Sediment Dynamics in Changing Environments (Proceedings of a symposium held
in Christchurch, New Zealand, December 2008). IAHS Publ. 325, 2008.

Morphometric analysis of interfluve topography for scaling soil erosion rates from local to regional scales

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Abstract Intensively cultivated areas are often affected by human-accelerated soil erosion. In European Russia most of the arable land occupies interfluves and relatively gentle interfluvial slopes. There are a number of case study sites within the Central Russian Plain for which detailed information on local soil redistribution rates have been obtained. However, transition from local-scale to regional-scale assessment of soil erosion rates still presents a serious problem as it cannot be satisfactorily achieved by simple interpolation between the case study points. Analysis of the variability of interfluvial morphometry enabled us to identify criteria for extrapolation of locally derived erosion and soil redistribution rates. We identified a key morphometric parameter at the 1:500 000 scale, i.e. the area of elementary interfluvial slope unit connected with the Hortonian first-order stream thalweg. We also discuss other morphometric parameters relevant at different spatial scales.

Key words geomorphometry; interfluves; soil erosion; upscaling

INTRODUCTION

Most of the current soil erosion estimations are related to the local scales of key sites because of the specific methods and techniques employed. However, it is often required to extrapolate local findings to calculate sediment yield over larger regions. That requires determination of the position of the used sites within the regional geomorphic (sedimentary system) context in order to define the limits of and predictors for reliable extrapolation. The concept of erosion factors may be used as a basis to resolve this problem. There are a few main factors of erosion such as topography, climate, vegetation, soil, geological structure, and human activities. Climate, vegetation and geology usually do not vary significantly over the smaller spatial scales used in soil erosion assessments. Topographic relief, however, varies from slope to slope, which leads to significant changes of character and intensity of erosion. The hierarchical organization of the geomorphic structure within a region must be taken into account to assess the position of a given key site within various spatial scales. We suggest that morphometric analysis at different scales can be efficiently employed to resolve problems associated with spatial upscaling of empirically or numerically derived local soil erosion rates.

Morphometric analysis is widely used for general relief description, reconstruction of landform evolution, and landform and process modelling (Dikau *et al.*, 1995; Hennrich *et al.*, 1999). In the context of soil erosion, morphometric analysis is mostly applied at single spatial scales to extract local topographic factors relevant for erosion modelling. In this study, we are combining geomorphic approaches for describing relief hierarchy with erosion assessment. Morphometric analysis and soil erosion modelling at a range of spatial scales are accompanied by a few field-based methods which apply only to local key sites. The aim was to identify relationships between geomorphometric features and simulated soil erosion rates over a range of scales. The identified relationships may be used to improve input data for further modelling of soil erosion at the different spatial scales.

There are many erosion models used in different countries and landscapes. A substantial number of those are empirical models, often based on the USLE (Universal Soil Loss Equation; Wischmeier & Smith, 1978) or one of its analogues (Van Rompaey *et al.*, 2001; Verstraeten *et al.*, 2002, etc.). In this study we also used an erosion model based on the USLE approach, which was adapted for Russian environmental and agricultural conditions (Larionov, 1993) and combined it with an empirical model for snowmelt erosion developed at the Russian State Hydrological Institute (Bobrovitskaya, 2002).

Fig. 1 Location of the Zusha River basin.

The most active soil erosion can be found in agricultural areas, usually those occupying relatively gentle slopes and interfluves. This research has been concentrated on morphometric analysis of the interfluvial topography of selected parts of Central Russian Upland where the most intensive agricultural activities and associated water erosion rates in the European part of Russia are observed (Litvin, 2002; Litvin *et al*., 2003). We have selected the Zusha River basin which is located in the most elevated and dissected part of the Upland and almost completely cultivated (Fig. 1). For the study site, detailed local-scale quantification of soil erosion rates was carried out by field experiment (Belyaev *et al*., 2007). These results have been used here as a validation data set for the topographical analyses and soil erosion modelling applied here.

SELECTION OF SPATIAL SCALES

We chose a few scales from the available state topographic maps (1:25 000, 1:100 000, 1:500 000) as data sources for morphometric analysis, accompanied by data from larger scale surveys (about 1:2000) carried out at our key sites using theodolite and DGPS equipment. Short descriptions of the scales are given in Table 1.

In this research, we consider the DEMs built from our own survey data as precise presentations of the real local topography and use them as reference data for modelling purposes and comparisons with smaller-scale maps. The other scales were chosen from the range of scales of the Russian state topographic maps according to the morphometric specifics of this study. The 1:25 000 scale maps were selected as the largest state scale covering the whole country. 1:50 000 was excluded to avoid needless fragmentation. We chose 1:100 000 as the next scale and consider that further upscaling leads to some relief distortion and a different morphometric approach must be used here. The 1:200 000 and 1:300 000 scales were not used (Table 1). The final selected scale is 1:500 000 and allows coverage of the whole basin of a medium river such as the Zusha River.

MORPHOMETRC ANALYSIS AT DIFFERENT SCALES

Morphometric parameters were derived for the four selected scales. The representations of topography at the three map scales considered were then compared with the “ideal” representations of our detailed survey data. Thus, we could estimate the changes in morphometric parameters resulting from cartographic generalization and assess their influence on the reliability of soil erosion rate prediction. The details of relief representations of self-surveyed maps and state maps at the 1:25 000 scale are published in this book (Belyaev *et al*., 2008, this volume), accompanied by a comparison of field-based methods and modelling. As stated above, topographic mapping by

Table 1 Advantages and limitations of topographic maps of different scales.

Scale	Description
1:2000 (theodolite and GPS survey)	- “a scale of one slope” necessary in key site research projects - allows to catch small relief details - cannot be used in regional soil erosion assessment itself
1:10 000	- the largest Russian state topographic scale - available for only a few small regions and usually done for special orders - allows to cover small valleys catchments
1:25 000	- the largest Russian state topographic scale available for any Russian region - allows coverage of nearly 100 km^2 (one standard map sheet) in morphometric analysis, without too many man-hours
1:50 000	- state Russian topographic scale - mostly derived from 1:25 000 without big generalization
1:100 000	- state Russian topographic scale - officially considered as the smallest scale where all the contour lines conform to the actual heights of the real surface - relatively available for any Russian region - allows coverage of Hortonian first-order river basins
1:200 000	- state Russian topographic scale - available for any Russian region - mainly made for aviation and thus only administrative objects are reliably shown - usually not recommended for morphometric research by cartographers because of the original purpose of the mapping
1:300 000	- state Russian topographic scale - made from 1:100 000 by the exception of several contour lines and without big generalizations
1:500 000	- state Russian topographic scale - made by significant relief generalization - allows coverage of river basins of average Hortonian order

geodesic surveying at the hillslope scale gives local details of the relief. Thus, it is used as reference and as the input data for soil erosion assessment at the key sites (Fig. 1) by modelling based on the Universal Soil Loss Equation. Repeated erosion rate calculations by the same model were carried out with morphometric data taken from the 1:25 000 map. In both cases we used the same set of morphometric characteristics, the standard ones for general relief description and soil erosion research (length of flow lines and slope gradients according to the USLE LS factors, Wischmeier & Smith, 1978). A few field methods were applied on the same key site (a comparison of soil layer thickness, rill metering, and analysis of ^{137}Cs concentration). Comparison of the field and model data showed that the erosion model results based on morphometric characteristics are very close to the field observations. This indicates that the 1:25 000 maps can be used in local-scale soil erosion assessment.

A comparison of relief representation at 1:25 000 and 1:100 000 scales

The next step of our study is a comparison of the 1:25 000 and 1:100 000 scales, covering the same territory as the key site and its surroundings, to assess the utility of 1:100 000 maps for soil erosion modelling. Visual comparison shows the increased softness of contours and the general flatness of the relief representation at the 1:100 000 scale (Fig. 2). The biggest differences can be found on steeper slopes and erosional landforms. Within the interfluves, where slope gradients are small, the differences are minimal (Fig. 2(a) and (b)). The results of the comparison allow estimation of the qualitative advantages and disadvantages of these scales. We also made a quantitative comparison which may be useful for soil erosion assessment. A few morphometric characteristics relevant for erosion were selected (slope gradient, long profile character and elementary slope type – convergent and divergent catchment). Figure 3 shows slope gradient distributions at both scales for the same area. Insignificant changes in areas and disposition of

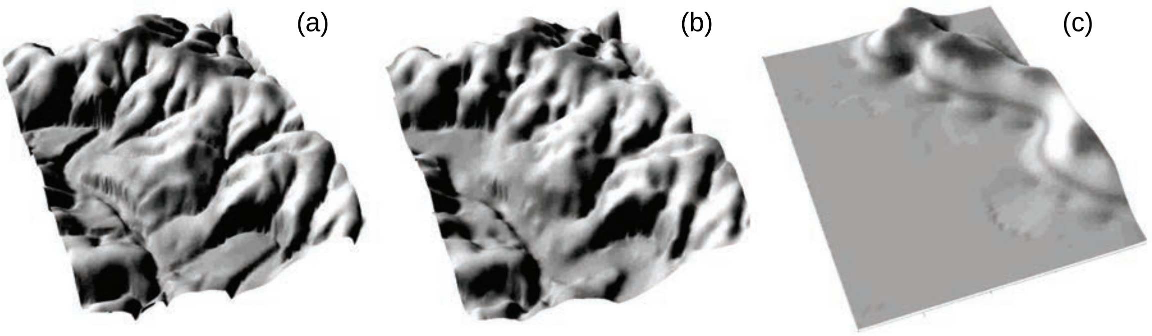

Fig. 2 A comparison of 3-D-relief representation at the scales of (a) 1:25 000, (b) 1:100 000, and (c) 1:500 000.

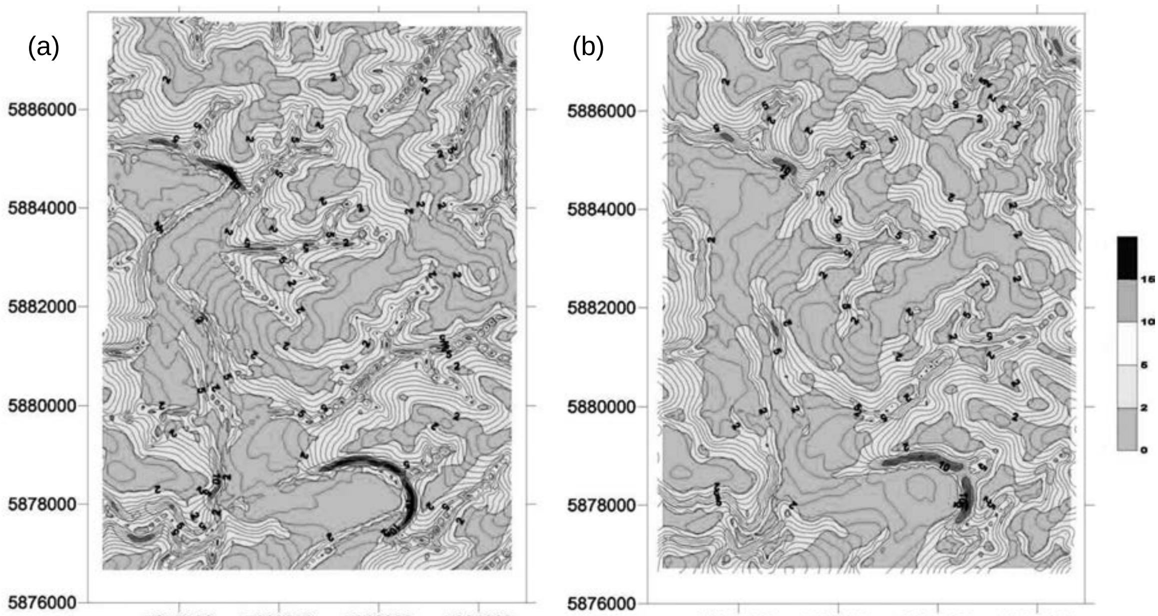

Fig. 3. Maps of slope gradients (in degrees) of the same territory as the case study site and its surroundings in the Zusha River basin. Coordinates are in metres (Gauss-Kruger projection, zone 7). The original map scales used for slope calculation are: (a) 1:25 000 and (b) 1:100 000.

Table 2 Slope gradient distributions according to occupied areas at scales of 1:25 000 (numerator) and 1:100 000 (denominator).

Parameter	0–2°	2–5°	5–10°	10–15°	>15°
Occupied area (km^2)	38.6/44.4	43.3/42.3	7.7/6.0	0.7/0.5	0.2/0.0
Fraction of total area (%)	42.7/47.6	47.9/45.4	8.5/6.5	0.7/0.6	0.2/0.0

places with small slope gradients are obvious. Substantial changes can be found in areas of greatest steepness, especially valley slopes. Interfluvial changes are mostly unnoticeable. Statistics of the distribution of slope gradients are presented in Table 2.

The errors related to generalization on the 1:100 000 map are very small (less than 5%) for gentle interfluvial slopes (0–5°). This error is within the error intervals typically considered in soil erosion estimations. We obtained the same results for other morphometric characteristics reflecting slope configuration. Thus we conclude that the 1:100 000 maps can be used for morphometric analysis for soil erosion assessment. The error is small and warranted by the same labour-intensiveness and possibility of covering larger areas – not only individual slopes but Hortonian first-order catchments.

The scale 1:500 000

It is important to note that standard morphometric criteria cannot be used at the 1:500 000 scale as done at the larger scales. The total relief transformation is indicated in Fig. 2(c). Only the largest forms are retained as a result of strong generalization. Thus even the main break lines of the relief cannot be determined with the same precision. Strictly speaking, the valley edges are actually the bottom of interfluves, but it is impossible define them at the 1:500 000 scale with the same precision. That is why we defined an interfluve as a territory between the thalwegs of the main valleys within the study area. In fact, a fragment of interfluves is joined as part of a valley. The river valley thalwegs and water dividing lines serve as the criteria for interfluve separation. Channels of Hortonian first order are not used as boundaries and are included inside the interfluves. This is done to avoid needless fragmentation. Dividing the territory this way, we get a number of surfaces which can be represented as interfluvial slopes for further morphometric analysis.

The selection of morphometric criteria and the subsequent division into districts is determined by the features of cartographic generalization at this scale. Only the main contours of large landforms have precise positions. Thus we conceive that the most well-founded morphometric analysis should be based on the plan structure of the surface. We chose interfluve area, flow line length, and areas of elementary interfluvial slope unit connected with Hortonian first-order channels. The first two are simple characteristics and describe the form of interfluves in plan. The third allows three-dimensional depiction of the position of the form. It could seem logical to use slope gradient, but at the 1:500 000 scale its use is impossible and meaningless. In the regions of plains and even upland hills, only two to three contour lines with a vertical interval of 50 m are shown at this scale for one catena from the interfluve top to the river valley bottom. Moreover, altitude marks are too sparse to calculate height gradients with enough precision. Therefore, slope gradient itself cannot be used in morphometric analysis at this scale and so the other indirect criteria were introduced. As stated above, we used an area of elementary interfluvial slope unit falling at one elementary erosional form indicated by one thalweg of first (in this scale) Hortonian order. It is known that the threshold upstream area necessary for channel formation depends on the steepness of the surface. The higher the slope gradient, the less upstream area is required to form linear erosional forms. As the factors for slope (soil) erosion and linear erosion are similar in general, the selected criterion can be used in morphometric analysis for soil erosion estimations as an indirect criterion of slope gradient.

About 900 fragments of interfluves were derived for the Zusha River basin. Morphometric characteristics were calculated for each of them. The data files obtained were treated statistically and bar graphs of frequency distribution were made for each criterion. The morphometric division into districts was carried out according to analysis of these graphs (Fig. 4(a)).

The usual influence of slope morphometry on soil erosion character and intensity is well known and can be described in a few lines: the larger the interfluvial areas and the longer the flow lines, the greater rates of erosion will be; the smaller the elementary interfluvial area and the steeper the terrain, the greater erosion rates will be. But in our case we have a strongly distorted representation of relief. Therefore the morphometry could differ from reality and an independent examination is necessary.

As a standard for comparison we took the map of lands subjected to erosive action made at a scale of 1:1500 000 for the European part of Russia (Litvin, 2002). This map is detailed enough and sufficient differences in erosion rates are marked within the Zusha River basin. The map is based on the same model as we have used in our key site study. Its use to compare such a small scale is justified by the manner of its map making. Relief factors as the input data for modelling were derived from a regular net of key sites on topographic maps of 1:25 000 scale. The

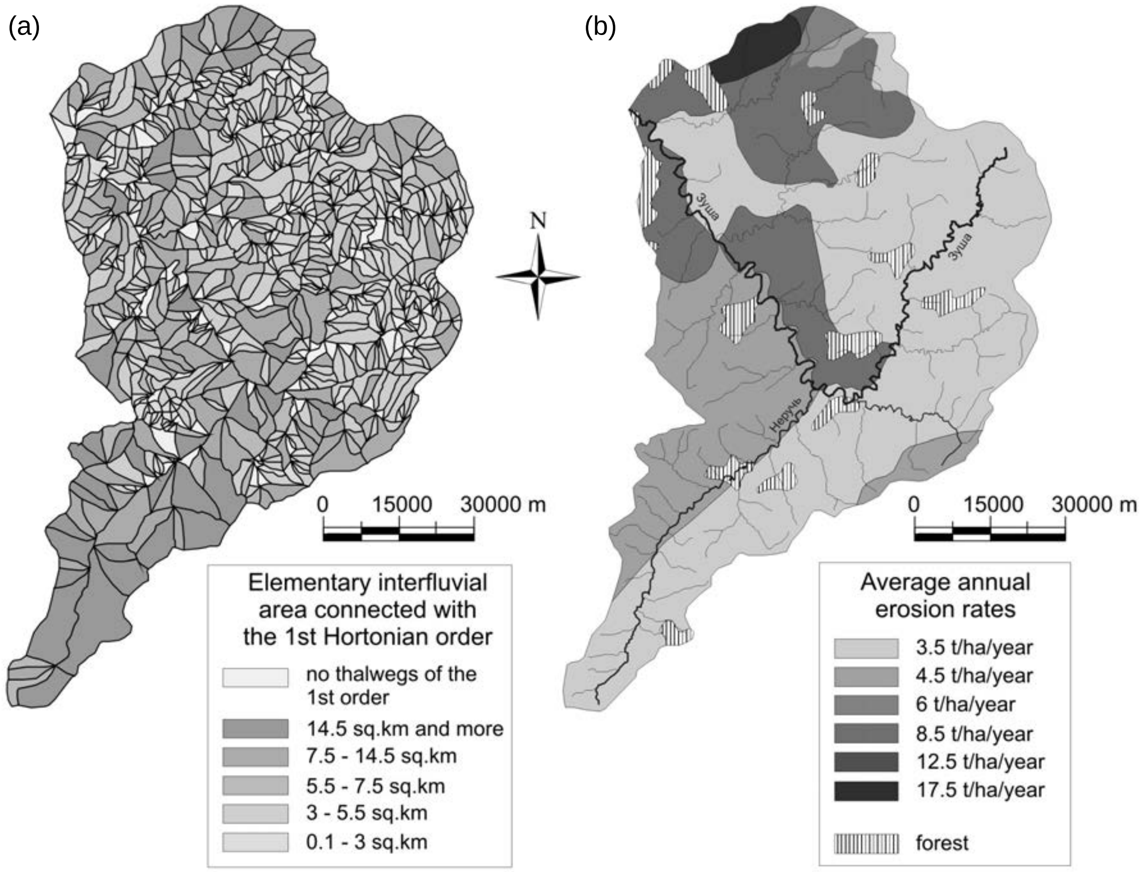

Fig. 4 (a) Distribution of interfluves over the Zusha River basin in accordance with elementary interfluvial area at the scale 1:500 000 (maps of the same type were made for every criterion, see text). (b) The map of lands subject to soil erosion (from Litvin, 2002).

morphometric data were derived for the whole geomorphic regions distinguished on topographical maps of 1:300 000 scale. As indicated above, both scales (1:25 000 and 1:300 000) represent the "real terrain" precisely enough in plain conditions. The enlarged part of this map covering the Zusha River basin is shown in Fig. 4(b). For comparison with our morphometric data we used only regions with the rates of erosion of 3.5, 4.5 and 8.5 t ha^{-1} year^{-1}. The other regions were not considered because of their small areas and thus complicated analysis. Estimation of the influence of the chosen morphometric criteria on soil erosion rates was done statistically. We calculated the total areas occupied by the interfluves with the same value of every morphometric criterion and derived their fractions of the total basin area. These area fractions were compared with soil erosion rates. Results of this comparison are shown in Fig. 5.

According to the bar graphs (Fig. 5(a) and (b)) interfluvial areas and flow line lengths calculated at the 1:500 000 scale do not show any significant relationship with erosion intensity − the distribution curves obtained have the same character in regions with different erosion rates. The third bar graph shows different results. The most vivid differences are expressed for maximum and minimum rates of erosion (3.5 and 8.5 t ha^{-1} year^{-1}). The larger the elementary interfluvial area (the lower the slope gradient), the lower potential rates of erosion will be. Accordingly the total increase of large elementary interfluves leads to the total decrease of erosion rates over the whole region. The continuous arrow (Fig. 5(c)) reflects the tendency of decreasing small elementary interfluves in regions with low rates of erosion. There is a slightly more complicated pattern in the regions with high erosion rates (dotted arrow in Fig. 5(c)). The largest part of them is occupied by elementary interfluves of average areas. The larger the elementary areas, the lower the slope

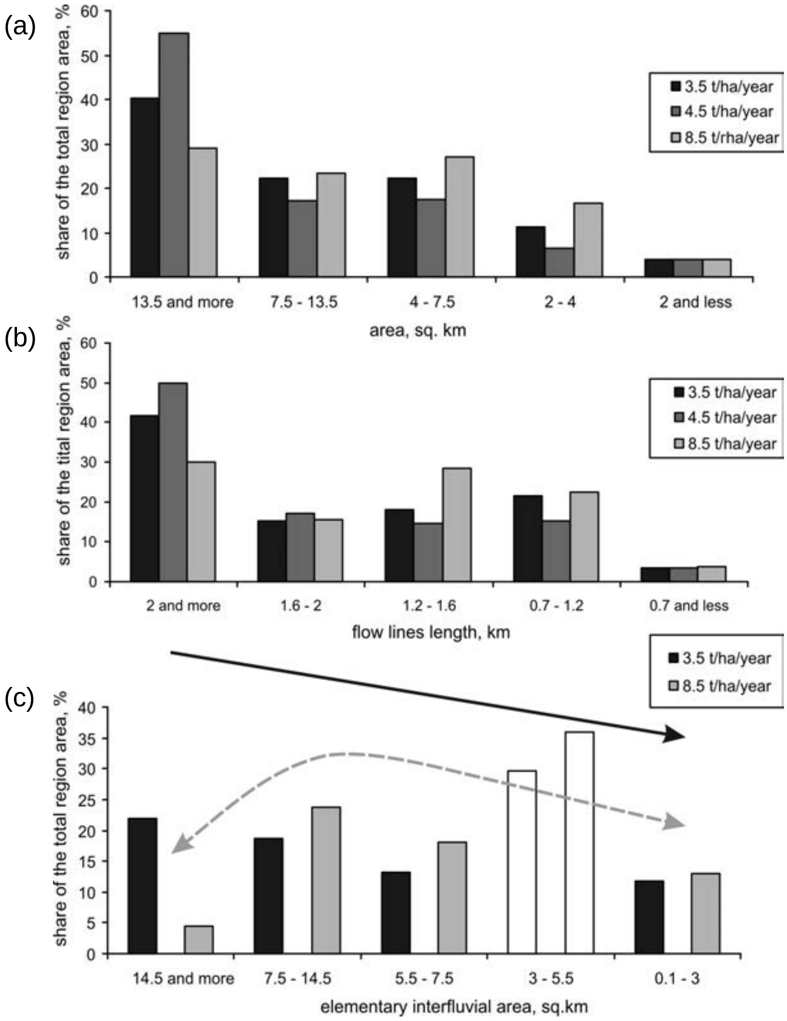

Fig. 5 The bar graphs comparing soil erosion rates with morphometric criteria distribution. Arrows in (c) indicate the observed trends (see text).

gradients, and the lower erosion rates will be. The smaller the elementary areas, the shorter the flow-line lengths, and again the lower erosion rates will be. This explains the peak observed for the 7.5–14.5 km^2 elementary interfluvial area.

Hence, elementary interfluvial area can be used for soil erosion rate assessment at scales of 1:500 000, which allows covering the whole river basin of a medium Hortonian order in conditions of elevated plains strongly affected by erosion. The use of other morphometric criteria, which normally work at larger scales (slope gradient, flow line length, area), does not give any positive results of soil erosion assessment at scales of 1:500 000.

CONCLUSIONS

Applications of morphometric analysis for soil redistribution assessment can provide valuable results at different spatial scales. The most important requirement for such assessments is to obtain reliable estimations of the effects of cartographic generalization on morphometric representation of relief. Our results show that a number of morphometric criteria (slope gradient, length of flow lines, area of morphologically uniform slope segments, plan type of slope) acquired from 1:25 000 and 1:100 000 scale maps can be used in soil erosion intensity assessment. Morphometric analysis of 1:500 000 scale maps must employ different criteria. It has been found that elementary interfluve fragment area is one of the criteria potentially applicable for erosion modelling at this scale.

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