Modelação de formas de relevo para aplicação à cartografia de solos

Soil-landscape modelling using breaks in the scaling regime of slopes

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Abstract

Despite the advances in digital terrain tools and pattern recognition techniques for the segmentation of landform units, there remain significant challenges to identify the thresholds to separate landform classes with pedological and hydrological significance at the landscape scale. If different scaling regimes exist on hillslopes, breaks can be detected by analysis of the aggregation pattern of terrain attributes in the drainage direction, i.e. changes in the scaling response of topographic attributes versus contributing area. It is suggested that for the identification of threshold values to be applied at the regional level, comparative analysis between different terrain attributes versus cumulative area distributions is performed and applied to catchments with different sizes. The most recurrent boundaries are then used to parameterise a discrete, semantic, knowledge-based landform model. Results for the Marina Baixa area (SE Spain) shows that breaks in the distributions are seldom concurrent between different catchments. However, breaks in the scaling of different terrain attributes within catchments often occur at the same distance from the summit, which indicates that those breaks are related to real changes in the shape of the land-surface and have, therefore, practical application in the separation of units for instance, for the regionalisation of soil properties and hydrological modelling.

Keywords

Landform segmentation, scaling regimes, soil mapping, digital terrain models.

Resumo

Apesar dos avanços em ferramentas de análise digital de terreno e de técnicas de reconhecimento de padrões aplicadas à segmentação de formas de relevo, é ainda difícil identificar limiares numéricos de modelos de terreno que possam ser utilizados para separar classes que tenham algum significado pedológico e hidrológico. Contudo, se existem diferentes regimes escalares nas vertentes, os seus limites podem ser detectados por análise do padrão de agregação de variáveis morfométricas no sentido da direcção da drenagem, isto é, pela análise das variações escalares na resposta das variáveis morfométricas versus área de contribuição de uma bacia hidrográfica. Assim, para identificar limiares de variáveis morfométricas na classificação de formas de relevo que sejam aplicáveis a nível regional faz-se uma análise comparativa dos regimes escalares de diversas variáveis morfométricas para bacias de dimensões diferentes. Os limiares que sistematicamente ocorrem com maior frequência são então utilizados para parameterisar um modelo heurístico e semântico de formas de relevo. O resultado da aplicação desta metodologia à área de Marina Baixa (província de Alicante) no SE de Espanha mostra claramente que os limites dos regimes escalares raramente se mantém entre bacias hidrográficas. Contudo, permanecem relativamente constantes e ocorrem às mesmas distâncias dos topos das vertentes dentro das mesmas bacias. Isto indica que os limites estão fortemente relacionados com a forma da superfície dos terrenos o que, por sua vez, tem aplicação prática na separação de classes de formas de relevo para a regionalização de propriedades de solos e para a modelação hidrológica.

Palavras-Chave

Segmentação de formas de relevo, regimes escalares, cartografia de solos, modelos digitais de terreno.

1. Introduction

To date, improvements in landform identification, segmentation, extraction and/or classification have come mainly from technical developments in GIS, digital terrain modelling and increasing availability of statistical and pattern recognition software. This is clearly reflected in copious literature, especially in the realm of soil-landscape modelling, focusing on the development of landform models, from semi-automatic, to unsupervised models, with discrete or continuous boundaries between landform units. In as much as the current paradigm of soil formation conforms to the idea that landscape controls the variability of soil properties, landforms can be successfully used, coupled with vegetation and geology data, to explain the variability of soils. However, whilst those works have improved our knowledge of soil spatial variability, it is becoming important to develop robust methods that link soil and ecological services variability to the landscape processes, via an improvement of our understanding of landforms and the partition of water and matter at the landscape scale.

According to Huggett and Cheesman (2002), landform elements are simply-curved geometric surfaces lacking inflections and are considered in relation to upslope, downslope and lateral elements. Thus, it follows that landform elements cannot be defined by their internal properties alone (Dehn et al., 1999). Therefore, for the delineation of landform segments it is necessary to use both local geometry and contextual variables.

Whilst the characterisation of the local geometry is fairly straightforward using topographic variables such as profile and plan curvatures to separate convex from linear and concave shapes in length and contour directions, placing the “geometrical surfaces” in the wider landscape setting requires more complex variables to establish linkages, interactions and flows between the “geometrical surfaces”. Indeed, the characterisation of landscape position requires knowledge on both compositional (i.e. altitude derivatives) and contextual (i.e. relative terrain position) variables.

Ideally, threshold values for the identification of landform segments should be (1) universally applicable, (2) the resulting segments should not be too sensitive to small departures from the defining thresholds and (3) the criteria used to define the thresholds should be related to the formative processes in the landscape (Howard, 1994). However, as there are no rigorous, quantitative definitions for qualitative geomorphic concepts, empirical threshold values tend to be used (Florinsky et al., 2002). Since one of the purposes of identifying the channel network in DEM data is to separate pixels according to their hydrological response (Ijjasz-Vasquez and Bras, 1995), it seems not only sensible but also logical to adapt the concepts of aggregation-pattern for drainage basins and of the scaling regime of slopes developed by those researchers in order to define generally applicable rules for the identification of thresholds between landform segments.

2. Objectives

The purpose of landscape classification is to reduce a complex system of varying soil-forming factors into explicitly defined classes which present more homogeneous soil-forming characteristics so that soil properties can be predicted more precisely (Wielemaker et al., 2001). Thus, the main objective of this work is to investigate the possibility of using the scaling regime of slopes to identify thresholds that are applicable within and between catchments of different sizes, in order to parameterise a landform model which can be used to predict soil properties in a variety of catchments.

3. Methodology

Geormorphology has progressed from an erstwhile descriptive science to a quantitative one (Scheidegger, 1991). The recent advances in geomorphometry and wider availability of DEMs is reflected on the number of landform classification schemes that start to proliferate in the literature, which are based on the combination of more or less complex terrain attributes (i.e. morphometric variables). The morphometric variables are used to discriminate areas with similar geometrical form (characterised by means of slope gradient and length, and profile and plan curvatures) and vector field action (e.g. gravitational and solar irradiation fields), which control flows, land surface evolution and soil formation processes (Shary et al., 2001).

3.1. Landform modelling

The five-unit land surface system described by Ruhe and Walker (1968) was chosen as the basis for the definition of landform prototypes. This system is suitably neutral in that it is comprehensive and its elements are simultaneously self-contained and not over-specified. In addition to the five hillslope segments in Ruhe and Walker's system (summit, shoulder, backslope, footslope, and toeslope), the slope geometrical shape, as defined by length and contour curvatures, is used to further split the hillslope elements into linear, concave and convex forms, which combined indicate areas of flow dissipation, transit or accumulation. Potential solar radiation is used to separate areas with different thermal regimes.

Thus, the first step in building the landform model is to develop a rule to separate the three possible land surface shapes using profile and plan curvatures. The second step involves the segmentation of classes with different topographic positions which also have environmental significance. The most commonly used contextual variable used to segment the landform into hydrological/pedological elements is upslope area per unit contour width. The identification of thresholds using upslope area values can be done simply by coupling and plotting the variation of upslope area with other morphometric variables (altitude, slope gradient, profile and plan curvatures, dispersal area, wetness and dispersive indices, and terrain characterisation index). The third step is to separate areas with different thermal regimes, i.e. to use the potential solar radiation variation to classify landform units in terms of maximum number of hours of sun incidence.

3.2 Identifying the thresholds of landform classes

After deriving the above mentioned morphometric variables from a 100m resolution DEM of the Marina Baixa, in SE Spain (Figure 1), using the PC-Raster freeware, slope steepness and profile and plan curvatures were used to classify the hillslopes into nine possible combinations of linear, convex and concave shapes in the length and contour directions. For the definition of a flat area, the limit of 3° of slope gradient was used, as this threshold is based on several published studies (Pennock et al., 1987) and has also been found to separate areas with insufficient gradient to cause rills to form (Govers, 1985). To characterise the shape curvature, the interval adopted here to define linear elements was [-0.0001m^{-1},0.0001m^{-1}] for both length and contour curvatures. Negative values of length curvature outside that interval band indicate concave shapes whilst negative values of contour curvature indicate convex shapes, and vice-versa.

Figure 1 – Location of the study area, Marina Baixa (SE Spain)

This was followed by the analysis of topographic thresholds in the drainage direction to detect boundaries that help split the hillslopes into the five units devised by Ruhe and Walker (1968). Many researchers have observed morphometric variables-area relationships (Moglen and Bras, 1995) and use them to model channel initiation as a change in the sediment transport process (Ijjasz-Vasquez and Bras, 1995) or found a significant relationship between contributing area and plan curvature (Thomas et al., 1999), which is explained by the fact that when the contributing area is sufficiently large to create concentrated flow and form a thalweg, the relief around must also allow for flow convergence. There are many ways of performing morphometric variables-area threshold analysis. The version adopted here is similar to the one presented by Ijjasz-Vasquez and Bras (1995) in that the data points in the diagram were binned according to the values of upslope area, with at least 300 points in each bin. The approach differs from their method because the diagram is semi-log (and not log-log) because some of the variables used here present negative values (e.g. the profile and plan curvatures).

According to Moglen and Bras (1995), breaks in the scaling regime of hillslopes reflect the relative strength of fluvial and diffusive transport forces as well as the degree of heterogeneity in the material being eroded from the hillslopes. As different magnitudes of diffusive and incisive erosion processes produce different topography, breaks in the scaling are a good indicator of the flow aggregation structure and of the dominant topographic features. Since the four main catchments of the Marina Baixa region show dissimilar topographic characteristics, the morphometic variables-area diagrams were plotted separately for each one of the largest catchments (Amadorio and Guadalest) but the remaining area, which include two smaller catchments (Torres and Arcos), was aggregated because it is required that there are at least 300 data points per bin in order to highlight some average pattern.

The combination of shape and topographic position classes produced in the two previous steps creates a landform map that is designed to replicate the landscape moisture pattern. Now it is necessary to add information on the radiation pattern. This is accomplished first by plotting potential solar radiation against aspect in order to separate distal from proximal slopes; then by plotting potential solar radiation against slope gradient in order to separate levelled from inclined surfaces.

4. Results

The most striking difference between the three different areas (Amadorio, Guadalest and the other smaller catchments) is the average slope length and distance to the channel: largest in the Amadorio catchment and smallest in the other catchments. Analysis of the breaks in the distribution in the three different areas shows that the values of the topographic attributes are seldom concurrent between catchments because the breaks in the gradient of each scaling response (i.e. a trend with different gradient) do not occur at the same values of upslope contributing area. Nevertheless, within the same catchment area, breaks in scaling tend to often occur at the same distance from the summits, i.e. breaks occur at similar upslope contributing area values.

It follows that the rules to separate the five types of landscape positions are as described below and as much as possible, threshold values for different topographic attributes are based on the identified breaks.

Summits are relatively levelled surfaces and as such, the slope gradient value cannot be above 3°. However, this rule is clearly insufficient as it would include toeslope areas and other haphazardly distributed flat pixels likely to appear in relatively rugged terrain such as the low areas of the Marina Baixa. Therefore, summit pixels are also constrained to upslope values below 10 pixels (100 000 m^2). However, this upslope area value might be too restrictive and do not allow for the correct identification of pixels that are relative crests and positioned in much lower areas of the landscape. Hence, pixels that simultaneously present upslope area values between 10 and 20 pixels and dispersal areas above 20 pixels (to avoid including levelled pixels close to channels) are also classified as summit pixels. Consequently, all the remaining pixels with slope values equal or lower than 3° and that were not classified as summit pixels are included in the toeslope class.

The shoulder/backslope interface occurs two to three pixels from the top and therefore, the first rule to identify the shoulder pixels is that the upslope area is below 30 000 m^2. The second rule requires the definition of slope boundaries, as there can be very steep pixels that are clearly part of the backslope at low upslope area values. Thus, apart from pixels presenting slope gradients larger than 3° (brought about by exclusion rules in the definition of summit and toeslope pixels), a maximum slope value needs to be specified. From observation of resulting diagrams and trial with different threshold values, 14° has been chosen as the upper slope gradient boundary for shoulder pixels. This is the average slope gradient value at 30 000 m^2 and it can be applied in the entire area of the Marina Baixa. However, these two rules are insufficient because it produces shoulder pixels in the lower areas of the Marina Baixa that are not close to summit areas. Thus, further restrictions have to be made. Analysis of the distribution of shoulder pixels shows that this problem arises in areas below 600 m of altitude and therefore, if falling in this altitudinal category, to be classified as a shoulder pixel, the dispersal area has to be larger than 1 000 000 m^2 which allows pixels to be identified as shoulder pixels only if they are close to crests. Note that this dispersal area threshold separates, on average, the summit pixel from the remaining areas and should therefore allow for the correct identification of shoulder pixels in low altitude areas.

The remaining pixels are backslope and footslope pixels and a slope threshold is required to separate those two landforms. Analysis of the breaks in slope scaling shows different slope values at the interface of back-footslope areas in the three different catchments of the Marina Baixa. Nevertheless, trials with different values show that the 9° slope gradient creates compact landforms and this value is identified as one possible threshold for the Guadalest catchment and in the Amadorio catchment there is a small break in the scaling around this gradient value too. Thus, pixels are classified as backslopes if slope is equal or steeper than 9°, footslope pixels have slope gradients in the range of]3°, 9°[, and for both classes pixels cannot have previously been classified as shoulder pixels.

Plotting potential solar radiation against aspect allows the identification of the threshold that separates south- from north-facing slopes as 10 900 W m^{-2}. This value approximately separates slopes with aspects between c. 90° and 270° from other aspects, which means that it separates warm from moderately cold/moist surfaces. Plotting potential solar radiation against slope gradient allowed the identification of the boundary between moderately warm and hot/dry surfaces. The upper radiation value limit that separates levelled from inclined surfaces was thus identified as being 11 400 W m^{-2}.

5. Discussion

The concurrence of breaks in scaling within catchments indicates that those breaks are related to real changes in the shape of the land or to critical upslope areas for the accumulation of water and associated erosive/sedimentational processes. However, the binning procedure somewhat influences the threshold values and these should therefore be read with care, as the boundaries are somewhat influenced by the number of cells used in the bins. Furthermore, mapping of those landform classes showed that there was a contiguity problem (e.g. the existence of summit pixels next to toeslope pixels) which was caused by restrictions imposed by the upslope and dispersal area thresholds in the definition of summit areas. This problem was easily resolved with (1) the application of a low-pass mode-adaptive filter on a 9x9 window, which identifies the background pattern but removes the speckle and returns the most frequently occurring landform within the specified window, for certain landform classes only; and (2) the application of an exclusion rule which prevents pixels in higher positions than surrounding backslope pixels of being classified as toeslopes.

The most striking feature is related to the different landscape position occupied by three different types of backslopes: noseslopes tend to occur in higher landscape positions than sideslopes and headslopes, and latter occupies the lowest positions, which concurs with Ruhe and Walker's (1968) hillslope system.

It was also noticeable a very strong association between landforms and lithology, with toeslopes being mainly constituted by slope deposits, limestone being largely the substrate of the south-facing backslopes and shoulders, and marls being generally associated with summits, north-facing backslopes and footslopes.

6. Conclusions

A semantic knowledge-based landform model is a better predictor of soil properties at the landscape scale than automatic models because classes conform to the way water and sediment flow in the landscape. Moreover, the thresholds identified for the separation of the landform classes are very likely to perform well in differentiating the same landforms elsewhere because rules were derived using regional data from catchments which have quite contrasting topographies. Nevertheless, for application to other areas, it is sensible first to examine the relationships between morphometric variables and upslope area to verify if breaks in the scaling occur at similar distances from the summit. This examination is especially necessary in the case of relationships based on altitude, because they have a range more likely to change from region to region.

Additionally, it was found that there is a strong association between landform classes and lithology, which suggests that the landscape is highly structured. The implication of this finding is that a structured landscape promotes higher variability of soil properties between landform classes. In turn, it is more likely that soil types will be closely associated with the landscape, which is the basis of the catena principle and therefore likely to spawn good soil property predictions over the landscape.

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