northeast of Madrid in the Puebla de Valles-Retiendas area of west Guadalajara province, the EU-funded research project IBERLIM (EV5V-0041) investigated the erosional impacts of existing and alternative land management practices. As part of this investigation runoff plots were used to quantify the overland flow and runoff response characteristics of different land uses. The bounded plots were typical of other plots being used in land degradation studies, e.g. MEDALUS, and measured 10 m in length by 2 m in width. Two plots were established in each land use. The plots were aligned with the principle downslope direction and were separated by no more than 3 m across the slope. Two runoff plots were used in an attempt to replicate results and hence act as a check on data reliability. However, the two adjacent plots established in the matorral land use showed quite differing runoff responses. On average the runoff from one plot was 34 per cent higher than the other. A simple visual inspection of the plots could not explain this discrepancy since both were adjacent to each other and both had a dense 100 per cent vegetation cover. The boundaries of the plots were inspected for breaches as were the collecting tanks, but no obvious problems could be found. The cause of the discrepancy lay in the variable nature of the alluvial sediments underlying the plots (Figure 1). The texture of these sediments varies from horizons dominated by gravels and sand to those dominated by silts and clays (Ternan *et al.*, 1998). Volumetric soil moisture (20 cm depth) measured using time domain reflectometry (TDR) was recorded every metre downslope within the plots and the values were found to reflect the texture of the underlying sedimentary horizons. Low soil moisture values were related to coarse-textured horizons whereas high soil moisture was related to horizons dominated by finer sediments. Figure 1 shows the alternating pattern of soil moisture reflecting the interbedded nature of the sediments with soil moisture ranging from 16–46 per cent over 1–2 m. These interbedded sedimentary horizons run diagonally across the slope, whereas both runoff plots are perpendicular to the slope. The sedimentary horizons closest to the plot outlets were therefore strikingly different in their textural composition and soil moisture content

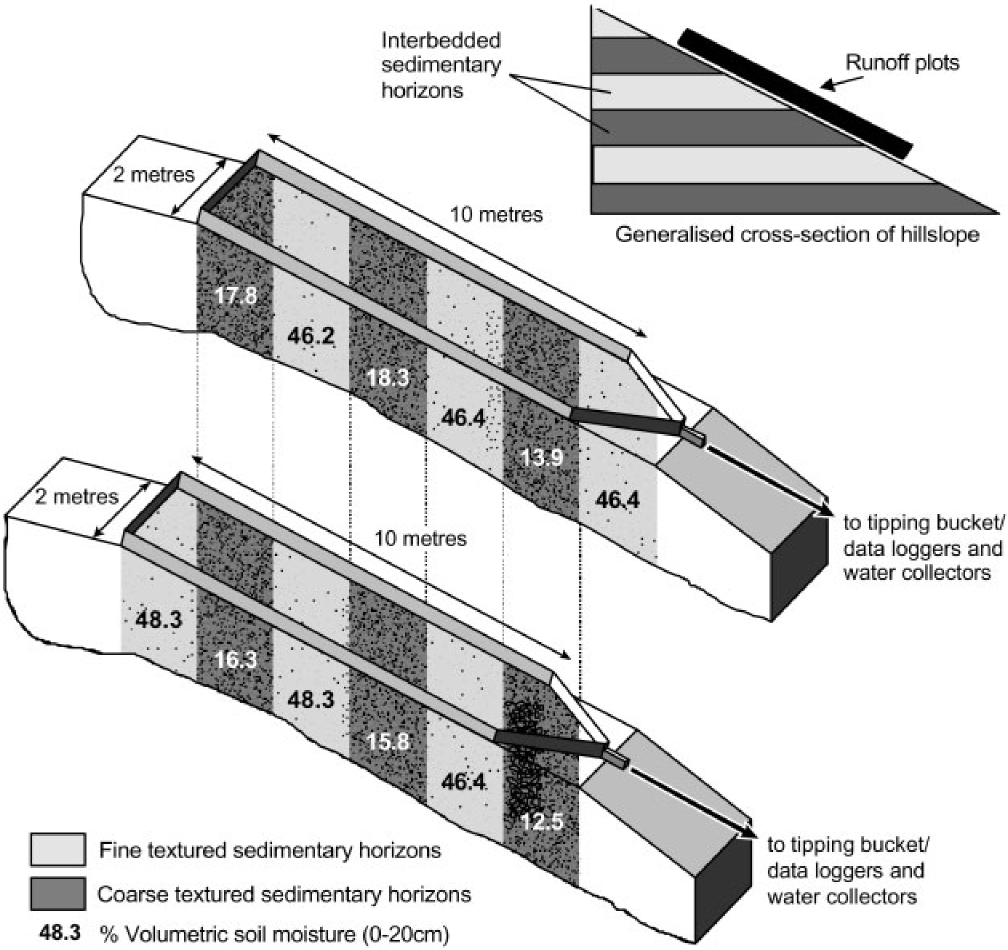

Figure 1. Variable sediment horizons and soil moisture content resulting in a contrasting runoff response from replicate runoff plots.

(Figure 1). The plot with consistently higher values of runoff was the plot whose outlet was adjacent to the finer sediment horizon where soil moisture was high. It was therefore hypothesized that during a rainstorm event runoff generation would be variable across the plots relating to the differing sediment horizons and that infiltration would be higher closer to the outlet of the plot where the sediment horizon's soil moisture was low. In arid and semiarid environments heterogeneity in vegetation cover may also lead to similar problems when using runoff plots. It has been shown by Johnson and Gordon (1988) and Morin and Kosovsky (1995) that patchiness in vegetation cover can produce a variable runoff response, where vegetation acts as a sink for runoff. The location of patches of vegetation in relation to the runoff plots outlet may therefore also influence the measured hydrological response.

It has been shown that variability in soil properties can lead to quite contrasting results from runoff plots which are similar in terms of vegetation cover. Soil variability therefore needs to be considered in land degradation studies. Furthermore, soil variability occurs at all scales and hence the problems associated with runoff plots may also be found at other scales from the the rainfall simulation plot scale to the catchment scale.

As part of the EU-funded project MEDAFOR (ENV4-CT97-0686) the spatial variability of several soil properties was measured under different land uses in order to assess the vulnerability of the land uses to land degradation and desertification. One of the land uses studied was a ploughed field located in a valley bottom with a 7 degree slope. A sampling grid was constructed across the field (170 × 45 m) with 5 m intervals giving 350 sampling points. Although the field appeared to be of fairly uniform slope with no outstanding features, surface soil moisture (0–15 cm) measured at each grid point using TDR was found to vary from 4·2–36·6 per cent. A geostatistical analysis of this dataset produced a pure nugget variogram indicating complete random variability at the sampling scale of 5 m. Furthermore, at 25 points on the grid other soil properties including organic carbon content, aggregate stability and texture were also measured. Organic carbon varied from 0·2–1·2 per cent, aggregate stability as measured by laboratory rainfall simulation (Ternan *et al.*, 1996) varied from 30–88 per cent stable aggregates. Clay content varied from 4·8–17·1 per cent and sand from 9·8–38 per cent. Although this land use has close to 0 per cent vegetation cover and a fairly uniform and gentle slope it can be clearly seen that the variability in several soil properties can be dramatic over distances as short as 5 m. Given these situations it is not unusual for the variability within a single land use to be greater than the variability between land uses. Such variability makes it extremely difficult to make an assessment or prediction regarding the vulnerability of these land uses to degradation.

## QUANTIFYING SOIL VARIABILITY

It is generally accepted that soil samples collected close to one another are more similar than samples collected further apart. Hence, a property's values lie on a continuum between two extremes and will exhibit a relationship between spatial dependence and distance (Trangmar *et al.*, 1985; Oliver and Webster, 1991). Geostatistical techniques have been proven to be widely applicable to the description of this spatial dependence and have been used with a wide range of environmental data to quantify spatial and temporal structures. Trangmar *et al.* (1986) used geostatistics to quantify the variability in soil texture, pH and phosphorus. Among other variables Gonzalez and Zak (1994) used geostatistics to describe the variability in organic carbon and nitrification. Several authors including Fitzjohn *et al.* (1998) and Western *et al.* (1998) have used geostatistics to quantify the spatial variability in soil moisture. Geostatistics has also been used for describing the temporal variability in soil properties (Hawley *et al.*, 1983; Munoz-Pardo *et al.*, 1990; Comegna and Basile, 1994). Geostatistics is not only used to describe spatial structures, but can also be used to understand or begin to explore the underlying processes responsible for the variation (Trangmar *et al.*, 1985; Oliver, 1987; Davidson and Watson, 1995). A fundamental tool necessary for geostatistical analysis is the variogram (Figure 2) (Journel and Huijbregts, 1978). The variogram shows the average

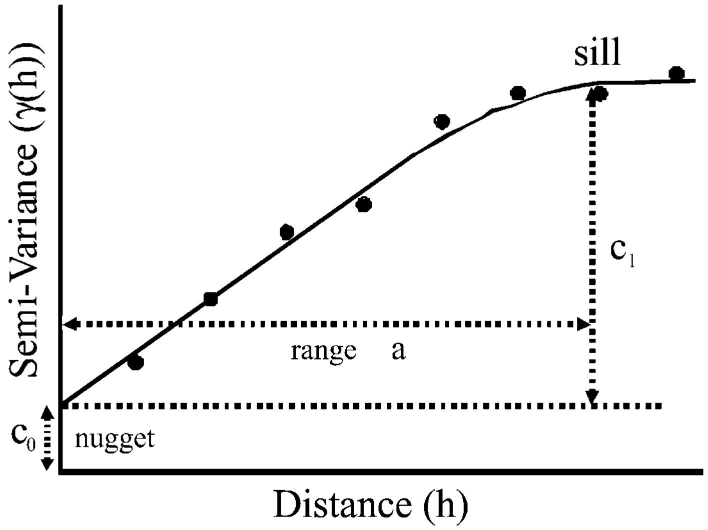

Figure 2. Variogram of a regionalized variable showing the sill ($C = C_1 + C_0$) the range (a), the spatially related variance ($C_1$) and the nugget variance ($C_0$).

rate of change of a property with distance. The average rate of change is termed semivariance and is defined as half the expected squared difference between values (Oliver and Webster, 1991). Each point on the variogram consists of pairs of measurements which are grouped into classes according to their separation distance. The more alike pairs are then the smaller the semivariance and the lower the variability. Hence, variograms often show increasing semivariance as the distance separating pairs increases (Figure 2) (Burgess and Webster, 1980). Three important components define the variogram, these are the sill, the range and the nugget (Figure 2). The sill is where semivariance rises to a constant value. The range is the separation distance at which the semivariance becomes constant, i.e. the sill (Journel and Huijbregts, 1978). The range represents the maximum distance of spatial dependence. Samples separated by distances shorter than the range are spatially related. Samples separated by distances greater than the range are not spatially related, implying random variation (Trangmar *et al.*, 1985; Webster and Oliver, 1990). The nugget represents unexplained or random variance which may be caused by measurement error and/or variability within the property which cannot be detected at the sampling scale (Burrough, 1993). To derive these three parameters a model which best matches the experimental variogram generated from the dataset is fitted, most commonly using a weighted least squares regression method (Trangmar *et al.*, 1985). Although a wide range of model types is available for fitting variograms, the most commonly used for soil properties are the spherical model, the exponential model and the unbounded linear model (Oliver, 1987; Oliver and Webster, 1991).

To demonstrate how geostatistics can be used to quantify variability, two hypothetical catchments with different spatial structures have been generated (Figure 3). Catchment B shows a highly variable and fragmented spatial pattern, whereas catchment A consists of large areas over which values are similar. Geostatistics was used to create a variogram to quantify the spatial pattern within each catchment (Figure 3). In catchment B the variogram is horizontal indicating that all of the variance is nugget, i.e. random. Hence, even at the shortest separation distance

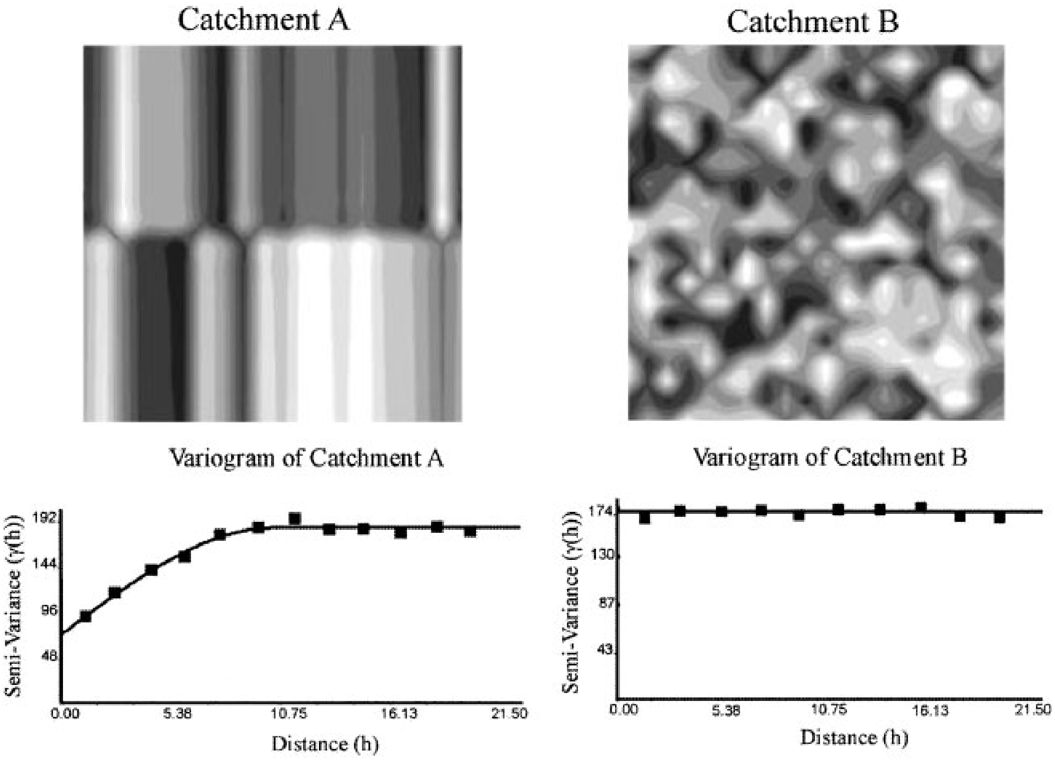

Figure 3. Two hypothetical catchments with different spatial patterns and variograms.

the sampling points are completely unrelated. This variogram clearly reflects the fragmented spatial pattern shown in Figure 3. In this instance the property studied can only be spatially correlated at distances smaller than the shortest sampling interval currently used. Hence, the best estimator within this dataset is the sample mean (Trangmar *et al.*, 1985). In contrast the variogram for catchment A shows semivariance rising to a constant value indicating that the property being measured is spatially correlated (Figure 3). The variogram has been fitted with a spherical model and the range of spatial correlation is approximately 10 units.

In recent years geostatistics has become an increasingly used tool for dealing with variable field data. A major drawback, however, of using geostatistics for spatial analysis is the number of samples needed to accurately estimate the variogram. Webster and Oliver (1992) have shown that variograms based on 50 or fewer samples are of little value, and that a minimum of 150 samples are needed to reliably estimate the variogram. Interpreting variograms also requires experience since their form can be complicated with unusual hidden structures. Other techniques used for describing and quantifying spatial patterns include cluster analysis, computer-aided pattern recognition analysis and fractal analysis, although geostatistics is the most commonly used.

## INCREASING SOIL VARIABILITY AS A STRATEGY FOR MANAGING RUNOFF AND EROSION

Spatially non-uniform runoff whereby a mosaic patchwork of contributing areas and areas capable of reabsorbing runoff exists has been reported by several authors (Amerman 1965; Blackburn 1975; Johnson and Gordon, 1988; Cerdà, 1995; Morin and Kosovsky, 1995; Fitzjohn *et al.*, 1998). Such spatially non-uniform runoff has been related to several variables including the patchiness of vegetation cover (Cerdà, 1995; Bergkamp *et al.*, 1996; Nicolau *et al.*, 1996), differences in soil moisture (Fitzjohn *et al.*, 1998), differences in lithology (Lavee and Yair, 1990), water repellency (Imeson *et al.*, 1992), surface roughness (Lavee *et al.*, 1995) and soil crusting (Bromley *et al.*, 1997). These 'source' and 'sink' areas can be delimited into units based on their differing hydrological response and spatial limits which can be defined from the variogram (Davidson and Watson, 1995). Since these units display a different runoff response they can be termed 'hydrological response units'. The spatial limits of the hydrological response units can be dynamic and therefore the degree of variability in runoff generation may vary for different time periods (Morin and Kosovsky, 1995). Studies where non-uniform runoff has been reported have shown that variability in hydrological response units produces discontinuous hydrological pathways, resulting in reduced runoff and sediment reaching the base of hillslopes and catchment outlets (Cerdà, 1995; Lavee *et al.*, 1995; Nicolau *et al.*, 1996; Grayson *et al.*, 1997). Runoff and erosion is therefore restricted to localized areas. These findings suggest that increasing variability in soil properties, producing a mosaic pattern of source and sink areas, may prove to be an effective management strategy for runoff and erosion hazard control.

### *Threshold Issues*

Fitzjohn *et al.* (1998) have suggested that increasing variability may only be successful in reducing runoff and erosion below critical threshold values. The sink areas within the mosaic pattern will have a limited capacity beyond which they themselves will act as source areas and generate runoff. This threshold value is determined by those factors which control runoff generation. This could be any one of several variables including rainfall intensity, infiltration capacity, antecedent soil moisture content, susceptibility to surface crusting and surface roughness. Once the thresholds of the sink areas have been exceeded variability will no longer restrict the area of runoff generation which will consequently be widespread. Therefore the effectiveness of increasing soil variability as a control for runoff and erosion hazard is dependent upon the threshold values of the sink areas. In many semiarid regions large areas are degraded implying low thresholds to runoff and erosion. Although these environments have high spatial variability in topography, soils and vegetation, thresholds are generally low and are frequently exceeded resulting in severe land degradation. Figure 4 shows an example where an area may have high variability (B), but low thresholds as indicated by poor soil physical and hydrological properties. In contrast area A has low variability, but much higher thresholds. Consequently, given the same meteorological conditions, the runoff and erosion risk from area A is lower than area B. Increasing variability is therefore not the only parameter for successfully reducing the runoff and erosion risk of an area. Raising threshold values above which

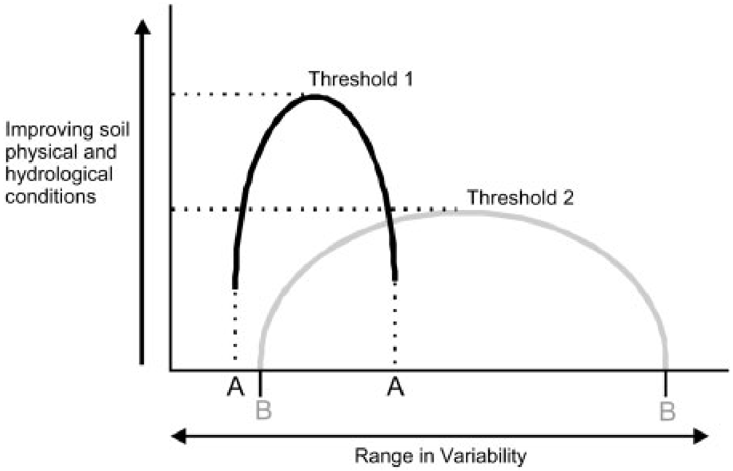

Figure 4. Area B may have high spatial variability, but if thresholds are low the runoff and erosion risk could be greater than areas where variability is low, but thresholds are high (A). The effectiveness of increasing soil variability as a control for runoff and erosion hazard is therefore dependent upon the threshold values of the sink areas.

runoff is generated should also be seen as a key priority in management strategies. Furthermore, in areas where thresholds are low or where the majority of the runoff and erosion is caused by two or three storms, quantifying spatial variability with the aim of interpreting hydrological response or for inclusion within hydrological models may prove to be unproductive since it has little effect on determining the runoff and erosion risk.

### *Scale Issues*

Hydrological response units have been reported over a range of scales from within runoff plots as small as $1{\cdot}5\,\mathrm{m}^2$ (Morin and Kosovsky, 1995; Bergkamp *et al.*, 1996) to hillslopes (Blackburn, 1975; Cerdà, 1995) and catchments (Imeson *et al.*, 1992; Yair, 1992). The mosaic pattern formed by areas of contrasting hydrological response may therefore be scale-independent, i.e. a mosaic pattern of contrasting hydrological response units may be found at all scales. For example, at the microscale the mosaic pattern may reflect differences in the hydraulics between the soil matrix and soil pores or root channels, whereas at the hillslope and catchment scale the mosaic pattern may reflect topography, lithology, land use and vegetation patterns (Kirkby *et al.*, 1996; Nicolau *et al.*, 1996). Furthermore, the mosaic pattern of hydrological response units found at one scale form one level in a multitude of nested mosaic patterns varying from the micro- to the macroscale (Figure 5) (Campbell and Honsaker, 1982; Bergkamp, 1995). At the catchment scale for example, there will be several nested levels of mosaic patterns such as the microscale, plot scale and hillslope scale (Figure 5). At each larger scale the factors that determine runoff at that scale may override the factors generating runoff at smaller scales (Seyfried and Wilcox, 1995). Therefore, for a storm to initiate catchment scale runoff and erosion it must overcome the spatial variability and thresholds of hydrological response units at all smaller scales. Widespread runoff and erosion at the catchment scale therefore requires prolonged or larger magnitude storms, whereas widespread runoff and erosion at smaller scales, with fewer nested levels, may be initiated by shorter duration or lower magnitude storms. The scale at which land degradation studies are undertaken may therefore influence the interpretation of the results collected. For example, runoff and erosion results collected at the rainfall simulation plot or runoff plot scale may overestimate the runoff and erosion at the hillslope and catchment scale (Evans, 1995; Poesen *et al.*, 1996). This is because plots are studies conducted at the small scale, where thresholds above which runoff occurs will be lower and hence exceeded more frequently than the thresholds necessary to generate runoff at larger scales. The likelihood of continuous hydrological pathways within plots is also greater than can be expected at the hillslope or catchment scale due to the shorter distances involved.

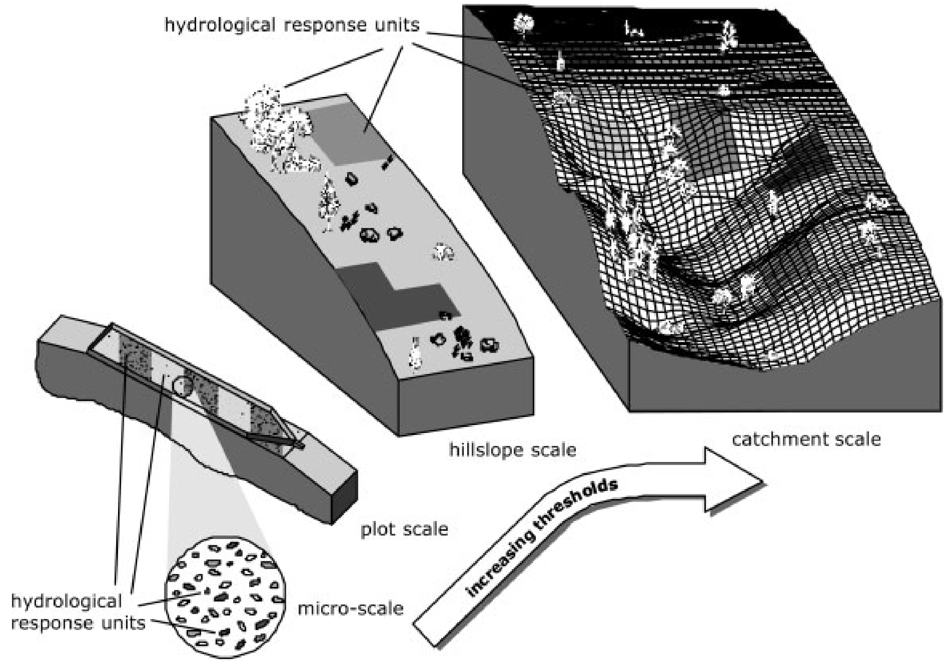

Figure 5. A multitude of nested mosaic patterns varying from the micro- to the macroscale. Thresholds above which runoff and erosion occur also increase with scale.

## CONCLUSIONS

Quantifying the spatial and temporal variability of key soil properties may improve our understanding of the often complex hydrological and erosional behaviour exhibited within semiarid and arid environments. Geostatistical analysis has been proven to be a useful tool for achieving this aim. Although soil variability may be seen as problematic for monitoring, understanding, interpreting and managing the environment, it has also been shown to reduce the risk of land degradation by minimizing the spatial extent of runoff and erosion. As a result an argument exists for increasing variability as a management strategy for reducing the runoff and erosion risk. Increasing variability may be achieved through the organization of land uses within a catchment so that hydrological pathways are discontinuous. Patches of forest land, agricultural land and shrubland can be spatially arranged to minimize the continuity of hydrological pathways while allowing potentially degrading management practices such as arable farming, to continue. Agricultural land which may be viewed as potential source areas of runoff and erosion, but which have important economical and social benefits, should be adjacent to land uses capable of absorbing this runoff and trapping sediment. This may be achieved through the spatial reorganization of existing land uses within a catchment and/or through the careful selection of agricultural land to be taken out of production (set-aside) for pasture or forestry grants. Following this strategy may allow for a sustainable coexistence between agriculture and reduced land degradation.

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