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THE USE OF MULTI-CRITERIA ANALYSIS FOR IDENTIFYING AREAS SENSITIVE TO LAND DEGRADATION AND WATER RETENTION

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Abstract

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The article presents a method of selecting critical areas (4th river basin) in terms of landscape degradation, with an emphasis on water retention, from a relatively larger unit (3rd river basin). For this purpose, indicators that point directly or indirectly to soil and landscape degradation or water retention were selected with regard to the scale of processing. The indicators were processed in a multi-criteria context using principal component analysis, which, based on the spatial layout pattern of the indicators, assigns weights of importance. These weights were then subsequently used to calculate the aggregation index, which indirectly indicates the sensitivity of the area to degradation and, in particular, water retention. Two catchment areas of the 3rd order – Čížina and Kyjovka – with different soil, climatic and economic conditions were selected for the study. Among the indicators of water retention in the landscape, our analysis included the share of agricultural land in the total area, the share of arable land, the average size of the field block, soil degradation according to the degradation model, runoff curve number, potential water erosion and surface drainage. The resulting procedure can be used to evaluate smaller areas. For a more detailed solution, a number of other methods and indicators could be used, which are also outlined in the article.

Key words: sensitivity analysis, landscape, degradation, retention, modelling.

Introduction

All human life depends on the landscape, with all its parts including soil and water. If we look at the statistics, more than half of the arable land in the world is moderately or heavily degraded and the damage is caused not only by agricultural production loss and diminished livelihoods but also by the lost value of ecosystem services previously provided, including water filtration, erosion prevention, the nutrition cycle and the provision of clean air (ELD Initiative, 2015).

The resulting land degradation (LD) is a global process and the result of various factors, including climatic variations and human activities, and it progressively leads to a reduction in soil fertility, which is a phenomenon commonly regarded as soil degradation (SD) (Jie et al., 2002; Fullen, 2003). Land degradation and desertification are caused by natural and anthropogenic processes (Gisladottir, Stocking, 2005; Johnson, Lewis, 2007; Imeson, 2012) and lead to a reduction in land productivity with ecological and socio-economic consequences. The role of anthropogenic pressures is assumed (Bajocco et al., 2011).

The question is how to assess the degradation of land. In a number of studies, the use of visual observation, field measurements, social enquiries, environmental indicators derived from statistical sources, remote sensing, and mathematical models has been proposed (Basso et al., 2000; D'Angelo et al., 2000; Bathurst et al., 2003; Gad, Lotfy, 2008; Simeonakis et al., 2007; Costantini et al., 2009; Santini et al., 2010; Salvati et al., 2013, 2016).

A number of methodological approaches use indicators, where their selection is very important and ensure the most effective use of available data (Kosmas et al., 2003; Rubio, Recatala, 2006). An example of these approaches can be the ESA (e.g., Rubio, Bochet, 1998; Simeonakis et al., 2007; Thornes, 2004).

The paper deals with water retention in the landscape. This is mainly influenced by changes in the landscape and affects the runoff process and water storage capacity, which are consequently related to other parameters such as field capacity (FC) and saturated hydraulic conductivity (Ks) (Marshall et al., 2014). Surface runoff closely relates to landscape degradation (Kosmas et al., 2000) and can be determined using the runoff curve number (CN) model (Hawkins et al., 2009). Due to its simplicity, this model has been used to identify the direct surface runoff in agricultural basins (Mishra, Singh, 2006). CN relates to the water retention potential of soil (S) and the curve number model considers many factors including changes in land-use, soil type, land management, treatment, antecedent soil moisture and surface condition (Michel et al., 2005) and is involved in many complex and water retention simulation models (e.g., Soulis, Dercas, 2007; Singh et al., 2008). According to Mantey and Tagoe (2013), the main parameters for CN model are hydrological soil groups (HSGs), land use and the digital elevation model.

Runoff processes are also associated with the most serious soil degradation factor, which is water erosion. A wide range of approaches can be used to model it, for example, the spatially explicit erosion model PESERA (Kirkby et al., 2004) that takes into account climate, soil, land use and relief.

There are a number of methodological approaches to the study of degradation effects. They are, however, mostly assessed individually without any link to other influences. Our task was to find suitable indicators, sensitive to water retention and soil degradation threat, and process them, if possible, in a multi-criteria context in a way that could classify the analysed areas according to their sensitivity to water retention. In the most sensitive areas, the remedial measures would be preferentially applied.

Material and methods

The areas of interest for our study are the catchment areas of Čížina and Kyjovka, as shown in Fig. 1. The source of the river Čížina lies southwest of Horní Benešov (49.9528425N, 17.5540864E) at an altitude of 630 m and flows into the river Opava from the right near Brumovice at 280 m above sea level. The catchment area is 102.7 km^2, the flow length is 20.8 km^2 and the average discharge at its confluence with the Opava is 0.45 m^3s^{-1}. Geologically, most

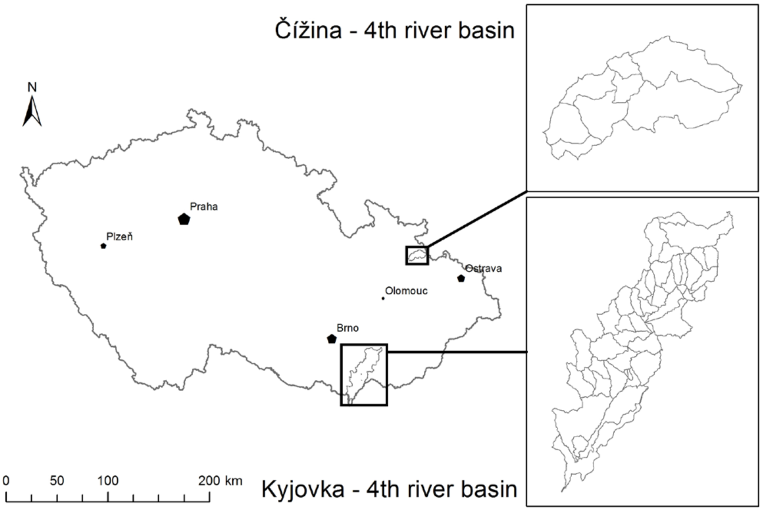

Fig. 1. Čížina and Kyjovka basins – our areas of interest.

of the catchment area consists of Culmian greywackes, sandstones, conglomerates and slates, with loess and glacial deposits in the lower part of the river.

Climatically, it is within the climatic regions of moderately warm MW9 and MW4 (centre), with the upper part of the catchment area in the moderately warm MW2 region. Opava meteorological station registers an average annual temperature of 8.0 °C and an average rainfall of 640 mm/yr. The most common soil type in the catchment area is Cambisol; the agricultural land occupies about 57% of the area, of which 66% is arable land and 33% permanent grassland. Forest accounts for 38% of the area.

The Kyjovka River is a left-hand tributary of the Dyje River. Its source is located in the Chřiby Mountains, on the southern slope of Vlčák hill (561 m above sea level) at an altitude of 512 m above sea level (49.1612092N, 17.2834028E), near the village of Stará Huť. Together with its tributaries, it drains a water catchment area of 665.8 km^2. The average flow of the river at its mouth is about 1.09 $m^3 s^{-1}$. The length of the river is 86.7 km. Geologically, the Kyjovka flows through two major units of the Western Carpathians, the Carpathian flysch belt and the Vienna Basin.

The catchment area falls into three climatic regions – very warm (VW), warm (W3) and moderately warm (MW2) with an average total rainfall of 500 to 650 mm. The most common soil type is chernozem, agricultural land occupies about 60% of the area, of which 83% is arable land, 7% permanent grassland and 8% vineyards. Forest represents about 29% of the area.

The catchment area of the Čížina incorporates a total of 9 further sub-basins of the fourth order. The Kyjovka basin incorporates another 48 sub-basins of the fourth order. Two water catchments with different soils (chernozems vs. Cambisols), climatic conditions (very warm, dry to warm, slightly humid, slightly warm, slightly humid to slightly cold, wet region) and economic conditions have been deliberately chosen for the study.

As indicators of water retention in the landscape, the following factors were included: the share of agricultural land in the total area, the percentage of arable land, the average size of the field block, soil degradation, CN curve, potential water erosion and surface drainage. The choice of this input data was influenced by the fact that this data is freely available or can be calculated based on the available free data.

Mainly vector geo-data was used with the exception of potential water erosion. In the case of Total Degradation factor from the Degradation Model of the Palacky University in Olomouc, the data had to be generalized to individual sub-basins because the original model only contains data for cadastres. Drainage values were obtained from the information system of the Czech Office of Surveying and Cadastre. The Land-parcel identification system (LPIS) was used to calculate potential water erosion, CN curves, and farmland size. Another basis was the Estimated pedologic ecological unit (EPEU) data set freely provided by the State Land Office. The altitude model was derived from the 4th Generation Digital Surface Model of the Czech Republic with a pixel resolution of 5x5 m; the calculations were performed in statistical software R and the maps were processed in ESRI – ArcGIS 10.2.2 GIS software.

The actual work deals with the methodology of the selection of interest areas in terms of water retention in the landscape. After studying different methodological approaches, we chose a model designed by Salvati et al. (2011), the output of which is the value of the aggregation risk index for each sub-basin, in a normalized range from 0 to 1, where 1 is the most sensitive area. The aggregation index was obtained on the basis of the multidimensional statistical analysis, which reduces the complexity of the input data bases, removes the interdependencies between the variables and each assigns a weighting parameter in terms of the importance of the observed phenomenon.

A fourth-order river basin was chosen as the basic mapping unit.

Our processing involved several steps:

1. Normalization of input data.
2. Principal component analysis (PCA) analysis of the normalized matrix.
3. Calculation of the synthetic vulnerability index of the catchment area.

Values of input parameters for each of 9 (Čížina) and 48 (Kyjovka) sub-basins respectively were obtained and modified as follows:

If the influence of the individual variable is negative with increasing value of the variable (i.e., it shows the need for solution), the variable is normalized to the range 0–1 according to the formula:

$$x_i^{'} = \frac{x_{i,j} - x_{i,\min}}{x_{i,\max} - x_{i,\min}}.$$

Otherwise, according to the formula:

$$x_i^{'} = 1 - \frac{x_{i,j} - x_{i,\min}}{x_{i,\max} - x_{i,\min}}, \text{ where}$$

$x_{i,j}$ represents the value of the i-th monitored variable in the j-th water sub-basin, $x_{i,\max}$, or $x_{i,\min}$ symbolizes the maximum, respectively the minimum value of the monitored variable across the whole water sub-basin.

The dependencies of the individual variables are shown in Table 1 using emoticons, where :-) means a positive effect of the variable and :-(a negative effect.

PCA analysis was applied to the resulting matrix of normalized variables. The weights of individual factors were determined by multiplying the contribution of each variable (V_i) to the most important variables (explaining 90% variability) by the proportion of their variance (C_k). The sum of these products for all the most important variables represents the individual weight (w_i) attributed to each indicator as the formula expresses:

$$w_i = \sum_{k=1}^{m} (V_i C_k)$$

Subsequently, the relative weights (W_i) were calculated by the ratio of the absolute weights to the sum of the weights of all the indicators.

$$W_i = \frac{w_i}{\sum_{i=1}^{6} w_i}$$

Each of these weights describes the extent to which a single factor contributes to the overall vulnerability of the territory.

The resulting IC sensitivity index is calculated based on the linear combination of normalized factors and their calculated significance weights.

$$IC = W_{ag} * Ag' + W_{ar} * Ar' + W_{fb} * Fb' + W_{cn} * CN' + W_{ero} * Ero' + W_{dm} * DM' + W_{sdr} * Sdr' \quad ,$$

where individual abbreviations represent normalized values:
Ag – agricultural land, Ar – arable land, Fb – average size of field block, CN – average value of CN curve, Ero – potential water erosion, DM – Total Degradation according to UPOL model and Sdr – surface drainage in individual sub-basins.

From the nature of the method, IC results are within the range of (0.1), where 1 indicates the highest sensitivity to degradation hazard (retention).

Results

The range of input parameters for both catchment areas is shown in Table 1. PCA analysis was used to evaluate the sensitivity of sub-basins to water retention in the landscape, which evaluates the spatial significance of the individual components and quantifies it in similarly calculated weights of the individual factors.

In the catchment area of Čížina, the percentage of arable land (W_{Al} = 18.1%) was the most important parameter, the second most important factor was surface drainage (W_{Sdr} = 17.1%).

T a b l e 1. Basic descriptive statistics of input variables included in the calculation.

		DM [0.1]	Ero [t/ha/yr.]	Ar [-]	Fb [ha]	Ag [-]	CN [0.100]	Sdr [-]	Area [ha]
Kyjovka	Min	0.30	0.1	0.01	1.8	0.04	46.7	0.000	37.8
47 sub-basins	Max	0.76	37.0	0.79	27.3	0.85	87.8	0.729	6449.7
	Avg	0.51	16.1	0.48	8.3	0.54	71.0	0.094	1304.2
Čížina	Min	0.48	1.7	0.04	1.2	0.27	67.8	0.000	15.2
9 sub-basins	Max	0.66	15.6	0.59	14.0	0.67	80.5	0.262	3130.4
	Avg	0.60	8.11	0.25	7.94	0.48	71.41	0.09	1085.92

Notes: Ag – agricultural land, Ar – arable land, Fb – average size of field block, CN – average value of CN curve, Ero – potential water erosion, DM – Total Degradation according to UPOL model and Sdr – surface drainage in individual sub-basins.

T a b l e 2. Results of PCA analysis for individual variables.

	Dependency	Code	Čížina – weight	Kyjovka – weight
Percentage of agricultural land	:-)	Ag	15.1%	17.8%
Percentage of arable land	:-)	Ar	18.5%	17.4%
Average size of fields in ha (arable)	:-)	Fb	10.8%	9.4%
Soil degradation (UP model)	:-)	DM	13.5%	11.6%
CN curve	:-)	CN	14.1%	10.5%
Potential water erosion in t/ha/yr	:-)	Ero	10.9%	23.7%
Melioration data - surface drainage	:-)	Sdr	17.1%	9.6%

In the Kyjovka basin, the most important factor is clearly potential water erosion (W_{Ero} = 23.7%). Detailed results for all the factors are summarized in Table 2.

In the catchment area of Čížina, the worst sub-basin is 2-02-01-074 with IC = 0.87 and the values of the most important factors Ar = 59% (worst among the sub-basins) and Sdr = 23% (2nd worst among the sub-basins). In the catchment area of Kyjovka, the worst sub-basin is 4-17-01-076 with an IC = 0.73 and the most significant ERO = 32.3 t/ha/yr (worst among sub-basins) and Ag = 73% (12th worst among sub-basins). The graphical representation of the resulting IC values for each river basin is shown in Figures 2 and 3.

Discussion and conclusion

The aim of our research was to propose suitable and easily accessible indicators, which determine or affect degradation of the agricultural landscape, with an emphasis on water retention. On the basis of these indicators, it should be possible to identify the most problematic areas at the level of 4th order river basin. Another objective was to choose a suitable method of processing which would reflect the importance of indicators in terms of their spatial distribution pattern. The results of processing are weights showing the importance of indicators for the studied research topic.

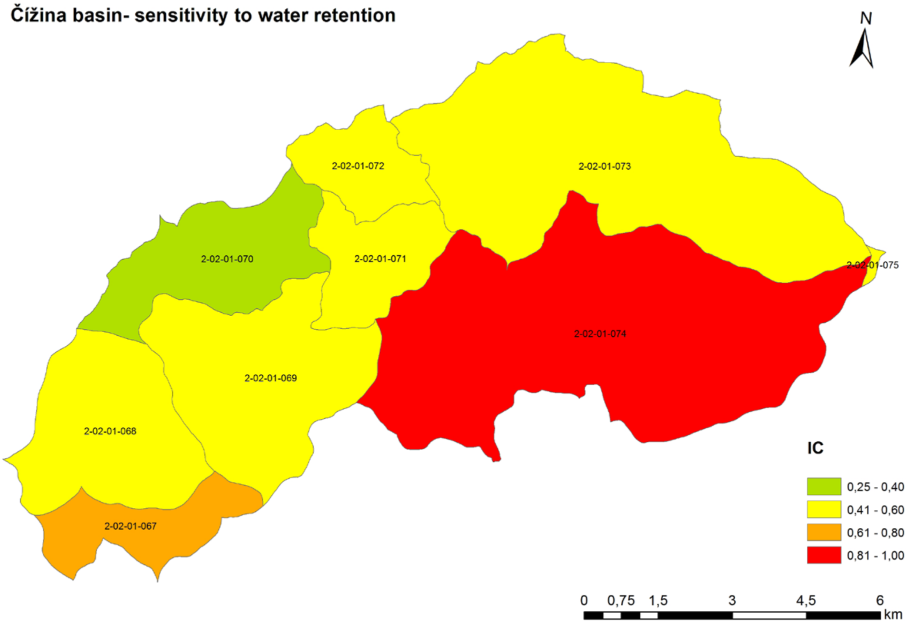

Fig. 2. Sensitivity of the 4th order of the Čížina River Sub-basins to land degradation with the emphasis on water retention.

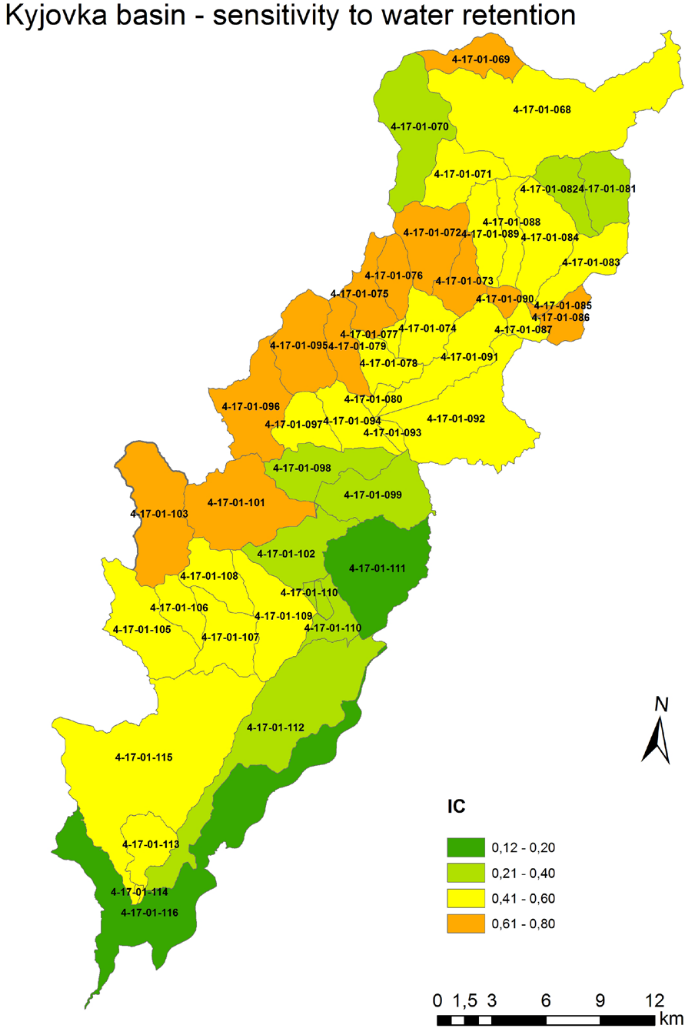

Fig. 3. Sensitivity of the 4th order of the Kyjovka Sub-basins to land degradation with the emphasis on water retention.

There are a number of methods of selecting indicators that affect water retention in the landscape at the level of individual sites. Geroy et al. (2011) studied retention with selected soil characteristics, which they investigated in relation to morphometric parameters of the landscape, especially aspect. Krnáčová et al. (2016) developed an algorithm that can indirectly derive the hydro-limits of soils from the soil ecological unit classification system used in Slovakia. In the Czech Republic, the method of CN curves is often used to analyse the

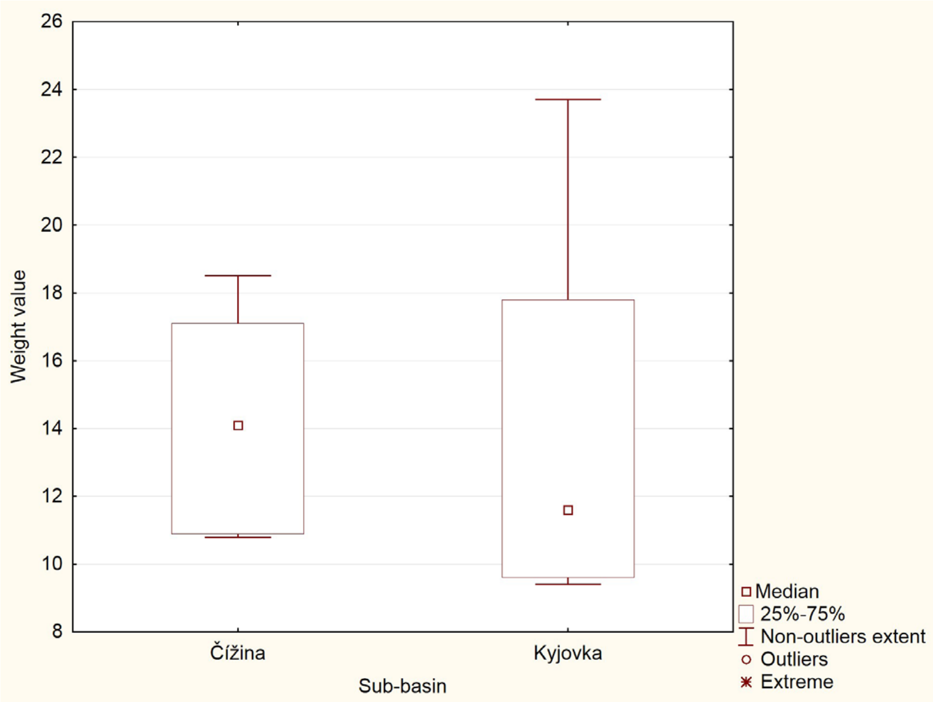

Fig. 4. Comparison of weight distribution between Čížina and Kyjovka basins.

retention capacity of the landscape. Based on the combination of the hydrologic group of soils and land use, this can determine the water retention capacity of the studied area. Another approach may be to use rain-flow data in relation to water retention. Palát et al. (2013) use multidimensional statistics tools to derive the relationship of retention characteristics to rainfall levels of the river basins.

The assessment of landscape degradation is elaborated by Salvati and Zitti (2005) who used several variables and indicators in the ESA Index (ESAI), including the assessment of climate, soil quality, vegetation cover and land management, taken as significant factors leading to land degradation. In other papers (Salvati et al., 2009, 2011), the authors describe a multivariate approach to derive the weights to be assigned to each selected indicator. The resulting Multivariate Soil Degradation Vulnerability Index (MSDVI) provided an estimation of the level of land vulnerability by aggregating more indicators. Krnáčová and Krnáč (1995) used the method of factor analysis in conditions close to CZ conditions for the identification of significant factors of the ecosystem and their relationship to environmental variables.

A number of similar studies have been conducted in Mediterranean areas, notably MEDALUS – The Mediterranean Desertification and Land Use project, using the aforementioned four quality indicators to map different types of environmental sensitivity to desertification (Basso et al., 2000; Lavado Contador et al., 2009; Ladisa et al., 2010; Salvati, Bajocco, 2011; Jafari, R., Bakhshandehmehr, L., 2016). Under CZ conditions, the issue of degradation of agricultural land has been dealt with by Šarapatka and Bednář (2015), who created an aggregated index of the total degradation, which takes into account the influence of several key degradation factors.

In our research, we used a method similar to Salvati et al. (2011). The resulting weights of individual indicators were determined on the basis of PCA analysis, and then linearly converted into a single aggregate index expressing the area's sensitivity to degradation, and water retention in particular. The aim of our work was not to directly and specifically determine individual landscape areas with problematic retention and degradation loads, but the creation of a tool for the evaluation of smaller areas, which would capture relatively problematic areas, where a number of other methods and indicators can be used for detailed research.

The method of selection of problem areas was tested in the catchment areas of Čížina and Kyjovka. These river basins differ in size, flow, climatic conditions and pedogeographic conditions, but have a similar percentage of agricultural land, land block size, drainage area, and average CN curve size. The difference lies in the structure of agricultural land; in both cases, arable land prevails (83 and 66%), but more significantly in the case of Kyjovka. The opposite is the case with permanent grassland (33 and 7%), higher in Čížina. Most of the Kyjovka river basin is occupied by arable land, which occurs evenly throughout the basin except its northern part. During long periods of rainy weather, the retention capacity of soil and vegetation is exhausted, and the overwhelming majority of the precipitation flows off the surface. It is therefore not surprising that the most important factor computed by the method is potential water erosion, in the case of the Kyjovka, which reaches average values from 0.1 to 37 t/ha/yr.

The Boxplot diagram of weighing results (Fig. 4) shows a more or less even weight distribution of individual parameters in the catchment area of Čížina, where the weight of none of the parameters significantly exceeds the average value of 13%. It is a different case in Kyjovka, where factors with higher overall impact are more pronounced – mainly erosion, but also the share of agricultural and arable land. From this, we can assume that the number of individual cases, which, in the presence of higher values (47 sub-basins in Kyjovka compared with 9 in Čížina), can bring a more significant definition of decisive factors, is important in the application of the proposed method. In the areas identified by the proposed method, we are currently examining selected soil characteristics, from which it is possible to indirectly derive soil hydro-limits and propose specific remedial measures in the landscape.

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