Effect of topographic scale on the estimation of soil erosion rates using an empirical model

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Abstract Many studies of soil erosion involving application of computational models face the problem of precision of the available topographic data. Limited availability of maps and a necessity to extrapolate detailed-scale data over larger areas often force investigators to use small scale maps with relatively low precision of relief representation. Many other factors influencing soil erosion are usually less spatially variable than geomorphic conditions, which may change within and between slopes. Thus a loss of topographic information due to cartographic generalization can result in errors related to estimated soil erosion rates. This work presents a comparison of soil erosion rate estimations produced by a USLE-based empirical model for the same case-study site (a small catchment in the Central Russian Upland) using the input topographic data of different scales. Morphometric parameters of the three selected slope units to be used as input data for an empirical erosion model were derived from digital elevation models constructed using results of the detailed slope survey by digital tacheometer and two scales of topographic maps (1:10 000, 1:100 000). The results of modelling at the largest scale (detailed tacheometric survey) were used as a reference for comparison with modelling at smaller scales (1:10 000, 1:100 000). Model runs using each of the three available topographic input data sets produced average annual values of soil erosion rates and spatially distributed data sets of within-slope variability of erosion rates for the three studied slope units. The USLE model was also used to estimate soil erosion rates for five different crop rotations, which were applied within the studied catchment over its 150-year long history of cultivation. Modelling results were compared with average soil redistribution rates obtained for the entire cultivation period using the soil profile morphology approach.

Key words soil erosion; empirical modelling; slope morphometry; topographic generalization; variability; soil profile morphology; scale dependent error

INTRODUCTION

Quantitative characteristics of slope morphometry, climatic parameters, soil properties as well as crop rotation and cultivation practice, are common input data for soil erosion models. The main sources for such information are topographic maps and digital elevation models (DEMs). The latter until recently were made by creating vectors from scanned topographic maps or on the basis of geodetic surveys. With recent progress in the development of remote sensing techniques, DEMs can now be created directly, for example, from both terrestrial and airborne laser scanning or from satellite-based radars. At present, there exists an openly available DEM covering most of the Earth (http://www2.jpl.nasa.gov/srtm/) with a 90 m regular grid resolution, and built from the satellite survey data of the American Shuttle Radar Topography Mission (SRTM). However, these data have not yet been evaluated regarding their applicability and precision for soil erosion modelling.

Reliability of the input topographic data is one of the main factors limiting accuracy of the results of soil erosion modelling. The problem associated with changing topographic precision in source data at different scales is of concern for studies related to estimating soil erosion rates on local case-study sites or over larger areas. In such cases, error is related to a systematic decrease of relief representation precision and complexity when transferring the data to a smaller scale and comparison of field-based data with modelling results.

The issue of the use of topographic information of different scales has received considerable attention in the geomorphic literature (Strahler, 1952; Evans *et al.*, 1979; Golosov, 1983; Simonov, 1998; Hennrich *et al.*, 1999; Litvin, 2002). In the present study, soil erosion rates were calculated for the three slope units within a small catchment selected due to availability of historical land-use data. The modelling results are compared with average soil redistribution rates obtained for the entire cultivation period using the soil profile morphology approach (Belyaev *et al.*, 2005, 2009).

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STUDY SITE DESCRIPTION

The Gracheva Loschina (Fig. 1) is a small experimental catchment (1.98 km^2) located about 20 km southeast of Kursk in the headwaters of the Vorobzha River, which is a part of the Dnieper River basin. The site is situated within the fertile chernozem zone of European Russia. The entire upper part of the Vorobzha River basin, including the Gracheva Loschina catchment, belongs to the territory of experimental landownership of the Russian Institute of Agriculture and Soil Protection from Erosion (RIASPE). The Gracheva Loschina catchment is almost entirely cultivated, except at the bottom and sides of the small dry valley and the two narrow hollows that form its source. The cultivated inter-fluve slopes have a convex shape with maximum gradient of 5–7º, while the slope of the grassed valley sides ranges from 10 to 15º. In the 1980s, an experimental system of soil conservation measures was introduced in subcatchments of the two hollows occupying about 70% of the total catchment area. The system includes a set of double-rowed forest belts with runoff-retention ditches between the rows. In addition, within the catchment of the northern hollow three contour terraces were constructed in spaces between the neighbouring two forest belts. The remaining ≈30% of the catchment area was kept under traditional cultivation. A dam was built at the catchment outlet in 1986 to monitor runoff.

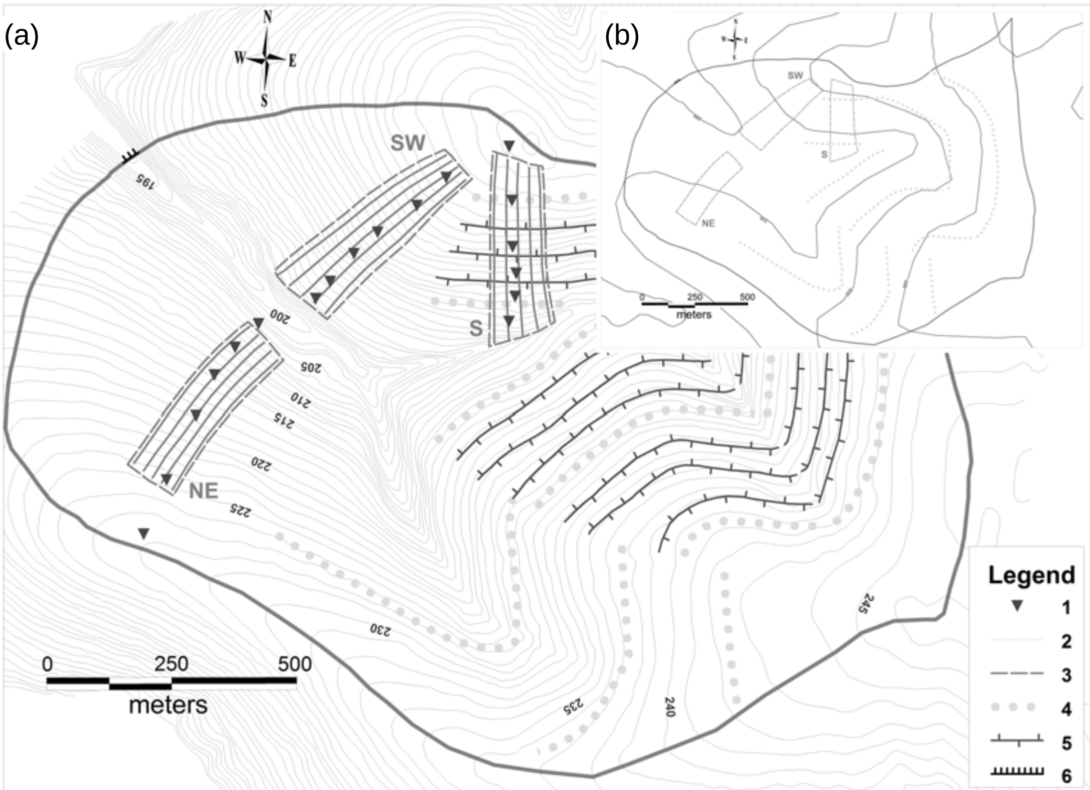

Fig. 1 Scheme of the Gracheva Loschina catchment made on the basis of vectorized topographic map of 1:10 000 (a): (1) soil pits; (2) flow lines used in soil erosion rates calculations; (3) the limits of the studies slope units; (4) forest belts; (5) roller-terraces; and (6) earth dam in the mouth of the catchment. The letters point at abbreviated names of the slopes according to the display. For comparison of relief representation precision there is also a schematic of the same catchment (b) made on the basis of the 1:100 000 scale topographic map.

Soil erosion rates were measured for three arable slope units on northeastern (NE), southwestern (SW) and southern (S) aspects (Fig. 1(a)). Flow lines in the cultivated parts of slopes were from 340 to 400 m long (Table 1). Within the same slope units, a number of pits were dug for detailed soil profile description (Fig. 1(a)). The NE and SW slopes are situated within the part of the catchment with traditional cultivation. The S slope has a system of forest belts and contour terraces (Fig. 1(a)). Soil erosion rates in the latter case were calculated for two variants of local conditions – with and without soil conservation measures. Forest belts and contour terraces divide the slope into a number of short sections with flow lines of 50–70 m long. Soil erosion rates were calculated along the five regularly spaced flow lines for each of the slope units (Fig. 1(a)). For the S slope with soil conservation measures, 25 short flow lines were taken into account (lowest section of that slope was abandoned from cultivation after construction of the forest belts and contour terraces). The main morphometric parameters used as the model input data (Table 1) are: (i) length of flow lines; (ii) slope gradient changes along flow lines; (iii) slope aspect; and (iv) slope profile (convergent, divergent, straight). Longitudinal profiles of slope morphology represented by different topographic data sources and scales are presented in Fig. 2.

Table 1 Principal morphometric parameters of the three slope units studied.

Slope unit	Slope aspect	Average length of flow lines, m	Average slope gradient, deg.	Long and transversal profile features
1	NE	350	3.2	Convex, straight
2	SW	400	3.4	Convex-concave, slightly undulating, straight
3	S	340	3.2	Convex-concave, with anthropogenic microtopography, slightly divergent
3 (with soil conservation)	S	60	3.2	Convex-concave, with anthropogenic microtopography, slightly dispersive

METHODS

Soil erosion rates were calculated using topographic data with three scales (detailed tacheometric survey of the studied slope units and the two official scales of the Russian state topographic maps – 1:10 000 and 1:100 000). A tacheometric survey was conducted at ≈20 m intervals and additional points were surveyed to characterize slope breaks and microtopographic features. A DEM was constructed from the survey data which is considered the most accurate representation of surface topography. A 1:10 000 scale topographic map is the largest scale of the Russian state topographic maps and is widely used in detailed (for individual slopes) soil erosion modelling. Maps of this scale are also most frequently used as a topographic base for land use planning and crop rotation maps within individual landownerships. Terrain surface contour line intervals of 1 m on maps of this scale are used to represent geomorphic conditions of the Central Russian Upland (Fig. 1(a)). Longitudinal profiles of slopes derived from the 1:10 000 map do not differ significantly from tacheometric profiles, except for slight natural undulations on the NE and SW slopes (Fig. 2(a),(b)) and artificial microforms located on the S slope (Fig. 2(c)). There is some distortion of these profiles derived from the 1:100 000 map. A systematic lowering of general elevation and thus slope steepness are notable on the NE and S slopes (Fig. 2(a),(c)). A general lowering in the SW slope unit was observed, but the local slope gradient and character of its profile do not change significantly (Fig. 2(b)).

In this study, an empirical model and soil profile morphology method (SPM) was used to provide quantitative estimates of soil erosion rates. The model was developed in the Laboratory of Soil Erosion and Fluvial Processes (Faculty of Geography, Moscow State University) by a scientific group led by G.A. Larionov (Larionov, 1993; Larionov *et al.*, 1998). It is based on a combination of the two main approaches. Calculation of the rainfall-induced erosion is based on the widely known USLE approach (Wishmeier & Smith, 1965; Renard *et al.*, 1994) modified and adapted for Russian conditions (Larionov, 1993; Belyaev *et al.*, 2005). A snowmelt-induced erosion model developed at the Russian State Hydrologic Institute (Bobrovitskaya, 2002) was used (Larionov, 1993) and implemented as a PC-based program with partly automatized procedures.

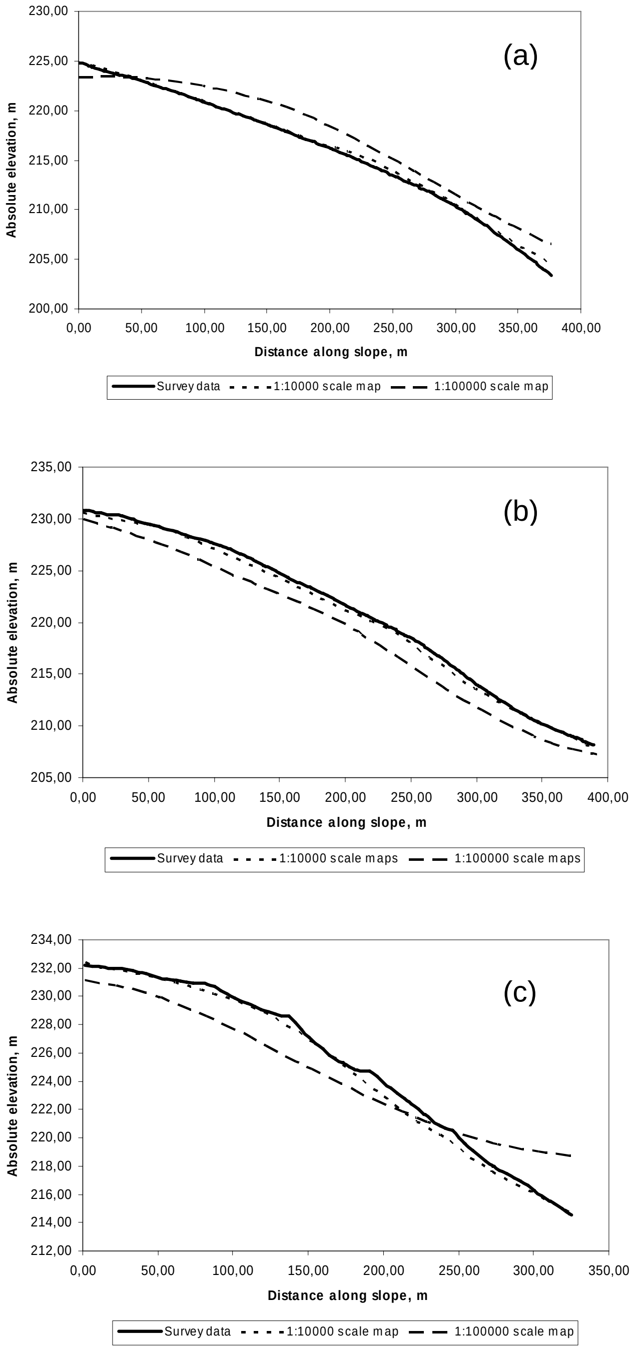

Fig. 2 Longitudinal profiles of the three slope units (along the soil survey transects designated by pits on Fig. 1) as obtained from DEMs constructed using the source topographic data of different scales: (a) NE slope; (b) SW slope; (c) S slope.

Empirical coefficients of soil erosion factors are used as input data to the model which represents regional average values (rainfall erosivity, erosional indexes for individual crops) for most of the agricultural area of Russia. Crop rotation data, including information on history of their changes, were obtained from the RIASPE (Fig. 3). The topography factor is described by slope length and gradient derived from the DEMs (grid-based with 10 m grid spacing), which were constructed from the available topographic data using the Golden Software Surfer software package. Tacheometric survey was conducted by means of the Leica Smart Station TPS 1200

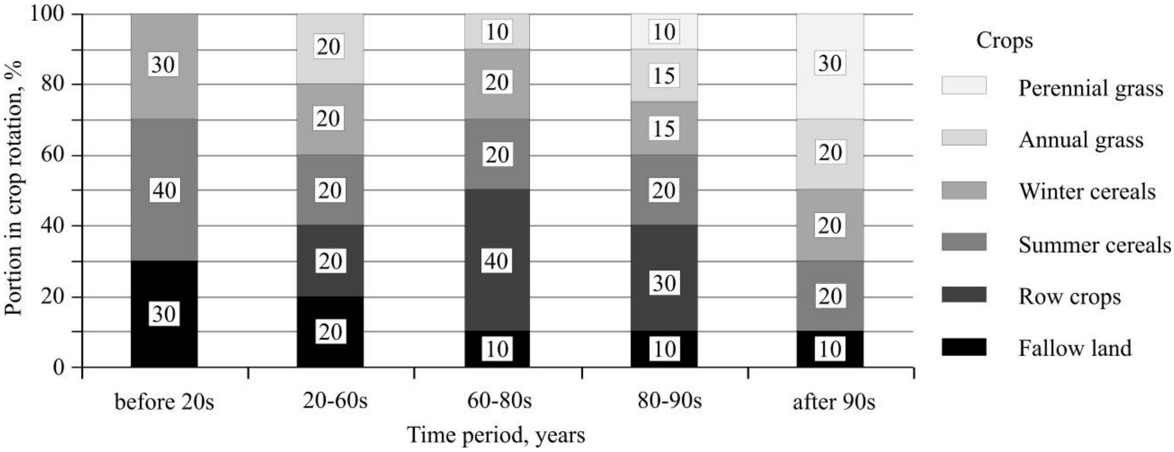

Fig. 3 Crop rotation change history as documented for the Gracheva Loschina catchment. The last crop rotation (after 1990s) is used only within the area where soil conservation measures have been introduced (Fig. 1).

digital tacheometer. Soil properties were acquired during laboratory analyses of samples from the soil pits (Fig. 1(a)).

Estimated average annual soil erosion rates obtained for the 3 slope units (5–6 pit in unit, Fig. 1(a)) were compared. Soil pits locations were chosen before a tacheometric survey was conducted and small deviations of soil survey transects from topographic flow lines derived from the DEM (Fig. 1(a)) due to relatively simple slope morphology and low surface gradients were apparent. This is especially notable for the NE slope (Fig. 1(a)).

DISCUSSION

Two types of output data have been produced by the model using three scales of topographic and five types of crop rotation data: (i) average erosion rates for each flow line; (ii) variation of erosion rates along each of the flow lines over 10 m long spans. Average rates estimated for each of the studied slope sections vary substantially depending on the crop rotation used in the model input (Fig. 4, Table 2A). The most intensive erosion was observed in areas where crop rotations were used from 1920 to 1980, with fallow land and row crops representing up to 40–50% of the study area. Perennial grasses became important in crop rotations applied over the last two decades, which resulted in a notable decrease in estimated average soil erosion rates for this period (Fig. 4, Table 2A).

Significant differences were observed between soil erosion rates estimated using topographic input data of different scales. For two of the studied slope sections (NE and S), these differences are more or less obvious. The quality of slope morphology representation decreases only insignificantly between the survey data and 1:10 000 scale topographic map (Fig. 2). Accordingly, soil erosion rates calculated using topographic input data from that map are underestimated by 6% only (Table 2B). The 1:100 000 map underestimates soil erosion rates by 23% for the NE slope and 53% for the S slope (Table 2B). The most significant difference for the S slope can be explained by the highest degree of distortion of its long profile on the 1:100 000 scale topographic map, which is evident as a decrease in gradient in the lower part of the slope (Fig. 2(b)).

Variability of soil erosion rates estimated by the model using different scales of topographic input data for this slope is very low (±1–3%) for the SW slope. This can be explained by the most adequate representation of real morphology of this particular slope section on the topographic maps at both scales used in this study (Fig. 2(b)). Even the 1:100 000 scale map correctly represents total slope elevation range, long profile shape and downslope change of surface gradients, though giving systematically lower absolute elevation values. Variability of estimated

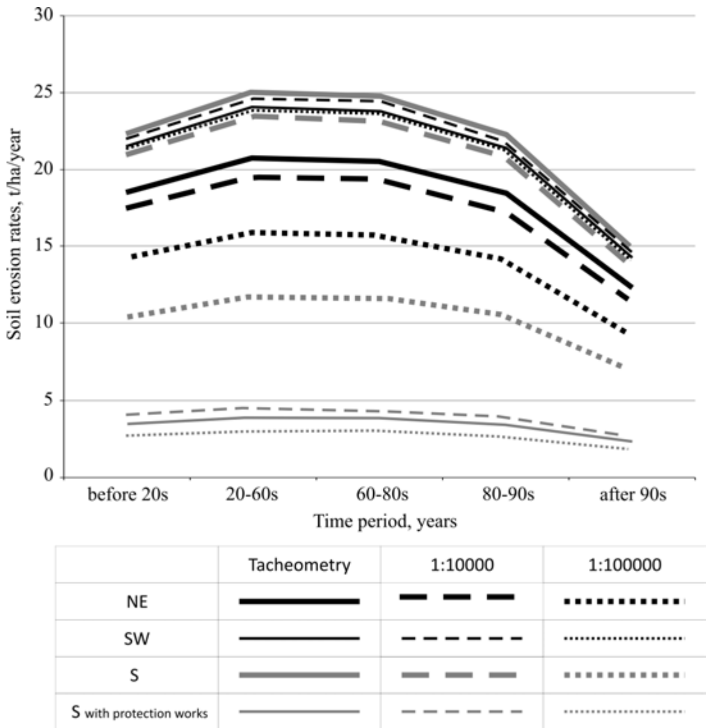

Fig. 4 Average annual soil erosion rates for the studied slope sections estimated for five types of crop rotation using the three scales of input topographic data.

Table 2 Relative variation of average soil erosion rates estimated by model for the studied slope sections: (A) depending on differences in crop rotations; (B) depending on differences of topographic input data.

Slope sections	A Relative variation of estimated soil erosion rates (%) depending on differences in crop rotations (upper row – numbers of crop rotations)					B Relative variation of estimated soil erosion rates (%) depending on differences in scales of topographic input data		
	1	2	3	4	5	Survey	1:10000	1:100000
NE	100*	+12	+10–11	–1	–34	100**	–6	–23
SW	100	+12	+10–11	–1	–34	100	+3	–1
S	100	+11–12	+10–11	–1	–34	100	–6	–53
S (with forest belts and contour terraces)	100	+11–12	+5–11	–1	–35	100	+6–12	–23–24

*Average soil erosion rates estimated for the crop rotation 1 are considered as 100%, values for other crop rotations are compared to those and given in % difference.

**Average soil erosion rates estimated using the most detailed topographic survey data are considered as 100%, values estimated using other scales of input topographic data are compared to those and given in % difference.

soil erosion rates between 1 and 3% can be regarded as negligible. Hence, it can be concluded that both 1:10 000 and 1:100 000 scale maps can be used as topographic data sources for soil erosion modelling on slopes characterized by simple morphology.

For the S slope separated on shorter segments by forest belts and contour terraces, average annual erosion rates estimated by the model are very low. Flow lines were generally 4–6 times shorter than for the entire slope section. Therefore, in this case loss of topographic information with decreased map scale for shorter flow lines becomes generally less significant. Conversely, the S slope is characterized by the most complex natural morphology added by anthropogenic microtopography (Fig. 2(c)). These two factors have opposite effects on erosion rates estimated by the model and the relative variability of these values (±6–24%) are related to differences in scales of topographic input data (Table 2B).

A series of block-diagrams with maps of the model-estimated soil erosion rates was constructed to evaluate spatial variability related to differences of the topographic input data. Figure 5 presents soil erosion estimates for crop rotation 3. The most significant differences are observed when using the 1:100 000 scale topographic maps for the NE and S slopes. These diagrams are characterized by significant areas of decreased erosion rates in lower parts of the slopes (Fig. 5). For the SW slope, differences are insignificant (Fig. 5). It is interesting to note that maximum values of erosion rates for the SW slope were produced by the model run using the topographic input data from the maps rather than from the survey data (Fig. 5). This can be explained by the slightly undulating morphology of this slope which was reflected only by the tacheometric survey data (Fig. 2(b)). Instead of gradual wavy undulations appearing on the SW slope surface; zones of artificially increased gradient are formed on the topographic maps of both 1:10 000 and 1:100 000 scales (Fig. 2(b)). These undulations are characterized by maximum soil erosion rates (Fig. 5). Block-diagrams for the S slope with soil conservation measures show a significant decrease of soil erosion rates compared to slopes without conservation measures, irrespective of the topographic input data scale (Fig. 5). Similar to the SW slope, maximum erosion rates estimated from the 1:10 000 map are related to the effect of loss of representation of the slope microtopographic features, but in this case – of anthropogenic contour terraces.

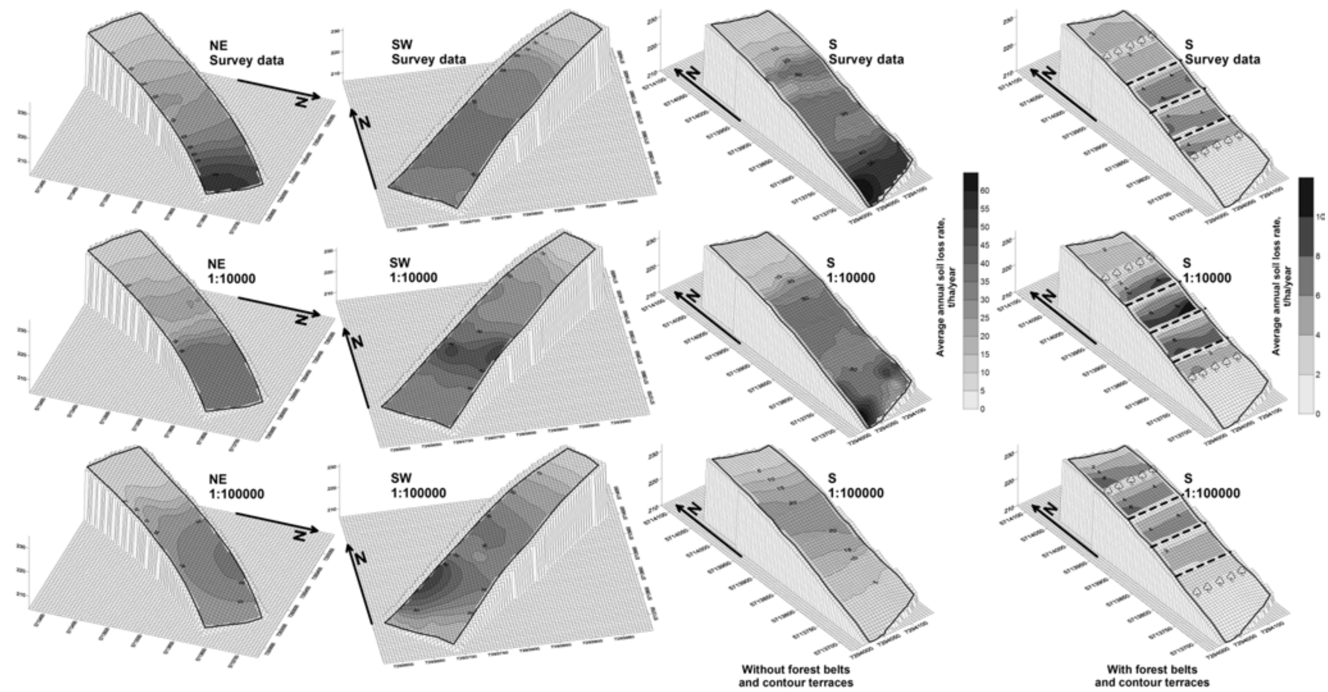

Fig. 5 Block-diagrams of the studied slope sections with maps of the model-estimated soil erosion rates for crop rotation 3 using the different topographic input data. For the S slope 2, columns of diagrams represent estimates with and without soil conservation measures – forest belts (designated by tree signs) and contour terraces (designated by dashed lines).

To compare average annual soil redistribution rates produced by the model and those obtained from analysis of the soil survey data, we have re-estimated the former, taking into account documented historical changes of crop rotations over the past 150 years. For the NE and SW slopes, the documented history of crop rotation changes includes 62 years of crop rotation 1, 40 years of crop rotation 2, 26 years of crop rotation 3 and 22 years of crop rotation 4. For the S slope, it includes 62 years of crop rotation 1, 40 years of crop rotation 2, 26 years of crop rotation

3, 10 years of crop rotation 4 and 12 years of crop rotation 5. An average annual soil erosion rate for the entire 150 year-long cultivation period was estimated for each slope unit using equation (1):

$$\overline{R}_{150} = \frac{\sum R_i t_i}{150} \tag{1}$$

where R_i is average annual soil redistribution rate for crop rotation i (t ha^{-1} year^{-1}) and t_i is duration of application of crop rotation i (years).

This calculation was carried out by means of arithmetic operations with GIS grid layers (with layers of spatially distributed R_i values within the studied slope units for each of the 5 crop rotations) available in the Golden Software Surfer software package. Variations of the model-estimated 150-year average erosion rates were plotted along the soil survey transects to allow direct comparison with the SPM data (Fig. 6). In addition, block-diagrams with spatial distribution of the model-estimated 150-year average erosion rates were created for each of the studied slope units, with individual values of soil redistribution rates obtained using the SPM method overlain on those at the soil pit locations (Fig. 7). Relative differences between the soil erosion rates obtained by the two independent methods are presented in Table 5.

It is notable that the general pattern of downslope variability of soil erosion rates calculated by the modelled and estimated by the SPM method are relatively similar for all 3 slope units studied (Fig. 6). From the block-diagrams it can be seen that the soil pits with calculated erosion intensities are in most cases located within modelled zones with the same or very similar values of the soil loss rates. The exceptions are related to local sediment redistribution within parts of the

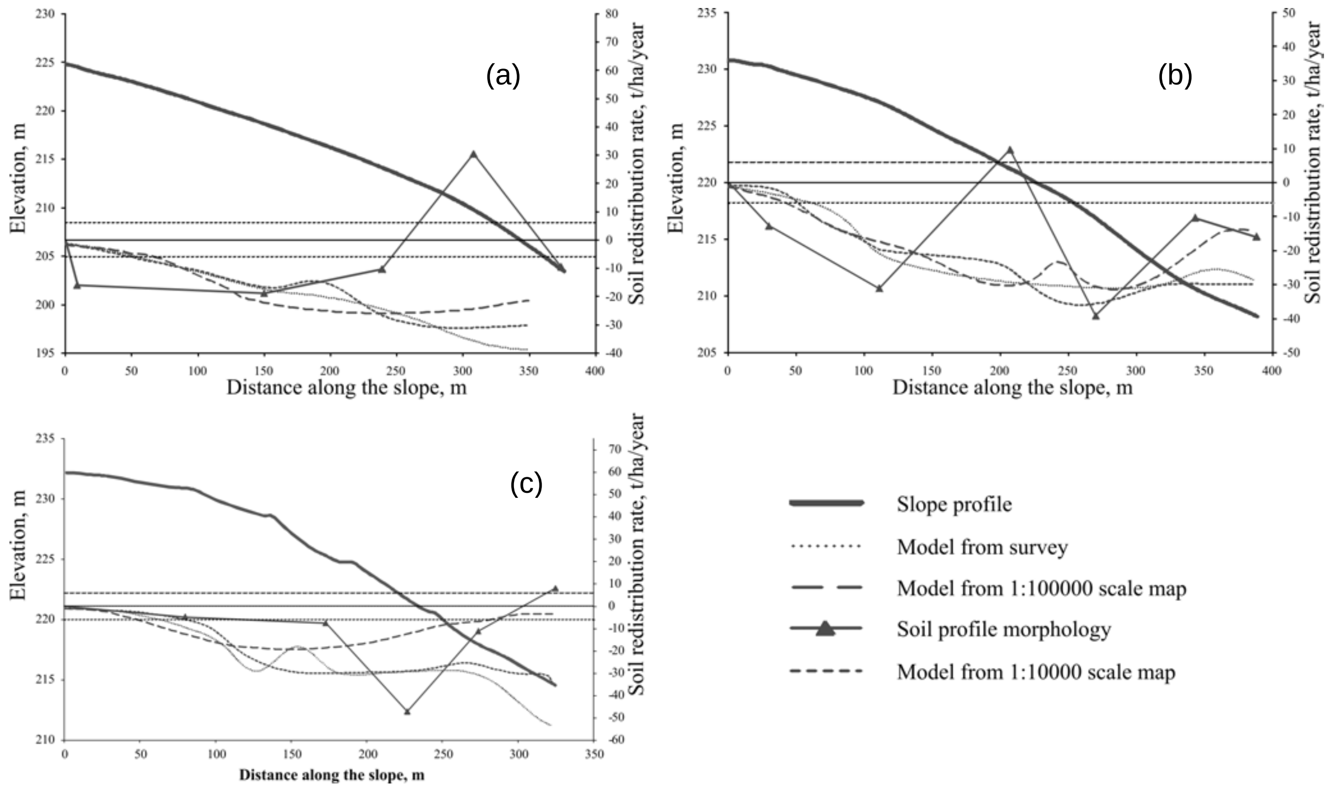

Fig. 6 Comparison of the 150-year average soil erosion rates estimated by the model using the topographic input data of different scales with average annual soil redistribution rates obtained from the SPM method plotted along the soil survey transects for the NE (a), SW (b) and S (c) slopes. Fine horizontal dashed lines represent a range of uncertainties of the SPM estimates corresponding to the natural variability of soil profile properties determined from the soil pits dug in undisturbed conditions (±6 t ha^{-1} year^{-1}).

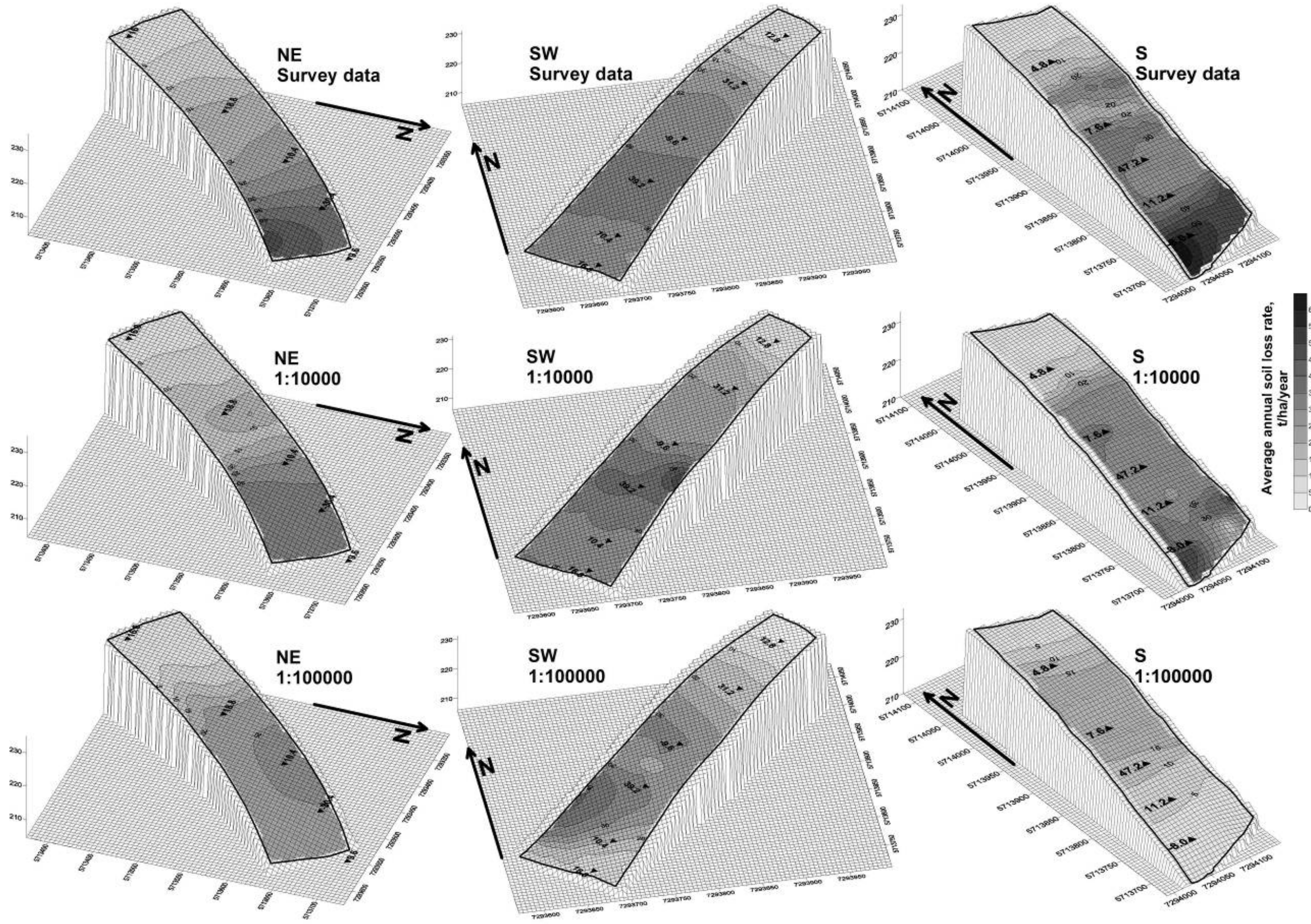

Fig. 7 Block-diagrams of the studied slope units with the maps of average soil erosion rates modelled for the last 150 years (according to the documented history of crop rotation changes) using morphometric data of different scales. The points with exact values correspond to average annual soil redistribution rates estimated by the SPM method, negative values represent deposition. For the S slope the variant without account of soil conservation measures is presented.

Table 5 Comparison of average annual soil redistribution rates for the entire 150-year long cultivation period calculated by the model and obtained from the SPM method (upper values – erosion rates in t ha^{-1} year^{-1}, lower values – relative % difference from the SPM-produced value with account for within-slope redeposition taken as 100%).

Slope units	SPM		Model					
	Without account for within-slope sediment redeposition	With account for within-slope sediment redeposition	Survey		1:10 000 scale map		1:100 000 scale map	
			Soil survey transect	Entire slope unit	Soil survey transect	Entire slope unit	Soil survey transect	Entire slope unit
NE	12.0	8.2	19.7	19.44	18.2	17.66	18.3	16.71
	+46.3	100	+140.2	+137.1	+122.0	+115.4	+123.2	+103.8
SW	18.9	18.1	22.1	23.48	20.7	24.5	20	22.05
	+4.4	100	+22.1	+29.7	+14.4	+35.4	+10.5	+21.8
S	10.6	9.3	23.5	25.89	20.7	22.05	10.8	10.29
	+14.0	100	+152.7	+178.4	+122.6	+137.1	+16.1	+10.6

NE and SW slopes and the individual severely eroded locations at the upper part of the lower third of the S slope (Figs 6 and 7). This general correspondence of spatial patterns makes it clear that the empirical model used in this study makes it possible to obtain generally adequate maps of soil erosion rates which represent the spatial distribution of erosion for individual slopes. This approach may be useful for the design and implementation of soil conservation measures (Fig. 5, the S slope with a system of forest belts and contour terraces).

In general, the difference between soil erosion rates modelled and calculated by the SPM decreases with decreasing map scale for the topographic input data used for the modelling (Table 5). However, this cannot be related to an increase of estimation precision. The most likely explanation is the balance between two opposite tendencies. Firstly there is a trend to overestimate erosion rates because the model does not take into account within-slope redistribution and secondly there is a tendency to underestimate erosion rates due to the loss of accuracy of topography representation in smaller scales (lower elevation range and gradients, higher slope profiles distortions). Thus it is not reasonable to make a conclusion about the higher validity of 1:100 000 maps from the analysis of the Table 5. Conversely, for soil erosion assessment of large areas, the input data for models must be based on detailed soil erosion estimates at key sites, where modelled results may be controlled in the field by independent methods (model validation). It is also necessary to improve the model in order to take into account within-slope soil redistribution.

CONCLUSIONS

This study shows that the scaling effect of topographic data sources and the corresponding accuracy of relief representation should be taken into account in soil erosion studies based on the model applications. In some cases, errors caused by insufficient morphometric data precision may be >50% of calculated erosion rates and significantly exceed variability of the process intensity related to changes in crop rotations.

The error value in estimated erosion rates is highly dependent on cartographic generalization and local geomorphic (slope morphology and morphometry) conditions. The largest errors appear with the scale reduction at convex or concave slopes with the increase of slope long profile deviation from a straight line. The same dependence is typical for the slopes complicated by natural or artificial slope breaks and other linear microtopographic features. These features, even those hardly visible on the real slope surface, may be important for the diversion, dissipation or collection of runoff, thus promoting noticeable changes in the spatial distribution of soil erosion rates within the slopes. Neglecting such features may cause large discrepancies and loss of accuracy in modelling output data.

A comparison of modelling results with the soil erosion rates obtained by the soil profile morphology method shows that the empirical model used in this study produces an adequate representation of erosion intensity along the flow lines, except for local within-slope areas where sediment redistribution occurs. However, there is a significant overestimation of average erosion rates caused by the unaccounted effect of local redeposition. The study shows that calculations of soil erosion rates based on topographic maps covering large areas must be validated by more detailed study of sites where modelling results can be verified by independent field-based approaches.

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