STATISTICAL VERIFICATION OF SELECTED EROSION MODELS FOR USE IN ECOLOGICAL OPTIMIZATION OF LANDSCAPE

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Abstract

Accuracy of three erosion models (RUSLE, USPED, WATEM/SEDEM) was tested in this study. The models have been selected because they are based on the Universal Soil Loss Equation (USLE). The input data for selected models are easily accessible; therefore, the models are applicable for the erosion evaluating in ecological optimization of landscape. A new simple method was developed to efficiently quantify erosion and deposition rates based on vineyard posts unearthing measurements. The erosion has been measured on ploughed, hoed, and cultivated vineyards in Horný Ohaj. Based on these measurements, the models have been validated and tested. Root mean sqare error, Pearson correlation index, and model efficiency statistic was calculated to compare the field data with the modelled results. It has been shown that the models are quite accurate for predicting the erosion. Problems are in the deposition areas. The RUSLE doesn't simulate the deposition, the USPED is very sensitive for slope curvature; and therefore, is showing the deposition on erosion areas, and the WATEM/SEDEM overestimates the deposition rates. For the ecological optimization of the landscape is good to use the RUSLE for quantifying the erosion rates and USPED for allocating the deposition areas. This approach was practically used for erosion evaluating in the project of territorial system of ecological stability in Vráble cadastral area.

Kľúčové slová

water erosion, RUSLE, USPED, WATEM/SEDEM, ecological optimization

1 Introduction

The water erosion is the most extended soil degradation process in the Slovak Republic. Evaluation of the erosion and projecting the erosion control measurements became an important step in landscape ecological optimization projects. The universal soil loss equation (USLE), developed by Wischmeier and Smith (1978), is most widely used for that. This is mainly due to a simple form of the equation, accessibility of input data, and user's experiences with the model. But the USLE has many drawbacks as inability to simulate the deposition of eroded soils, the insensitiveness to complex slope patterns, and the problems with calculating the geomorphological factor from digital elevation model. Because of that ,the USLE has been revised and the new models have been developed. The aim of this study is to validate and test 3 selected models based on the USLE. First is the Revised Universal Soil Loss Equation (RUSLE) by Desmet and Govers (1996); second model is the United Stream Power Erosion-Deposition (USPED) proposed by Mitasova et al. (1996), and third model is Water Erosion model and Sediment Delivery model (WATEM/SEDEM) developed by Van Oost et al. (2000).

2 Methods

First, there was a need to get a field data for models validating, so the first step was the erosion measurement. Then, the water erosion has been modelled with selected models. The measured and modelled data have been compared in a third step. There have been shown the advantages, disadvantages, and usability of the models. Last step was a test of selected models in landscape-ecological optimization process.

The erosion and deposition intensity was measured in Horný Ohaj vineyards. The measurement was based on change of vineyard post height due to an erosion or deposition process. There has been measured height of 353 posts in 3 different vineyards: ploughed, hoed, and cultivated. The owners of the vineyards were asked to provide information about whole posts length, initial deepness of the posts and year when the posts have been digged in. The annual erosion or deposition was calculated according to formulas 1 and 2.

$$\Delta h = \frac{\text{whole post lenght (mm)} - \text{initial post deepnes (mm)} - \text{measured post lenght (mm)}}{\text{measurement year} - \text{year when the post has been digged in}}$$

Δh - soil erosion or deposition (mm/year)

$$\Delta A = \rho_d .10.\Delta h$$

ΔA - soil erosion or deposition ($t.ha^{-1}.rok^{-1}$)
ρ_d - soil bulk density ($g.cm^{-3}$)

The erosion and deposition process was simulated by use of three selected models: RUSLE, USPED, and WATEM/SEDEM. The models are based on the Universal Soil Loss Equation, so the basic input data are the same. Rainfall erosivity (R factor) is determined as a function of total storm kinetic energy and its maximum 30-min intensity. There was used the value R = 25,71 for Vráble meteorological station, derived by Malíšek (1990). Soil Erodibilty (K factor) is a function of soil texture, organic matter content, structure and permeablilty. The K factor values were derived from Bonited Soil-Ecological Units according to Ilavská, Jambor, Lazúr (2005). Land cover (C factor) was interpreted from Vráble landcover map (Izakovičová, et. al., 2008). The values were taken from Hrnčiarová (2001) and Malíšek (1992). The erosion control practice (P Factor) was computed for each type of vineyards management from measured erosion data. A digital elevation model (DEM), as an input for topographical (LS Factor), was derived from contours maps 1:10 000. The elevation data were refined by geodetics measurements with the use of GPS device ProMark 3. The DEM was intrpolated be using the regularized spline method.

The results yielded from RUSLE and WATEM/SEDEM were compared to measured data using the Nash and Sutcliffe (1970) model efficiency statistic, root mean square error, and the Pearson correlation coefficient. The USPED outputs are in relative units, so only the correlation coefficient was used for the comparison. The model efficiency (ME) value represents the proportion of the initial variance accounted for by the model. The closer the value of ME approaches 1, the more efficient model is. Values of ME < 0 mean that the model produces more variation than could be observed, which means the model is inefficient.

$$ME = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O_{mean})^2}$$

n - number of observations
O_i - observed value
P_i - predicted value
O_{mean} - the mean observed value

The accuracy of the models was evaluated by the root mean square error (RMS).

$$RMSE = \sqrt{\tfrac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2}$$

The relation between the observed and measured data has been evaluated with Pearson correlation coefficient:

$$r = \frac{\sum_{i=1}^{n}(O_i - O_{mean}) - (P_i - P_{mean})}{\sqrt{\sum_{i=1}^{n}(O_i - O_{mean})^2}\sqrt{\sum_{i=1}^{n}(P_i - P_{mean})^2}}$$

r - Pearson correlation coefficient
P_{mean} - the mean predicted value

The coefficient ranges from −1 to 1. A value higher than zero means that observed and modeled data are positively related (O_i with P_i increases). A higher value means the stronger positive relation, values lower than 0 means negative relation (O_i increases as P_i decreases). A value of 0 shows there is no relation between observed and modeled data.

3 Results

3.1 Revised Universal Soil Loss Equation

The Revised Universal Soil Loss Equation is a simple approach, where the inputs factors are just multiplied, so only the vertical relations between the erosion factors are modeled. The difference between the USLE and RUSLE is in topographical factor computing.

$$E = R \,.\, K \,.\, L_{i,j} \,.\, S_{i,j} \,.\, C \,.\, P$$

E – annual soil loss ($t.ha^{-1}.year^{-1}$)

The slope length is replaced with unit contributing area. The modified slope length factor is computed according to Desmet, Govers (1996).

$$L_{i,j} = \frac{(A_{i,j-in} + D^2)^{m+1} - A_{i,j-in}^{m+1}}{D^{m+2}.x_{i,j}^m.(22,13)^m}$$

$L_{i,j}$ - modified slope length factor

$A_{i,j-in}$ - unit contributing area (m.m^{-2})

D- the grid cell size (m)

$x_{i,j}^m$ - shape correction factor

m - exponent

S factor is calculated as the grid area divided by the total length of streams in the same grid. Slope angle β is taken to be the mean angle of all sub-grids in the steepest direction. (McCool et al. 1989)

$$S_{i,j} = 10,8.\sin\beta + 0,03 \text{ ak } \tan\beta < 0.09$$
$$S_{i,j} = 10,8.\sin\beta - 0,5 \text{ ak } \tan\beta > 0.09$$

β - slope angle

The RUSLE simulates only the erosion process, deposition is neglected. That causes the big differences between the measured and observed data at deposition areas. It is reflected in model efficiency index, RMS error, and correlation coefficient (tab. 1). In the erosion part of the slope are these indicators good; at the deposition area is lower model efficiency, high RMS error and negative correlation with the measured data.

Tab. 1: The correlation coefficient, RMS error, and model efficiency index for RUSLE

	ploughed vineyard			**hoed vineyard**			**cultivated vineyard**		
	eros.	**depos.**	**slope**	**eros.**	**depos.**	**slope**	**eros.**	**depos.**	**slope**
ME	0,444	-2,132	0,359	0,299	-0,808	0,025	0,092	-0,656	0,102
RMS	13,532	67,781	27,428	13,935	100,184	45,163	11,006	113,254	47,858
r	0,688	-0,551	0,717	0,562	0,066	0,406	0,416	-0,248	0,495

eros. – erosion part of the slope, depos. - deposition part of the slope, slope – whole slope

3.2 Unit Stream Power - based Erosion Deposition

Unit Stream Power - based Erosion Deposition (USPED) is a simple model which predicts the spatial distribution of erosion and deposition rates for a steady state overland flow with uniform rainfall excess conditions for transport capacity limited case of erosion process. For the uniform soil and cover properties represented by Kt=const., the net erosion/deposition rate is estimated as a divergence of the sediment flow (Mitas, Mitasova 1996):

ED(r) = div qs(r) = Kt { [grad h(r)] . s(r) sin b(r) - h(r) [kp(r) + kt(r)] }

s(r) - unit vector in the steepest slope direction
h(r) - water depth (m)
A(r) - upslope area
kp(r) - profile curvature

kt(r) - tangential curvature

The sediment flow at sediment transport capacity can be estimated from USLE factors:

$$T = R\ K\ C\ P\ A^{m} (\sin\ \beta)^{n}$$

m, n – coefficients(m=1.6, n=1.3 for prevailing rill erosion; m=n=1 for prevailing sheet erosion)

The model shows overestimated distribution of deposition areas. It is caused by high sensitivity for terrain curvature. The equation gives the same weight to plan and profile curvature, but the terrain experiences show the higher influence of profile curvature on the sedimentation process. There are error lines, showing high erosion and deposition rates, on the edges of different soil types or landuse categories. It is error of the model caused by derivation of non-continues erosion factors. Outputs of the model are in relative units; for that reason, only correlation index was possible to compute (Tab.2). The index is very low in erosion areas, but high in depositional areas of the slope.

Tab. 2: The correlation coefficient, RMS error, and model efficiency index for USPED

	ploughed vineyard			**hoed vineyard**			**cultivated vineyard**		
	eros.	**depos.**	**slope**	**eros.**	**depos.**	**slope**	**eros.**	**depos.**	**slope**
ME	-	-	-	-	-	-	-	-	-
RMS	-	-	-	-	-	-	-	-	-
r	0,147	0,710	0,564	-0,329	0,931	0,629	0,218	0,609	0,594

eros. – erosion part of the slope, depos. - deposition part of the slope, slope – whole slope

3.3 Water Erosion Model / Sediment Delivery Model (WATEM/SEDEM)

The basic inputs are the same as in RUSLE or USPED, but some of them are in different units. The soil erodibility factor is in $kg.m^{-2}.h.MJ^{-1}.mm^{-1}$, so the K factor from Ilavská, Jambor, Lazúr (2005) has to be multiplied by 100. Rain erosivity factor is in $MJ.mm.m^{-2}.h^{-1}$; therefore, the R factor according to Malíšek (1990) has to be divided by 1000. The topographical factor is calculated automatically from DEM. The C factor is derived from a parcel map. It's a map of roads, built up areas, rivers, fields, grasslands. The model also simulates the landcover effect on rainfall infiltration, and the impact of field boundaries on rainfall infiltration is simulated as well. Optional inputs are a river map and a ponds map. WATEM/SEDEM can calculate the amount of sediments, which are delivered to rivers and ponds on the maps.

The special inputs are coefficients α, β, γ for a transport capacity (TC) computing. The erosion/deposition simulation is based on comparison of erosion rate with the transport capacity of the grid cell. If the local TC is smaller than the sediment flux, then the deposition is modeled; if the TC is higher, then the sediment transport will be supply-limited. In the WATEM/SEDEM 2005 is TC calculated as:

$$TC = \alpha \times R \times K \times A^{\beta} \times S^{\chi}$$

The α, β, γ values were determined by trial-and-error method. For the study area with grid cell size 4x4 meters the values are: α = 0,001; β = 1,35; γ = 0,95. WATEM/SEDEM simulates the erosion as a RUSLE, but the deposition is 4 times overestimated. Therefore there is a low model efficiency, high RMS error, and low correlation with the measured values (tab. 3).

Tab. 3: the correlation coefficient, RMS error, and model efficiency index for WATEM/SEDEM

	ploughed vineyard			hoed vineyard			cultivated vineyard		
	eros.	**depos.**	**slope**	**eros.**	**depos.**	**slope**	**eros.**	**depos.**	**slope**
ME	-18,95	-8,797	-5,463	-0,229	-0,503	0,120	-46,46	-1,387	-2,299
RMS	81,087	119,886	78,369	18,455	91,340	42,907	79,595	135,967	91,706
r	0,268	0,595	0,538	0,232	0,874	0,863	0,127	0,122	0,275

eros. – erosion part of the slope, depos. - deposition part of the slope, slope – whole slope

4 Discussion and conclusion

The ME index, RMS error, and correlation values are influenced by 2 factors: measurement error and error of the model. The model error is mainly occurring in deposition areas. A very high deviation of few measurements in these areas has a strong impact on statistical indexes of model precision. According to standard statistical process the outliers should be deleted, but for the practical use of the models is better to know the errors and calculated with them.

The study showed that use of RUSLE is acceptable in erosion areas. The model doesn't work in the areas, where the power of runoff is decreasing (concavities) and deposition is occurring. RUSLE is showing high values of erosion, although the deposition is occurring there. For the landscape ecological optimization is the spatial distribution of deposition more important than intensity. Therefore, the deposition areas could be identified with use of USPED or ERDEP. The ERDEP is simplified version of USPED, where only DEM is used as an input. The models are very sensitive for relief curvature, so there is a need to find right value of erosion/deposition index for deposition areas identifying. WATEM/SEDEM is more sophisticated and more input data are needed. The transport capacity indexes have to be calibrated. Model is suitable for complicated task as a computing the amount of sediments in rivers or ponds, deposition quantifying, or tillage erosion simulating. Use of the model in detailed scales could result to problems with the deposition overestimating, therefore is better to use the model in more general scales (e.g. 1: 50 000)

RUSLE and ERDEP have been practically used in ecological optimization of Vráble cadastral area. RUSLE has been used for analyze the real erosion, and the deposition areas have been identified with ERDEP (Annex 1). The deposition areas have been removed, and the net erosion map was used as one of the layer for projection of positive and negative factors and processes (Annex 2). Erosion control measurements has been proposed in the local territorial system of ecological stability proposal map (Annex 3)

5 References

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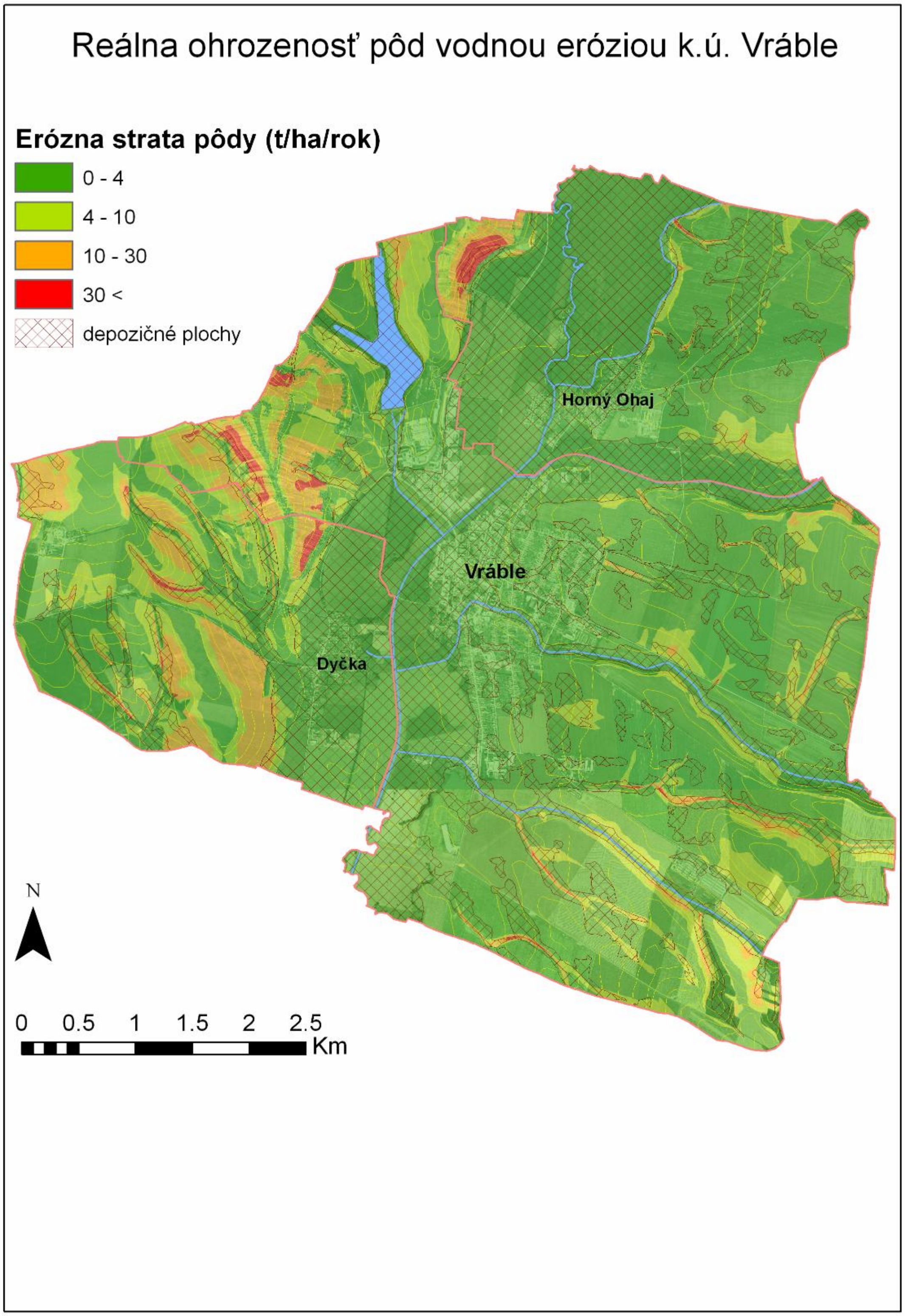
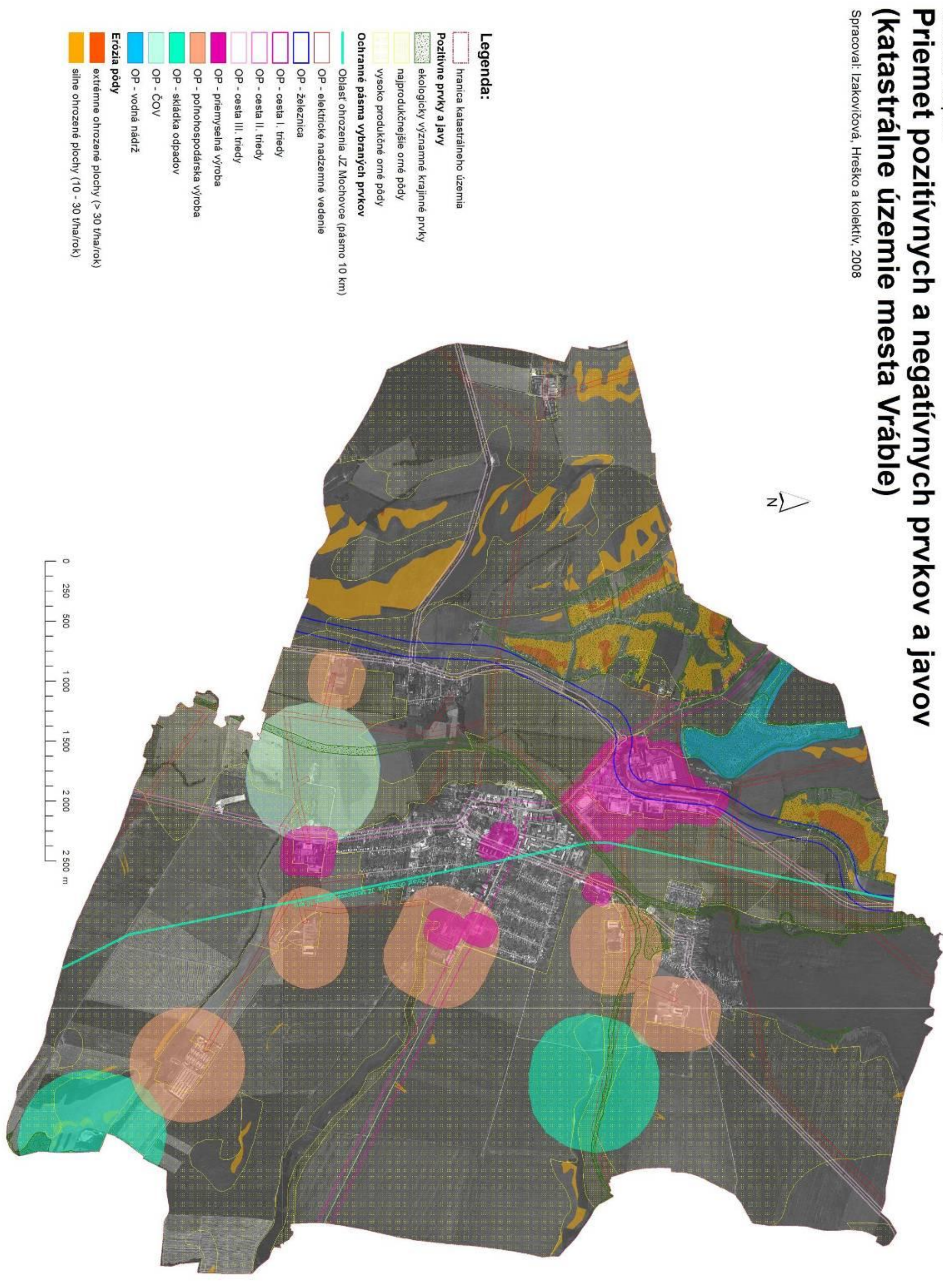
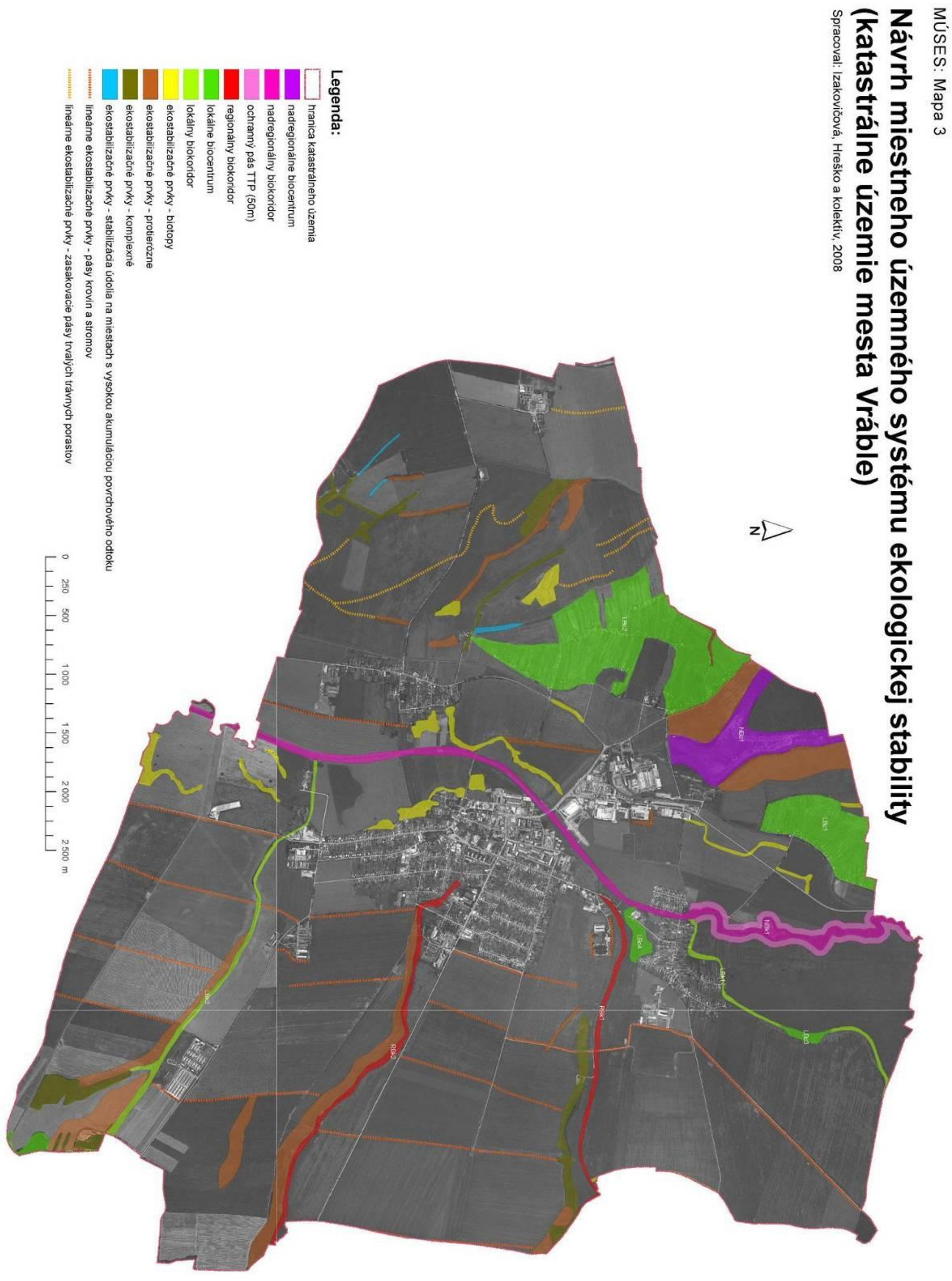


Annex 1: Real soil erosion treatment of Vráble cadastral area.(dark green 0 – 4 $t.ha^{-1}.year^{-1}$, light green 4 – 10 $t.ha^{-1}.year^{-1}$, orange 10 – 30 $t.ha^{-1}.year^{-1}$, red more than 30 $t.ha^{-1}.year^{-1}$; crosshatch – deposition areas)



Annex 2: Projection of positive and negative factors and processes of Vráble cadastral area. (orange – high threaten soils by water erosion, red – extremely threaten soils by water erosion)



Annex 3: Proposition of local territorial system of ecological stability of Vráble cadastral area. (brown areas – erosion control measurements, dark yellow lines – anti erosion infiltration belts)