VERSITA DOI: 10.2478/v10303-012-0004-5 Acta Silv. Lign. Hung., Vol. 8 (2012) 39–55

Soil Erosion Analysis in a Small Forested Catchment Supported by ArcGIS Model Builder

Péter CSÁFORDI[a*] – Andrea PŐDÖR[b] – Jan BUG[c] – Zoltán GRIBOVSZKI[a]

[a] Institute of Geomatics and Civil Engineering, Faculty of Forestry, University of West Hungary, Sopron
[b] Department of Geoinformation Science, Faculty of Geoinformatics, University of West Hungary, Székesfehérvár
[c] Institute of Physical Geography and Landscape Ecology, Faculty of Natural Sciences, Leibniz University of Hannover

Abstract – To implement the analysis of soil erosion with the USLE in a GIS environment, a new workflow has been developed with the ArcGIS Model Builder. The aim of this four-part framework is to accelerate data processing and to ensure comparability of soil erosion risk maps. The first submodel generates the stream network with connected catchments, computes slope conditions and the LS factor in USLE based on the DEM. The second submodel integrates stream lines, roads, catchment boundaries, land cover, land use, and soil maps. This combined dataset is the basis for the preparation of other USLE-factors. The third submodel estimates soil loss, and creates zonal statistics of soil erosion. The fourth submodel classifies soil loss into categories enabling the comparison of modelled and observed soil erosion. The framework was applied in a small forested catchment in Hungary. Although there is significant deviation between the erosion of different land covers, the predicted specific soil loss does not increase above the tolerance limit in any area unit. The predicted surface soil erosion in forest subcompartments mostly depends on the slope conditions.

GIS / forest cover / erosion modelling

Kivonat – Talajeróziós elemzések egy erdősült kisvízgyűjtőn az ArcGIS Model Builder segítségével. A tanulmány egy új munkafolyamatot mutat be, amely az Általános Talajvesztési Egyenlet (USLE) térinformatikai környezetben való alkalmazását könnyíti meg. Az ArcGIS Model Builder-ben létrehozott négyrészes keretrendszer meggyorsítja az adatfeldolgozást és biztosítja a talajeróziós térképek összehasonlíthatóságát. Az első modul – a digitális domborzatmodellből kiindulva – előállítja a lefolyáshálózatot és a kapcsolódó vízgyűjtőket, megadja a lejtőadottságokat és az USLE LS faktorát. A második modul egyesíti a lefolyáshálózatot, az utakat, a vízgyűjtőhatárt, a felszínborítást, a területhasználatot és a talajtérképet tartalmazó vektoros rétegeket. Ez az egyesített adatbázis az alapja a többi USLE-tényező előkészítésének. A harmadik modul kiszámolja a talajveszteséget, és területi statisztikákat képez a talajerózióhoz táblázatos és térképi formában. A negyedik modul vektoros talajveszteségi térképeket konvertál, ahol az egyes poligonok megegyeznek az egyes talajveszteségi osztályokkal. Így lehetővé válik a modellezett és a terepen felmért talajerózió összehasonlítása. A keretrendszert egy hazai erdősült kisvízgyűjtőn alkalmaztuk. Habár jelentős eltérést tapasztaltunk a különböző talajborítású területek eróziója között, a megengedett talajveszteségi értéket egyik területi egységben sem haladta meg a modellezett felületi talajpusztulás. A vizsgálati területen – az egyes erdőrészleteket tekintve – a felületi talajpusztulást legfőképp a domborzati adottságok befolyásolták.

GIS / erdőborítás / eróziómodellezés

[*] Corresponding author: csafordip@emk.nyme.hu; H-9400 SOPRON, Bajcsy-Zs. u. 4.

1 INTRODUCTION

Water-driven erosion is a natural process which is responsible for landscape degradation. Forest vegetation generally is good for soil protection, however, human disturbances may accelerate erosion on territories with high relief energy. Climate change (e.g. including more intensive storms) is also responsible for soil loss intensification. Several studies discuss how forestry activities (Surfleet – Ziemer 1996, Lisle 1998) and land use change influence the sediment transport (Sorriso – Valvo et al. 1995, García – Ruiz et al. 2008). Removing trees reduces evapotranspiration and rainfall interception leading to increased surface runoff. Furthermore without vegetation, soils become vulnerable to surface erosion. Uprooting and road cuts may decrease slope stability and cause mass movement erosion. Heavy equipment can compact soils during roadwork, log skidding, construction. Roads and landings decrease infiltration, increase and concentrate overland flow. Linear structures alter drainage paths and redirect water to more erodible areas. The construction of stream crossings and roads are a major source of erosion in forested catchments due to the low permeability of the road surface (Lewis 1998, Chang 2006).

Soil loss leads to a decrease of the water holding capacity, nutrient availability and organic matter content and to a reduction in the overall fertility of arable lands. Siltation of streams and lakes is another consequence of soil erosion. Diminishing reservoir capacity and flow cross-section of channels may cause a higher flood risk. Aquatic habitats may change if the channel morphology changes (Shen – Julien 1993, Gordon et al. 2004, Gomi et al. 2005, Chang 2006). The eroded and then suspended sediment increases turbidity, reducing the visibility distance in the water body, and the depth at which photosynthesis takes place. Suspended sediment can directly damage fish gills, diminish drinking water quality and impair irrigation systems (Lewis 1998, Gomi et al. 2005).

1.1 Goals and motivations for the study

The need for multi-institutional collaboration motivated the development of this framework. The soil erosion risk of forested catchments in Hungary is being researched by the Hungarian Forest Research Institute in the Mátra Mountains (Bánky 1959, Újvári 1981), and by the University of West Hungary in the Sopron Hills (Kucsara – Rácz 1988, Gribovszki 2000, Gribovszki – Kalicz 2003, Csáfordi et al. 2010, Csáfordi 2010). Several studies from Leibniz University of Hannover have analysed the effects of soil conservation activities on agricultural plots in Lower Saxony, Germany (Mosimann et al. 2004, Sanders 2007, Bug 2011). A comparative study concerning potential soil erosion estimation with the USLE is planned in cooperation with the University of Hannover. The scopes of the study are

- to develop a workflow in the ArcGIS Model Builder which predicts soil erosion with the Universal Soil Loss Equation (USLE) in a uniform way, creates a similar type of zonal statistics based on potential soil loss, and compares the results of different study areas. This framework can be a new tool which simplifies and accelerates the soil erosion prediction for different land use practices, land cover, and rainfall scenarios related to expected climate change;
- to model the potential surface erosion in the Farkas Ditch (Sopron Hills);
- to reveal USLE-factors, which significantly influence surface erosion in the study catchment, using correlation analysis.

1.2 Spatially distributed physical soil erosion models and the USLE

Many models have been developed to predict areas that are susceptible to water erosion, to predict soil loss, and to evaluate soil erosion-control practices. Physically based models like WEPP (Nearing et al. 1989), EROSION-3D (von Werner 1995), or LISEM (De Roo et al. 1996) take the spatial variability of land use and hydrological processes into account and estimate soil loss based on physical laws on a watershed scale. However they often can not be used because of extensive data requirements. Many input parameters require further calibration, complex laboratory analysis or expensive field data collection (Ma 2001, Beskow et al. 2009). Lack of data may lead to unrealistic predictions (Fistikoglu – Harmancioglu 2002).

In contrast to physically based models, Martin et al. (2003) note that empirical models such as the USLE require less site specific data. Therefore the USLE is more widely applied for predicting of soil losses and for planning soil conservation measurements, especially in developing countries (Jain – Kothyari 2000, Lu et al. 2004, Onyando et al. 2005, Erdogan et al. 2007, Pandey et al. 2007). The USLE is an empirical equation originally developed by Wischmeier – Smith (1978) in the USA, where the average specific soil loss pro unit area can be computed by multiplying the following six factors:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \tag{1}$$

In *Eq. (1)* A is the mean annual soil loss ($t \cdot ha^{-1} \cdot yr^{-1}$); R is the rainfall-runoff erosivity ($kJ \cdot m^{-2} \cdot mm \cdot h^{-1}$), which represents the erosion potential of locally expected rainfalls on cultivated soil without vegetation cover. K is the soil erodibility ($t \cdot ha^{-1} \cdot m^{2} \cdot kJ^{-1} \cdot h \cdot mm^{-1}$). It shows the rate of soil loss per unit of rainfall for a specific soil for a clean-tilled fallow. L is the length of the slope (dimensionless), the rate of soil loss compared to the soil loss from a slope 22.13 m long. S represents the slope steepness (dimensionless), the rate of soil loss compared to the soil loss of a slope with a 9% inclination. C is the cover-management (dimensionless), which shows the influence of plants in contrast to bare fallow. P is the erosion-control practice (dimensionless). Control practices are usually contours, strip cropping or terraces (Centeri 2001, Amore et al. 2004). The calculated soil loss can be compared to the tolerable soil loss. The tolerable soil loss is the maximum level of soil erosion that still allows a high level of crop productivity over the years (Stone – Hilborn 2000, Severin et al. 2003).

Many authors have discussed the applicability of the USLE in different study areas. Originally, the USLE allows the long term prediction of soil loss only for standardised agricultural plots (Wischmeier – Smith 1978, Schwertmann et al. 1987). The adaptation of the equation to a wider scale and to different land uses, such as forests, is not recommended by Wischmeyer – Smith (1978). However, several other authors have proven that the USLE is capable of estimating soil loss on a wider scale (Jain – Kothyari 2000, Onyando et al. 2005, Khosrowpanah et al. 2007, Beskow et al. 2009). Rácz (1985) has suggested factor values for the USLE adaptation in forest lands of Hungary. Bartsch et al. (2002) have applied the empirical equation to determine the most erosion sensitive areas in a rangeland with complex topography and varied land uses such as grazing and military activities. A major problem is the value of the predicted soil loss. It can exceed the actual values by one order of magnitude in forested areas. Because the soil distribution is mostly irregular and surface runoff is often prevented by organic debris (such as logs, twigs, and sometimes leaves), the USLE overestimates the soil loss (Risse et al. 1993). The USLE was developed for the prediction of sheet and rill erosion. However the results show no separate values for rill and inter-rill erosion, but overall soil loss only. The USLE is also not feasible for estimating the amount of deposition, and for calculation of sediment yield from gully, streambed and streambank erosion (Wischmeier – Smith 1978, Fistikoglu – Harmancioglu 2002, Andersson 2010). The equation was primarily designed for calculating long-term average annual rates of erosion

(Stone – Hilborn 2000, Beskow et al. 2009). It is therefore necessary to develop techniques to estimate soil loss for individual storm events (Jain – Kothyari 2000). Andersson (2010) cites that interactions between USLE-factors are not taken into account.

1.3 Soil erosion models and Geographical Information Systems

Soil erosion risk differs spatially because of heterogeneous topography, geology, geomorphology, soil types, land cover, and land use. Geographical Information Systems (GIS) are able to handle these spatially variable data easily and efficiently. The estimation of soil erosion with GIS techniques reduces costs and improves accuracy (Ma 2001, Erdogan et al. 2007, Khosrowpanah et al. 2007). State-of-the-art GIS provides the necessary mapping and interpolation methods to create a database, which includes all input datasets for erosion modelling. The resolution should reflect the spatial variation of the hydrological and erosion processes (Fistikoglu – Harmancioglu 2002, Beskow et al. 2009). Decreasing cell size and increasing scale requires a large amount of data for accurate prediction. GIS is therefore most appropriate for the management of a huge amount of data. It reduces time and costs for accessing and handling a database (De Roo – Jetten 1999). De Roo et al. (1996), Fistikoglu – Harmancioglu (2002), Khosrowpanah et al. (2007), and Pandey et al. (2007) describe even more advantages of GIS, such as the production of complex input maps and the combination of soil, land use and land cover information. With GIS techniques, the calculation of soil loss rates for alternative land management scenarios becomes easier.

The required data for the prediction of soil loss (rainfall erosivity, soil data, digital elevation model and land use) has to be converted into a GIS-format in order to implement the USLE in GIS. Different authors have used GIS-based techniques to model USLE-factors for predicting soil loss for larger watersheds on a grid cell basis (Erdogan et al. 2007, Andersson 2010). According to Martin et al. (2003), a combined USLE/GIS approach is able to identify discrete locations with precise spatial boundaries with a high erosion potential. Beskow et al. (2009) validate that the combined USLE/GIS technique shows an acceptable accuracy and allows mapping of the most susceptible areas. The studies by Onyando et al. (2005) and Erdogan et al. (2007) contradict this. The upscaling of the USLE-applications from plots to large watersheds is limited depending on the reliability and availability of direct field measurements. As Fistikoglu – Harmancioglu (2002) cite, the results of erosion risk assessment are more plausible for small grid sizes and smaller areas. Therefore larger watersheds must be analysed as sub-basins. A comprehensive USLE/GIS application was accomplished in Balaton Project in Hungary, where Kertész et al. (1992, 1997) have divided the Örvényesi watershed into "erotopes" which are "inclined parts of the relief with an unconcentrated runoff in more or less the same direction" (Kertész et al. 1997 p. 22). This technique makes it possible to analyse the impact of unconcentrated runoff and to model soil erosion in a larger catchment at quasi-plot scale or in slope segments.

The combined USLE/GIS approach is also limited by each input factor. Auerswald (1987) states that the calculated soil loss is highly sensitive to the slope. Modern GIS-based procedures support the calculation of other USLE-factors as well. Many studies applied remote sensing data to develop values for the C and P factors, to classify land cover categories and land use units (Ma et al. 2003, Beskow et al. 2009). These studies confirm that the original spatial limitations of the USLE can be avoided by using remote sensing data and GIS. Márkus – Wojtaszek (1993a,b) have conducted the USLE calculation in an ArcInfo environment and compared the density differences of aerial photographs and satellite images with the erosion sensitive areas. The results prove that remote sensing is a suitable method to check the modelled soil erosion categories and to follow the actual stage of the erosion processes. The integration of GIS-based techniques into the USLE is useful to describe areas that are vulnerable to soil erosion, enabling immediate conservation planning (Lee 2004, Beskow et al. 2009).

2 MATERIAL AND METHODS

The GIS framework which is introduced in this paper helps predict surface soil erosion. It has been developed for a forested catchment (Farkas Ditch, 0.6 km^2) in the Sopron Hills. Soil erosion occurs here on cutting areas and unpaved forest roads. Landslides, streambank, streambed and gully erosion are also observed in the study area.

The framework combines the pre-processing of digital data and different geoprocessing tools in the ArcGIS/ArcMap 9.3 environment to generate the required factors to predict soil erosion. In the Farkas Ditch, the input data consists of a 5x5 m raster resolution DEM (FÖMI, DDM-5), a 1:10000 scale digital topographic map (FÖMI, DTA-10), aerial photographs (FÖMI, "Aerial Measurement of Hungary 2008"; resolution 0.5 m), forest management plans (ÁESZ 1994, 2004), a soil map based on the analysis of soil samples from the Farkas Ditch, and a survey of the eroded areas. The DEM is the input for modelling the catchment boundary, the stream network, and the *LS* factor. A specific threshold is needed to model the stream network. A grid cell is considered to be a channel if the catchment above the point is greater than the specific threshold (Jain – Kothyari 2000). Land cover types, land use units, and roads of the catchment were digitalised on the basis of topographic maps, forest management plans, and aerial photographs.

2.1 Factors of the USLE

Land units in the vector layers such as land cover and land use maps provide the spatial distribution of the six USLE factors. To integrate the USLE in an ArcGIS/ArcMap environment, each factor must be available as a thematic raster layer. Therefore vector datasets must be converted into a grid format with the same raster resolution as the DEM. The USLE-calculation is a raster-based function, where the model multiplies the unique value of each spatially corresponding grid cell in the six thematic raster layers based on the *Eq. (1)*. The model output is the average annual soil loss (Andersson 2010). The *R* factor in this study is determined on the basis of rainfall data recorded in the 2008–2009 hydrological year in the Hidegvíz Valley rain gauge station (Sopron Hills). The *K* factor is estimated using a dataset of grain size analysis, water content measurement, and organic substance analysis of 25 soil samples collected from the upper 50 cm of the soil layer in the Farkas Ditch. The *C* factor is derived from the literature according to Ma (2001) and US EPA (2009). Recommendations by Rácz (1985) based on the tree harvesting and planting techniques were applied to define the *P* factor. The *C* and *P* factors are locally modified on the basis of field experience, forestry management plans, and visual interpretation of aerial photographs. Our previous papers (Csáfordi et al. 2010, Csáfordi 2010) describe the determination of the USLE factors in more detail.

The *LS* factor is based on the DEM and the unit stream power theory of Moore – Burch (1986). The following *Eq. (2)* was applied:

$$LS = \left(FlowAccumulation \cdot \frac{CellSize}{22.13} \right)^m \cdot \left(\frac{\sin\beta}{0.0896} \right)^n \tag{2}$$

In *Eq. (2) Flow Accumulation* is a raster layer representing the upslope cell number contributing to the surface runoff of a certain raster cell; *Cell Size* refers to the resolution of the DEM; *m* and *n* are empirical exponents. Due to the lack of detailed digital elevation data we applied the values $m = 0.4$ and $n = 1.3$, in correspondence to other international studies such as Lee (2004) and Demirci – Karaburun (2011). Values of *m* and *n* have been suggested by Moore – Burch (1986) for standard reference conditions of USLE, where the slope-length is 22.13 m and slope is 9%.

The tolerable soil loss values according to Rácz (1985) enabled the determination of the most sensitive areas to soil erosion. Limit values at different soil depths are: 1 t/ha/yr at 20 cm, 2.2 t/ha/yr at 40 cm, 4.1 t/ha/yr at 60 cm, 6.4 t/ha/yr at 80 cm, 9 t/ha/yr at 100 cm, 11.8 t/ha/yr at 120 cm, 15.0 t/ha/yr at 140 cm. According to the forestry management plan the average soil depth in the Farkas Ditch is between 60 and 100 cm. However the field assessment shows that the soil depth can be lower or higher if data with a higher spatial resolution is available. Therefore each tolerance category is applied to enable the creation of erosion risk maps for other catchments and local heterogeneities.

2.2 The Model Builder function of the ArcGIS/ArcMap 9.3

The ArcGIS/ArcMap Model Builder combines several GIS operations and runs these modules with different datasets (Pfaff – Glennon 2004). A model consists of three fundamental elements: input parameters, geoprocessing tools, and output data. Model parameters are specific model inputs which need to be defined by the user. For example, the user has to define the specific location of input data, or has the opportunity to specify thresholds. Geoprocessing tools produce output data in a user-defined sequence using the input datasets.

3 RESULTS

This chapter describes the framework developed for surface erosion analysis with the USLE in the ArcGIS environment, the predicted surface erosion in the Farkas Ditch (Sopron Hills, Hungary), and the results of correlation analysis which reveals the most important factors influencing surface erosion in the study catchment.

3.1 Development of the workflow "Erosion analysis" in the ArcGIS Model Builder

The framework "Erosion analysis" consists of the four submodels: "Relief analysis", "Soil and land cover", "Soil loss and statistics", and "Regionalisation".

3.1.1 The submodel "Relief analysis"

The submodel "Relief analysis" generates a flow accumulation grid, the channel network with connected catchments, and computes slope features and the *LS* factor. *Figure 1* presents the conceptual flow chart of the first submodel. The blue ellipses mark the input model parameters, while green ellipses are the input layers.

In the first section of the model run, the "Flow Direction" raster is produced after correcting gridding artefacts. The "Flow Direction" contains the preferred direction of flow of each cell, and provides the basis of the "Flow Accumulation" raster, namely the accumulated flow to each cell. The user must provide the *threshold area* for channel initiation in order to create an adequate "Channel Network". The threshold area in our study is based on a visual trial, a comparison between the results of testing different values and the real channel network observed in the field. The modelled channel network coincides with the real geographical conditions of the Farkas Ditch when the threshold area is 12,500 m². The model generates the "Catchment boundaries", the selection basis of the study catchment according to the "Channel network". Catchment boundaries and channel networks are available as raster layers at first, therefore the model converts them from raster layers into features in order to support the work with separated polylines and polygons during the following steps of erosion analysis. The modelled stream networks and catchment boundaries are only usable if the DEM supplies reliable outputs, therefore they have to be checked by the user. In our case study these layers were generated inaccurately and had to be digitized manually. The last steps of the first phase of the "Relief analysis" submodel are the calculations of slope conditions in degrees and percent rise.

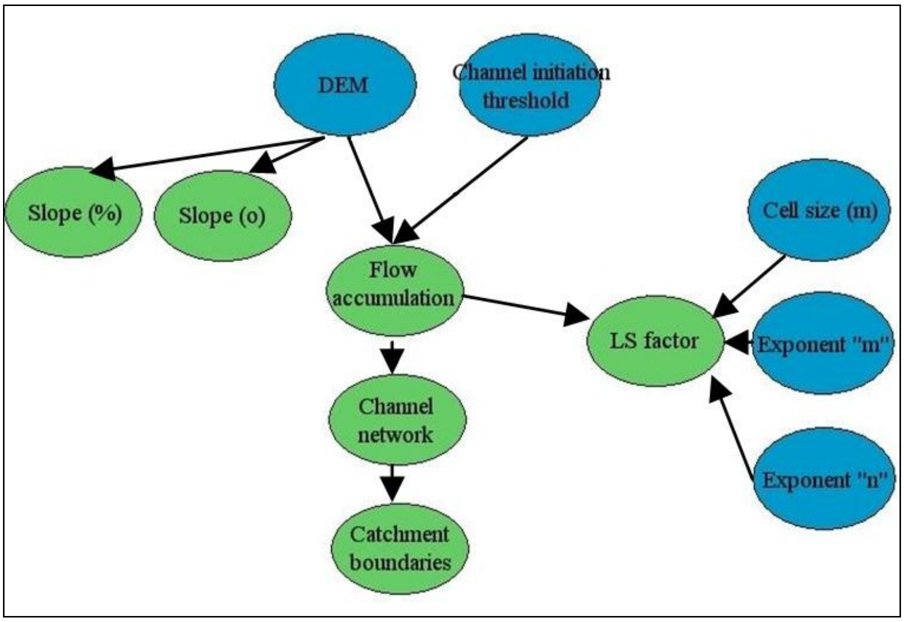

Figure 1. Conceptual flow chart of the first submodel "Relief analysis"

Eq. (2) describes the second part of the "Relief analysis", where the *LS* factor is computed using the parameters "Slope (^{o})" and "Flow accumulation", taken from the first part of the submodel. *Eq. (2)* needs three other inputs, such as "Cell size", "Exponent *m*" and "Exponent *n*". The cell size is 5 m according to the raster resolution of the DEM, and the exponent values are given in Chapter 2.1. For the calculation of *LS* factor, the terrain was simplified, and the slope-length modifying effect of artificial linear elements such as roads and ditches was neglected.

3.1.2 The submodel "Soil and land cover"

The feature layers *catchment boundary, channel network, roads, land cover types, land use,* and *soil map* are the result of pre-processing. The parameter "Land cover" includes the digitized land cover/vegetation categories. The layer "Land use" consists of polygons of different land use units, such as forest subcompartments and plots. "Soil types" shows the soil map which is based on physical soil properties. Linear spatial elements are represented as "Roads" and "Channel network". "Catchment boundary" refers to the borders of the study area. The submodel "Soil and land cover" (*Figure 2*) integrates these input layers and generates a feature layer ("Full soil and land cover dataset") containing all spatial information for uploading the USLE factors which are manually calculated.

The unpaved roads are mostly damaged by gully erosion caused by concentrated runoff in the experimental catchment. Since normally the impact of unconcentrated runoff is modelled by the USLE (Kertész et al. 1997), erosion calculation has not been conducted with the USLE on the surface of dirt roads and channels. Therefore all linear elements such as roads and channel networks must be removed from the study area. In the ArcGIS geoinformatical software, the vector layers "line type" do not have width. If linear elements need to be handled as areas in order to be erasable from the combined layer ("Union of land cover, land use, soil types, roads and channels,") width has to be added to the lines. Therefore the lines are buffered with a half cell size buffer distance (2.5 m in this study), consequently the lines can be rasterised and erased for subsequent USLE-calculations. After this step, roads and channels were replaced as hollows ("Land cover, land use and soil dataset without the area of linear elements.") Surface erosion modelling is not interpreted in these areas.

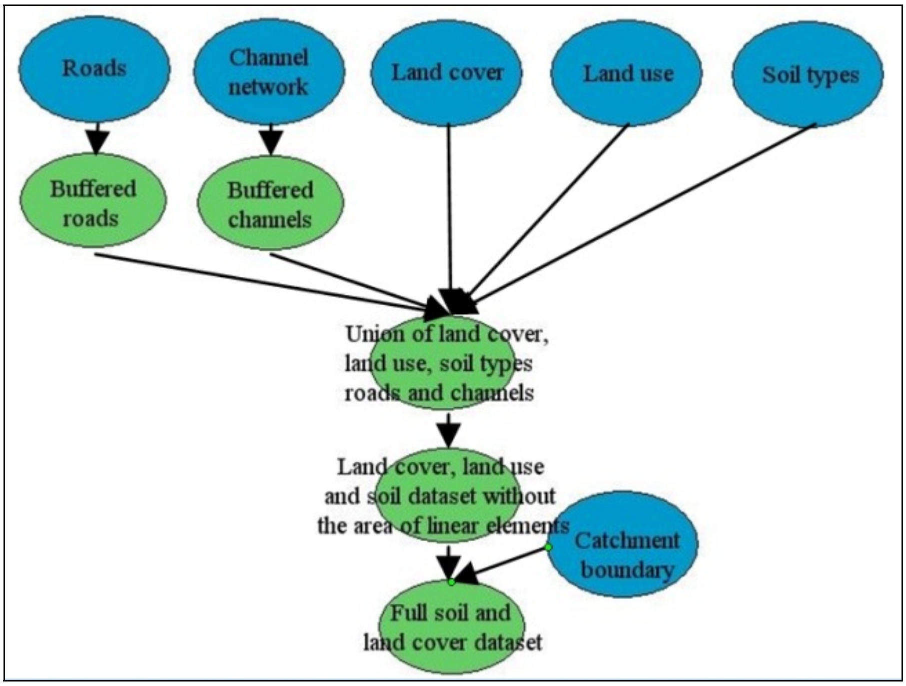

Figure 2. Conceptual flow chart of the second submodel "Soil and land cover"

The final section of the second submodel removes unnecessary attributes of the "Full soil and land cover dataset", as defined by the parameter "Drop Fields". This step provides the layer "Full soil and land cover", which shows the complete spatial database combination and the final structure of the attribute table for the soil erosion analysis. The attributes are: Object ID, Soil type, K factor, Land use unit, Land use practice, P factor, Code number of land cover category, Land cover category, C factor, Polygon area and R factor.

The *R* factor values are calculated with MS Excel. The *C* and *P* factors have to be filled in manually in the attribute table based on visual interpretation of aerial photographs and field experience. Because of this drawback the workflow is recommended principally for catchments smaller than 1 km^2. The benefit of the submodel is that several small polygons are produced with multiplied intersections, and different factor values can be given for each small polygon. This leads to a higher spatial resolution and to a more precise prediction of soil loss.

3.1.3 The submodel "Soil loss and statistics"

The submodel "Soil loss and statistics" (*Figure 3*) computes the potential soil loss, evaluates and summarizes soil loss and elevation data in each land use unit and land cover category. The parameter "Full soil and coverage" contains the attribute fields of *R*, *K*, *C* and *P* factors. These attributes are converted into separate thematic raster layers, using the cell size determined by the "DEM". The model multiplies the rasterised USLE factors on a cell-by-cell basis using the *Eq. (1)*, resulting in the potential specific annual soil loss by surface erosion for each cell.

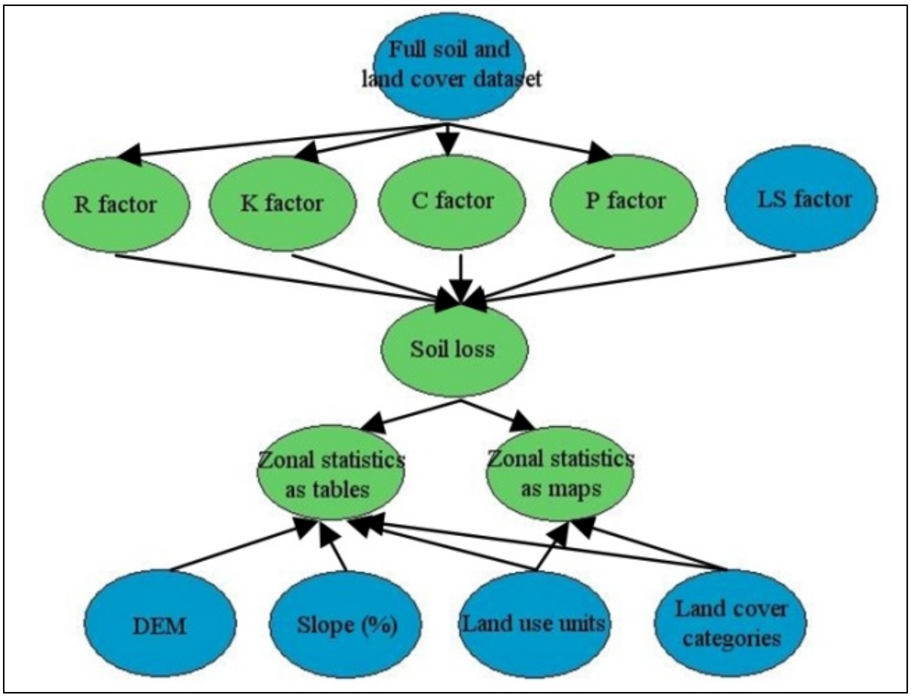

Figure 3. Conceptual flow chart of the third submodel "Soil loss and statistics"

The "DEM", "Slope (%)", "Land use units" and "Land cover categories" generated by the second submodel are the input layers for statistical analysis. The tool "Zonal Statistics as Tables" summarizes the values of a raster, such as elevation data, percentage slope conditions and soil loss, within the zones of another dataset (land use units and land cover/vegetation types). Tables contain the area of the polygons in the zone dataset, maximum, minimum, range, mean, standard deviation and sum. The tool "Zonal Statistics as Maps" reports the average and total soil loss for each land use category and land cover type as a raster map.

3.1.4 The fourth submodel "Regionalisation"

To enable an area-based comparison between predicted and measured soil erosion, the calculated soil loss is converted from a raster into vector format. This allows:

- the comparison of the location of potential and real eroded surfaces,
- the comparison of the size of modelled and observed eroded surfaces.

The submodel "Regionalisation" converts a classified raster layer of soil loss into polygons, keeping the soil loss categories of Rácz (1985). The input soil loss raster has to be multiplied by a given constant value 10 in the first section of model run, in order to avoid conversion errors at raster values smaller than 1. Conditional if/else evaluation on each cell of input raster is applied to select distinct soil loss classes, which are the basis of generating separated polygons. The last steps integrate polygons of each soil loss category and calculate their area in m^2. *Figure 4* shows the raster map of modelled soil erosion on the left and the soil loss classes as polygons after conversion on the right.

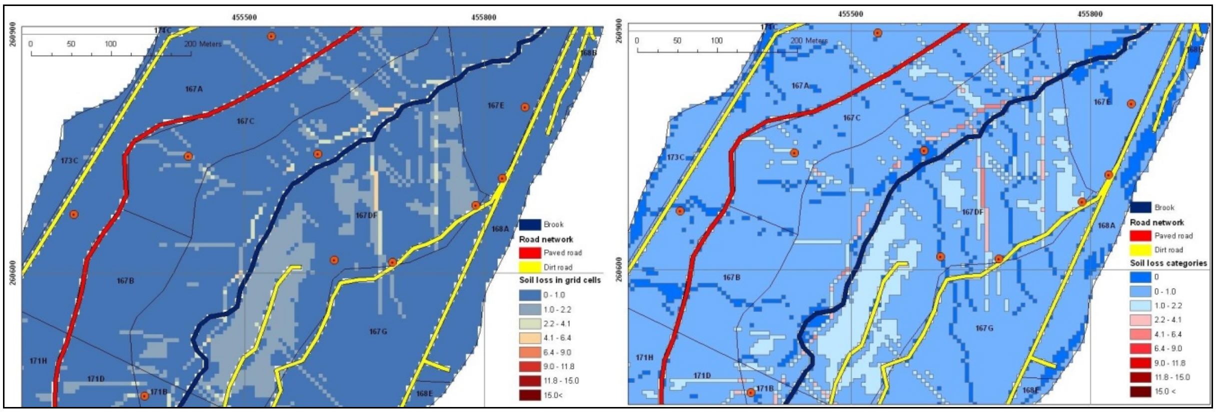

Figure 4. The raster map of modelled soil erosion and polygons after conversion

3.2 Soil erosion prediction in the Farkas Ditch

A surface soil erosion scenario was modelled with the ArcGIS Model Builder workflow for the hydrologic year 2008–2009 in the Farkas Ditch using the USLE factors shown in *Table 1*.

Table 1. USLE factors and predicted soil loss

	Factors of the USLE					
	R ($kJ \cdot m^{-2} \cdot mm \cdot h^{-1}$)	*K* ($t \cdot ha^{-1} \cdot m^{2} \cdot kJ^{-1} \cdot h \cdot mm^{-1}$)	*LS*	*C*	*P*	*A* ($t \cdot ha^{-1} \cdot yr^{-1}$)
Value / Interval	108.4 (constant)	0.32–0.42	0–95.6	0.003–0.01	0.2–0.4	0–6.1
Mean	–	0.36	6.9	0.006	0.24	0.5
SD	–	0.09		0.002	0.08	0.5

Figure 4 presents a part of the soil erosion risk map with the most endangered zones. *Figure 5* shows the percent area of each soil loss category according Rácz (1985) out of the total catchment area, proving that the predicted surface erosion does not exceed the 6.4 $t \cdot ha^{-1} \cdot yr^{-1}$ (the limit value at 80 cm soil depth) in any grid cell. Moreover surface erosion remains below 2.2 $t \cdot ha^{-1} \cdot yr^{-1}$ (82.89%) in the Farkas Ditch. The total predicted soil loss is 26.4 tons from the 0.56 ha area of the Farkas Ditch without roads and channels.

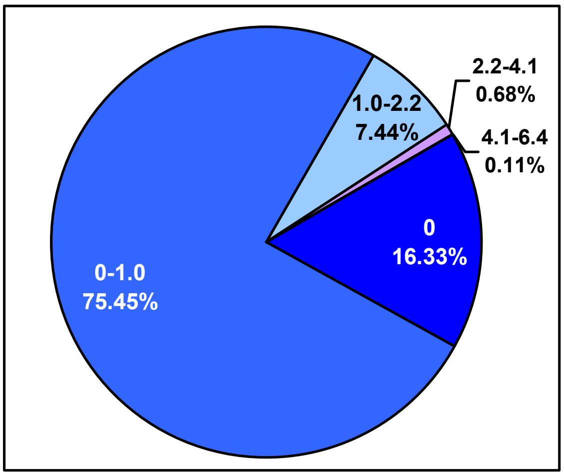

Figure 5. Percent area of the soil loss categories

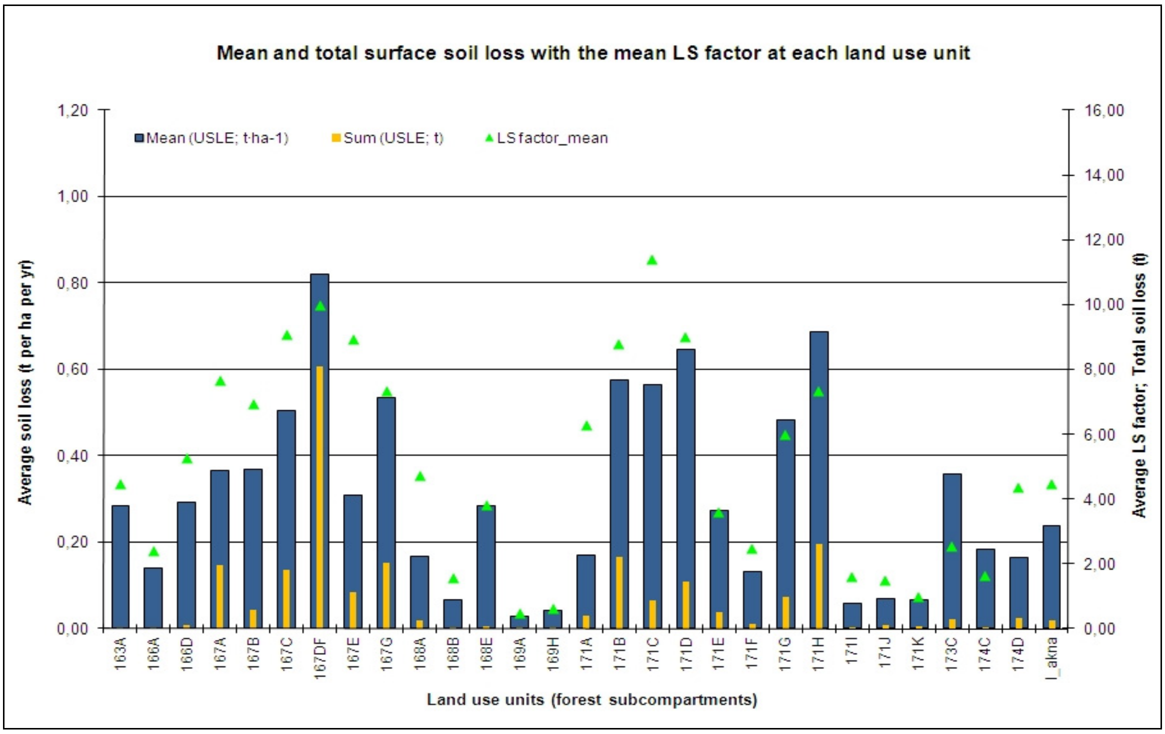

Figure 6. Mean and total surface soil loss with the mean LS factor for each land use unit

Mean and total surface erosion have been calculated for each land use unit and land cover type as given in *Figures 6* and *7*. The predicted soil loss does not rise above the tolerance limit in any area unit, but spatial variability of the erosion risk can be observed. The triangles represent the mean LS factor in each area unit, revealing that surface erosion risk has a significant correlation with the slope-length conditions in the forest subcompartments. Nevertheless, the *LS* factor does not account for the fluctuations of mean soil loss in the different land cover types.

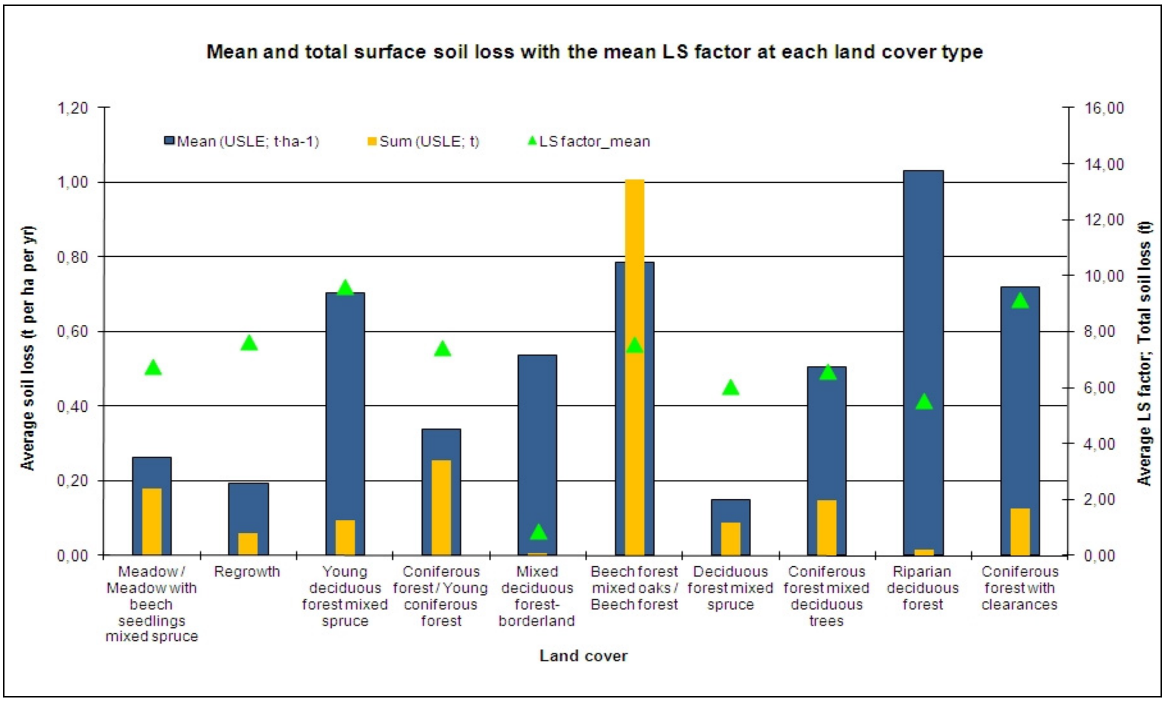

Figure 7. Mean and total surface soil loss with the mean LS factor at each land cover type

The preliminary assumption was that the lowest erosion risk is in forested zones, however the model results and field experience partly contradicted this hypothesis: e.g. “riparian deciduous forest” and “beech forest mixed oaks / beech forest” show the highest mean soil loss from steep slopes, the landslides next to the stream network, the sparse canopy closure, undergrowth and litter layer. However the highest mean soil loss value is also six times lower than the tolerance limit, emphasizing the soil protection role of forest vegetation.

3.3 USLE-factors influencing surface soil erosion in the Farkas Ditch

To assess the most determining factor for potential surface erosion in the Farkas Ditch, a site-specific correlation analysis was conducted. The results are shown in *Table 2*. Marked correlations (**bold values**) are significant at $p < 0.05$. The *C* factor is obviously the most important factor for the mean specific soil loss at the land cover categories, and the size of each unit has the most significant correlation with the total surface soil loss. More factors show significant correlations with the soil erosion on the land use units, and the *LS* factor has the strongest influence aside from the unit area.

Linear elements such as roads and channels were erased from the combined land use and land cover map, so the surface erosion analysis with the USLE was not interpreted in the areas of roads. To evaluate the soil detachment from dirt roads and skid trails, the physically distributed model EROSION-3D was applied in our previous paper (Csáfordi 2010). Calculations with EROSION-3D indicated that the mean soil loss from unpaved forest roads is six times higher than the average soil loss per land use unit. Consequently linear erosion has a higher importance as an erosion source in the Farkas Ditch than surface erosion.

Table 2. Correlation between soil loss and different factors influencing surface erosion

	Area	*LS*-mean	*LS*-max	*K*-mean	*K*-max	*C*-mean	*C*-max	*P*-mean	*P*-max
Land cover categories									
Soil loss-mean	0.00	0.06	–0.18	0.04	–0.22	**0.69**	0.38	0.41	–0.49
Soil loss-sum	**0.95**	0.24	0.22	0.06	0.23	0.19	0.23	0.21	0.30
Land use units									
Soil loss-mean	**0.72**	**0.86**	**0.77**	**0.50**	**0.64**	0.31	0.29	0.22	0.23
Soil loss-sum	**0.94**	**0.62**	**0.72**	0.26	**0.49**	0.19	0.26	0.17	0.16

4 DISCUSSION

A number of international studies describe USLE/GIS implementation, and our ArcGIS workflow provides evidence that erosion modelling with the USLE can be adapted to a GIS-environment. Producing thematic raster layers of USLE-factors in GIS and calculation of soil erosion using them is discussed among others by Kertész et al. (1992, 1997), Márkus – Wojtaszek (1993a,b), Jain – Kothyari (2000), Lu et al. (2004), Onyando et al. (2005), Erdogan et al. (2007), Pandey et al. (2007) and Beskow et al. (2008). Khosrowpanah et al. (2007), Andersson (2010) and Demirci – Karaburun (2011) have also performed their analyses within an ArcGIS/ArcMap framework. The workflow of Khosrowpanah et al. (2007) can achieve a more accurate prediction, because a C++ executable program (Van Remortel et al. 2004) computes the *LS* factor for each grid cell of the DEM input. Our research is limited to erosion prediction, but Jain et al. (2010) have calculated sediment yield and deposition besides soil loss, using the spatially distributed sediment transport capacity.

Although we do not have direct field measurements of surface soil erosion, a total sediment load has been applied to verify the reliability of the predicted soil loss. According to our previous study (Csáfordi et al. 2011) the total sediment yield is 95.1 tons in the hydrologic year 2008–2009 in the stream of Farkas Ditch. The total surface soil loss reduced the sediment delivery ratio by 50% (Csáfordi et al. 2010). There is a 13.9% portion (13.2 tons) from the annual sediment load, and a depleting sediment deposit behind a log jam has a 16.6% (15.8 tons) contribution to the sediment load. Surface erosion does not represent the major part of sediment resources in the Farkas Ditch in the reference period, therefore other erosion phenomena, such as mass movement and channel erosion, have to be calculated. Lee et al. (2004) have compared the surface erosion potential map with landslide location data and found that many landslides occurred where the *LS* factor is 0 and the soil loss value is 0. This fact draws our attention to the possible errors of the *LS* factor calculating process, to the requirement of DEM with a higher raster resolution, and that it is not sufficient to evaluate surface and linear erosion in the Farkas Ditch where landslides are frequent.

Erdogan et al. (2007) have demonstrated the same results as our study in the Kazan watershed, Turkey, that soil erosion potential of the poorly managed pastures was lower as in the land of the dense forest due to relatively higher *C* values. Furthermore, the topographical properties of the watershed had a greater influence on the magnitude of soil loss than land use/land cover types. The significance of slope conditions has also been confirmed by Demirci – Karaburun (2011), where 73% of the mostly agricultural Buyukcekmece Lake watershed had low and slight erosion risks with values under $3\ t \cdot ha^{-1} \cdot yr^{-1}$. The majority of land with low and slight soil erosion risks has slopes <5%. Nevertheless, predicted surface erosion remains below $2.2\ t \cdot ha^{-1} \cdot yr^{-1}$ on 82.9% of the Farkas Ditch, in the Sopron Hills, while this rate was only about 60% in the Kazan watershed. There is a significant difference in the judgement of erosion tolerance limits according to the soil depth, because Erdogan et al. (2007) mark the $>1\ t \cdot ha^{-1} \cdot yr^{-1}$ soil loss as an irreversible change, whereas soil loss below $4.1\ t \cdot ha^{-1} \cdot yr^{-1}$ means tolerable risk in our catchment (Rácz 1985).

5 CONCLUSION AND SUMMARY

This study describes a new implementation of the Universal Soil Loss Equation (USLE) in a GIS-environment using the ArcGIS Model Builder. The four-part combination of geoprocessing tools unifies the surface soil erosion prediction in small catchments and accelerates the working process. Nevertheless further studies are required to ensure the comparability of result structures (attribute tables, statistical values and maps) and the model efficiency, when the workflow is applied to evaluate potential soil erosion in different catchments with different land use and rainfall scenarios. Plans to apply the model in other forested catchments in Hungary and agricultural catchments in Lower Saxony have been made to further improve and to expand the model. With this application the spatial transferability of the workflow will also be analysed.

This paper describes a new aspect of GIS-supported erosion analysis in the field of forestry. Surface soil loss is computed with a cell-by-cell multiplication of six factors derived from rainfall records, soil maps, DEM, land cover and land use data. The first submodel "Relief analysis" delineates the catchments, produces the stream network, and computes the slope conditions and the LS factor. The submodel "Soil and land cover" combines land cover, land use and soil database into one layer generating an attribute table with *R*, *K*, *C* and *P* factors. The third submodel "Soil loss and statistics" calculates soil loss using rasterised USLE-factors from the attribute table of the input layer. The submodel aggregates and calculates a statistical analysis of elevation, slope and soil loss values as a table or as a map for land use units and land cover/vegetation categories. The submodel "Regionalisation" converts the raster layer of potential soil loss to polygon keeping the erosion risk categories set in the raster theme. The submodel computes the area of erosion classes enabling the comparison of predicted erosion to field data.

A surface erosion scenario for the hydrologic year 2008–2009 was modelled in a small forested catchment, Farkas Ditch in the Sopron Hills, using the developed ArcGIS model. Although there is significant deviation between the erosion of different land cover, the predicted soil loss does not rise above the tolerance limit in any area unit. Regenerated areas with dense grass cover also have a significant soil protection function, because neither the mean nor the maximum surface soil loss exceeds the limit value. The predicted soil erosion mostly depends on the slope conditions in the forest subcompartments.

To confirm the results of USLE-evaluations, direct field measurements of surface soil erosion are required. Some improvements are projected for the future in order to achieve more reliable prediction results for smaller catchments and to extend the framework for larger watersheds. More precise automatic delineation of stream networks and catchment boundaries can be ensured by application of detailed DEM involving artificial linear elements, such as roads and ditches, which modify the slope-length and rainfall runoff. To obtain an accurate LS factor, real slope-length has to be considered, and different calculation techniques should be used. Manual uploading of cover-management and erosion-control practice factors can be automatized. But this operation may lead to a decrease of the spatial resolution of factor values, because the user has no control over the setting of the *C* and *P* factors.

Acknowledgements: This research was supported by the TÁMOP 4.2.1/B-09/KONV-2010–0006 project, the scholarships "Aktion für Österreich-Ungarn" and "Deutsche Bundesstiftung für Umwelt". This publication was conducted in the frame of the TÁMOP 4.2.2. B – 10/1 – 2010 – 0018 project (title: Talentum – Development of the talent maintenance conditions in the University of West Hungary) supported by the European Union with the co-financing of the European Social Fund. The authors would like to acknowledge the support from the members of Leibniz University of Hannover, Institute of Physical Geography and Landscape Ecology, Institute of Geomatics and Civil Engineering, Faculty of Forestry, University of West Hungary, and Department of Geoinformation Science, Faculty of Geoinformatics, University of West Hungary.

REFERENCES

AMORE, E. – MODICA, C. – NEARING, M.A. – SANTORO, V.C. (2004): Scale effect in USLE and WEPP application for soil erosion computation from three Sicilian basins. J. Hydrol. 293: 100–114.

ANDERSSON, L. (2010): Soil loss estimation based on the USLE/GIS approach through small catchments. A minor field study in Tunisia. Technical report TVVR 10/5019. Division of Water Resources Engineering, Department of Building and Environmental Technology, Lund University. 5–14.

AUERSWALD, K. (1987): Sensitivität erosionsbestimmender Faktoren. Wasser und Boden 39 (1): 34–38.

BÁNKY, GY. (1959): A kisnánai eróziómérő állomás három évi munkásságának eredményei. [Three-year results of the soil erosion gauging station in Kisnána.] Erdészeti Kutatások 6 (3): 139–160. (in Hungarian)

BARTSCH, K.P. – VAN MIEGROET, H. – BOETTINGER, J. – DOBROWOLSKI, J.P. (2002): Using empirical erosion models and GIS to determine erosion risk at Camp Williams, Utah. J. Soil Water Conserv. 57 (1): 29–37.

BESKOW, S. – MELLO, C.R. – NORTON, L.D. – CURI, N. – VIOLA, M.R. – AVANZI, J.C. (2009): Soil erosion prediction in the Grande River Basin, Brazil using distributed modeling. Catena 79: 49–59.

BUG, J. (2011): Modellierung der linearen Erosion und des Risikos von Partikeleinträgen in Gewässer. Entwicklung und Anwendung von entscheidungsbasierten Modellen zur flächenhaften Prognose der linearen Erosionsaktivitäten und des Gewässeranschlusses von Ackerflächen. Doctoral thesis. Institute of Physical Geography and Landscape Ecology, University of Hannover. 24–100.

CENTERI, CS. (2001): Az általános talajveszteség becslési egyenlet (USLE) K tényezőjének vizsgálata. [Investigation of the K factor of the Universal Soil Loss Equation.] Doctoral thesis. Szent István University, Gödöllő. 13–14, 44–63. (in Hungarian)

CHANG, M. (2006): Forest hydrology. Taylor and Francis, Boca Raton. 237–282.

CSÁFORDI, P. (2010): Erózióveszélyeztetettség vizsgálata a Soproni-hegység erdősült kisvízgyűjtőjén az USLE és az EROSION-3D modellekkel. [Soil erosion risk assessment with the models USLE and EROSION-3D in the small forested catchment of Sopron Hills.] In: Proceedings of the "Environmental management conference for the liveable countryside". Siófok, Hungary. September 2010. 189–198. (in Hungarian)

CSÁFORDI, P. – GRIBOVSZKI, Z. – KALICZ, P. (2010): Contribution of surface erosion to sediment transport in a small forested headwater catchment in the Sopron Hills. Journal of Landscape Management 1 (2): 3–11.

CSÁFORDI, P. – KALICZ, P. – GRIBOVSZKI, Z. (2011): Erdősült kisvízgyűjtő éves hordalékhozamának becslése és egy hordalékkúp hatásának vizsgálata. [Estimation of annual sediment load and the depletion effect of a sediment trap in a small forested catchment.] Hidrológiai Közlöny [Journal of the Hungarian Hydrological Society] 91 (3): 46–54. (in Hungarian)

DE ROO, A.P.J. – WESSELING, C.G. – RITSEMA, C.J. (1996): A single-event physically based hyrological and soil erosion model for drainage basins. I: Theory, input and output. Hydrol. Proc. 10: 1107–1117.

DE ROO, A.P.J. – JETTEN, V.G. (1999): Calibrating and validating the LISEM model for two data sets from the Netherlands and South Africa. Catena 37: 477–493.

DEMIRCI, A. – KARABURUN, A. (2011): Estimation of soil erosion using RUSLE in a GIS framework: a case study in the Buyukcekmece Lake watershed, northwest Turkey. Environ. Earth Sci., DOI 10.1007/s12665-011-1300-9

ERDOGAN, E.H. – ERPUL, G. – BAYRAMIN, I. (2007): Use of USLE/GIS Methodology for Predicting Soil Loss in a Semiarid Agricultural Watershed. Environ. Monit. Assess. 131: 153–161.

FISTIKOGLU, O. – HARMANCIOGLU, N.B. (2002): Integration of GIS with USLE in Assessment of Soil Erosion. Water Resour. Manage. 16: 447–467.

GARCÍA-RUIZ, J. M. – REGÜÉS, D. – ALVERA, B. – LANA-RENAULT, N. – SERRANO-MUELA, P. – NADAL-ROMERO, E. – NAVAS, A. – LATRON, J. – MARTÍ-BONO, C. – ARNÁEZ, J. (2008): Flood generation and sediment transport in experimental catchments affected by land use changes in the central Pyrenees. J. Hydrol. 356: 245–260.

GOMI, T. – MOORE, R.D. – HASSAN, M.A. (2005): Suspended sediment dynamics in small forest streams of the Pacific Northwest. JAWRA 41 (4): 877–898.

GORDON, N.D. – MCMAHON, T.A. – FINLAYSON, B.L. – GIPPEL, C.J. – NATHAN, R.J. (2004): Stream hydrology. John Wiley and Sons, Chichester. 169–200.

GRIBOVSZKI, Z. (2000): Forest stream sediment transport in Sopron Mountain. In: Tóth, L. (ed.): Hungarian Agricultural Engineering 13. Gödöllő. 78–80.

GRIBOVSZKI, Z. – KALICZ, P. (2003): Analysis of headwater stream sediment parameters. In: Geophysical Research Abstracts. European Geophysical Society, 28th Joint Assembly. Nice, France. April 2003.

JAIN, M.K. – KOTHYARI, U.C. (2000): Estimation of soil erosion and sediment yield using GIS. Hydrolog. Sci. J. 45 (5): 771–786.

JAIN, M.K. – MISHRA, S.K. – SHAH, R.B. (2010): Estimation of sediment yield and areas vulnerable to soil erosion and deposition in a Himalayan watershed using GIS. Curr. Sci. India 98 (2): 213–221.

KERTÉSZ, Á. – MÁRKUS, B. – MEZŐSI, G. (1992): Soil erosion assessment using GIS methods. In: 3rd European Conference on Geographical Information Systems. Munich, Germany. March 1992. 885–893.

KERTÉSZ, Á. – RICHTER, G. – SCHMIDT, R.G. (eds.) (1997): The Balaton project. In: European Society for Soil Conservation, Newsletter 2–3: 3–36.

KHOSROWPANAH, S. – HEITZ, L.F. – WEN, Y. – PARK, M. (2007): Developing a GIS-based soil erosion potential model of the UGUM watershed. Technical Report No. 117. Water and Environmental Research Institute of the Western Pacific, University of GUAM, UOG station, Mangilao, Guam. 9–33.

KUCSARA, M. – RÁCZ, J. (1988): A fajlagos évi eróziós talajveszteség vizsgálata a Tacsi-árok erdővel borított vízgyűjtő területén. [Examination of specific annual soil loss in the forested catchment of Tacsi Valley.] Erdészeti és Faipari Közlemények (1–2): 81–88.

LEE, S. (2004): Soil erosion assessment and its verification using the Universal Soil Loss Equation and Geographic Information System: a case study at Boun, Korea Environ. Geol. 45: 457–465.

LEWIS, J. (1998): Evaluating the impacts of logging activities on erosion and suspended sediment transport in the Caspar Creek watersheds. In: Proceedings of the "Conference on coastal watersheds: The Caspar Creek story". Ukiah, USA. 1998. 55–69.

LISLE, T.E. – NAPOLITANO, M.B. (1998): Effects of recent logging on the main channel of North Fork Caspar Creek. Technical report PSW GTR-168. Albany, CA, Pacific Southwest Research Station, Forest Service, USDA. 81–85.

LU, D. – LI, G. – VALLADARES, G.S. – BATISTELLA, M. (2004): Mapping soil erosion risk in Rondonia, Brazilian Amazonia: Using RUSLE, remote sensing and GIS. Land Degrad. Develop. 15: 499–512.

MA, J. (2001): Combining the USLE and GIS/ArcView for Soil Erosion Estimation in Fall Creek Watershed in Ithaca, New York. CSS620- Spatial Modeling and Analysis. Online: http://www.docstoc.com/docs/52400644/Combining-the-USLE-and-GISArcView-for-Soil-Erosion-Estimation (Access date: 02.12.2011)

MA, J.W. – XUE, Y. – MA, C.F. – WANG, Z.G. (2003): A data fusion approach for soil erosion monitoring in the Upper Yangtze River Basin of China based on Universal Soil Loss Equation (USLE) model. Int. J. Remote Sensing 24 (23): 4777–4789.

MARTIN, A. – GUNTER, J.T. – REGENS, J.L. (2003): Estimating erosion in a riverine watershed Bayou Liberty-Tchefuncta River in Louisiana. Environ. Sci. & Pollut. Res. 10 (4): 245–250.

MARKUS, B. – WOJTASZEK, M. (1993a): A talajerózió becslése [Soil erosion estimation]. Vízügyi Közlemények 75 (2): 192–200.

MÁRKUS, B. – WOJTASZEK, M. (1993b): Estimation of soil erosion using USLE and applying ARC/INFO and remote sensing. BME Newsletter, Budapest.

MOORE, I. – BURCH, G. (1986): Physical basis of the length-slope factor in the universal soil loss equation. Soil. Sci. Soc. Am. J. 50: 1294–1298.

MOSIMANN, T. – SANDERS, S. – BRUNOTTE, J. – GROCHOLL, J. – MARAHRENS, S. – PREUSS, E. – STREUN, M. (2004): Bodenerosion selber abschätzen. Ein Schlüssel für Betriebsleiter und Berater in Niedersachsen. Institute of Physical Geography and Landscape Ecology, University of Hannover. 3–29.

NEARING, M.A. – FOSTER, G.R. – LANE, L.J. – FINKNER, S.C. (1989): A process-based soil erosion model for USDA-Water Erosion Prediction Project technology. Transactions of the ASAE 32 (5): 1587–1593.

ONYANDO, J.O. – KISOYAN, P. – CHEMELIL, M.C. (2005): Estimation of Potential Soil Erosion for River Perkerra Catchment in Kenya. Water Resour. Manage. 19: 133–143.

PANDEY, A. – CHOWDARY, V.M. – MAL, B.C. (2007): Identification of critical erosion prone areas in the small agricultural watershed using USLE, GIS and remote sensing. Water Resour. Manage. 21: 729–746.

PFAFF, R.M. – GLENNON, J.A. (2004): Building a groundwater protection model. ArcUser July-September 2004: 54–59.

RÁCZ, J. (1985): Erdővel borított lejtős területek ellenállása az erózióval szemben. [Soil erosion resistance of forested sloping areas.] In: Proceedings of the conference "The economical management of sloping areas". Gödöllő, Hungary. 1985. 196–200. (in Hungarian)

RISSE, L.M. – NEARING, M.A. – NICKS, A.D. – LAFLEN, J.M. (1993): Error assessment in the Universal Soil Loss Equation. SSSA 57 (3): 825–833.

RODDA, H.J.E. – DEMUTH, S. – SHANKAR, U. (1999): The application of a GIS-based decision support system to predict nitrate leaching to groundwater in southern Germany. Hydrolog. Sci. J. 44 (2): 221–236.

SANDERS, S. (2007): Erosionsmindernde Wirkung von Intervallbegrünungen in Fahrgassen. Untersuchungen im Weizen- und Zuckerrübenanbau mit Folgerungen für Anbaupraxis. Series: Geosynthesis. Institute of Physical Geography and Landscape Ecology, University of Hannover.

SCHWERTMANN, U. – VOGL, W. – KAINZ, M. – AUERSWALD, K. – MARTIN, W. (1987): Bodenerosion durch Wasser: Vorhersage des Abtrags und Bewertung von Gegenmaßnahmen. Ulmer, Stuttgart. 9–36.

SHEN, H.W. – JULIEN, P.Y. (1993): Erosion and sediment transport. In: Maidment, D.R. (ed.): Handbook of hydrology. McGraw-Hill. 12.1–12.61.

SORRISO-VALVO, M. – BRYAN, R.B. – YAIR, A. – IOVINO, F. – ANTRONICO, L. (1995): Impact of afforestation on hydrological response and sediment production in small Calabrian catchment. Catena 25: 89–104.

STONE, R.P. – HILBORN, D. (2000): Universal Soil Loss Equation (USLE). Series: Factsheet No. 00-001 AGDEX 572/751. Agricultural Engineering, Ministry of Agriculture, Food and Rural Affairs, Ontario. May 2000.

SURFLEET, C.G. – ZIEMER, R.R. (1996): Effects of forest harvesting on large organic debris in coastal streams. In: Proceedings of the "Conference on coast redwood forest ecology and management". Arcata, CA, Berkeley, CA, University of California. June 1996. 134–136.

ÚJVÁRI, F. (1981): Az erdők szerepének értékelése a vízgyűjtő területek hordalék-lemosódásának megakadályozásában. [Assessment of the soil protection role of forests in the catchment areas.] Erdészeti Kutatások 74: 107–124. (in Hungarian)

US EPA (2009): Water models / Barton Springs Salamander – Meadow. US Environmental Protection Agency. Online: http://www.epa.gov/oppefed1/models/water/bs_meadow.htm (Access date: 30.05.2010)

VAN REMORTEL, R.D. – MAICHLE, R.W. – HICKEY, R.J. (2004): Computing the LS factor for the Revised Universal Soil Loss Equation through array-based slope processing of digital elevation data using a C + + executable. Comput. Geosci. 30: 1043–1053.

VON WERNER (1995): GIS-orientierte Methoden der digitalen Reliefanalyse zur Modellierung von Bodenerosion in kleinen Einzugsgebieten. Doctoral thesis. Freie Universität Berlin.

WISCHMEIER, W.H. – SMITH, D.D. (1978): Predicting rainfall erosion losses – A guide to conservation planning. Series: Agriculture Handbook No. 537. USDA, Washington DC. 3–4.