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RATING OF WATERCOURSE BANK STABILITY THROUGH RIPARIAN HERBAL COMMUNITIES

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Abstract

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Riparian vegetation performs an important and irreplaceable role in the countryside. The paper deals with the stabilizing effect of herbal communities on the banks of watercourse Breznický potok in geomorphological unit Kremnické vrchy (Central Slovakia). We analyzed the relationships between the vegetation coverage VEG % (%) and factor of stability (F_s) which was computed according to Bank Stability and Toe Erosion Model (BSTEM) on experimental banks. We also analyzed the relationships between VEG % (%) and BEHI (Bank Erosion Hazard Index). The value of aditional cohesion c_r was calculated by RipRoot Model in BSTEM for present vegetation. The research was conducted on 20 experimental sections with 20 experimental profiles with the presented vegetation coverage (%) based on the detected percentage of grass and herbaceous on the riparian banks. The calculated results of F_s were evaluated in accordance with existing erosion damages of experimental banks which were determined in the terrain through visual classification. Research has shown a strong correlation between vegetation cover of bank VEG % and a stability factor F_s (correlation coefficient Iyx = 0.976) and between VEG % and BEHI (Iyx = 0.956). Data according to BEHI and BSTEM show similar results (Iyx = 0.912). The results were statistically tested.

Keywords: riparian vegetation, torrent, factor of stability, RipRoot model, BSTEM

INTRODUCTION

An essential component of a balanced countryside is natural riparian vegetation also perceived as a natural stabilizing linear corridor along the watercourses (WTC) and other water areas. The riparian vegetation and their categorization is determined through their effects, properties and functions in riparian parts of WTC and countryside. Many authors confirmed the positive significance of vegetation in various papers, in terms of its impact on the stability of watercourses and water reservoirs banks Valtýni (1981), Wu (1984), Valtýni and Jakubis (2000), Bennett and Simon (2004), Wynn (2004), Wynn and Mostaghimi (2004, 2006), Jakubisová (2011), Šlezingr (2009), Bugala and Pitner (2010), Yang *et al.* (2014) etc. The stabilization function in the countryside is only one of the functions which has riparian vegetation along the banks of WTC. Vegetation as a natural part of the banks of WTC has a positive impact for their stability and increases the degree of their protection before erosion. Additional positive effects include, for example: landslides control, infiltration of surface water into the soil, filtration of inflowing surface water, water level shielding and reduction of evaporation; reduction of deflation impact; biodiversity enhancing; aesthetic and recreational effects in the landscape etc.

MATERIAL AND METHODS

The aim of this paper is evaluation of the stabilization effect of herbal vegetation (grass – herbaceous) with its different coverage of the WTC banks. The effect of vegetation reinforcement is based in assessment of real bank erosion. Quantification of the stabilizing effect of grass-herbaceous vegetation on WTC can be calculated through additional cohesion (cr) according to Rip-Root Model within Bank Stability and Toe Erosion Model – BSTEM (Simon *et al.*, 2009, 2011). This quantification has great importance in the landscape management with an emphasis on utilizing of the natural properties of vegetation and erosion control of WTC beds. Measured and calculated data also have use for practical management and forecasting of potential erosion damages on the banks of watercourses.

With the issue of vegetation and stability on the banks of WTC dealt Abernethy and Rutherford (2000). They identified the critical zone where vegetation brings the greatest effect and reducing streambank erosion. Micheli and Kirchner (2002a) investigated the effect of herbal – grass vegetation on stability of the banks of WTC and mechanical damages of meandering stream in the mountain stream banks. They measured the effect of wet meadow vegetation on the bank strength and failure mechanics of a meandering montane meadow stream, in California's Sierra Nevada. Banks of watercourses colonized by wet meadow vegetation were on average five times stronger than those colonized by dry xeric meadow and scrubs vegetation. Their measurements show that strengt of the streambank correlates with vegetation density indicators, including stem counts, standing biomass per unit area, and the ratio of root mass to soil mass. Easson and Yarbrough (2002) found that consolidating soil through the rooted vegetation is manifested significantly greater in cohesive soils than in non-cohesive. Other authors looked at the influence of riparian vegetation on the morphological characteristics of the river beds, especially in connection with changes of their widths such as Murgatroyd and Ternan (1983), Beeson and Doyle (1995), Trimble (1997) *etc*. Valtýni and Jakubis (2000) analyzed the relationships between the sites conditions of riparian vegetation in context with hydraulic characteristics of stream channel. The issue of vegetation effect in the interest of soil protection and its stabilization is very extensive because on different place and at different time are present various factors that may affect on the results of research within the meaning of potential controversial data and arguments. By examining of mechanical and biological properties of vegetation, using the knowledge of mathematical modeling were developed methods to determination of soil – protective effect of vegetation. The models were developed through the knowledge from different scientific disciplines by several authors such as Pfankuch (1975), Rosgen and Silvey (1996), Composite authors (2007), Simon *et al.* (2009, 2011) and through with their practical experience. Simon *et al.* (2009) proposed a comprehensive methodology of Rip Root model, relying on the most recent interdisciplinary knowledge for determination of stabilization effect of vegetation root systems with the use of their mechanical and biological properties. The authors define the value "c_r" as the additional reinforcement (or additional cohesion) of banks according to of calculated additional reinforcement of the banks through vegetation root system. Methodology fundamentals began to form Thorne (1990), Gray and Leiser (1982), Wu (1984). They have been performed field and laboratory experiments in special soil boxes in which were quantified the forces needed to disengaging of roots from soil. Wu *et al.* (1979) developed a widely-used equation that estimates the increase in soil strength (c_r) as a function of root tensile strength (T_r), areal density and root distortion during shear:

$$c_r = \frac{1}{A}\sum_{n=1}^{n=N}(A_r T_r)_n\left[\sin(90-\zeta)+\cos(90-\zeta)\tan\phi'\right] \quad (1)$$

where:
c_r....... cohesion due to roots (kPa)
A ...... area of the shear surface (m^2)
A_r ..... area of roots in the plane of the shear surface (m^2);
T_r...... tensile strength of roots (kPa);
ϕ'....... friction angle of soil (°)
N ...... total number of roots crossing the shear plane
n .... n^{th} root
ζ........ the variable:

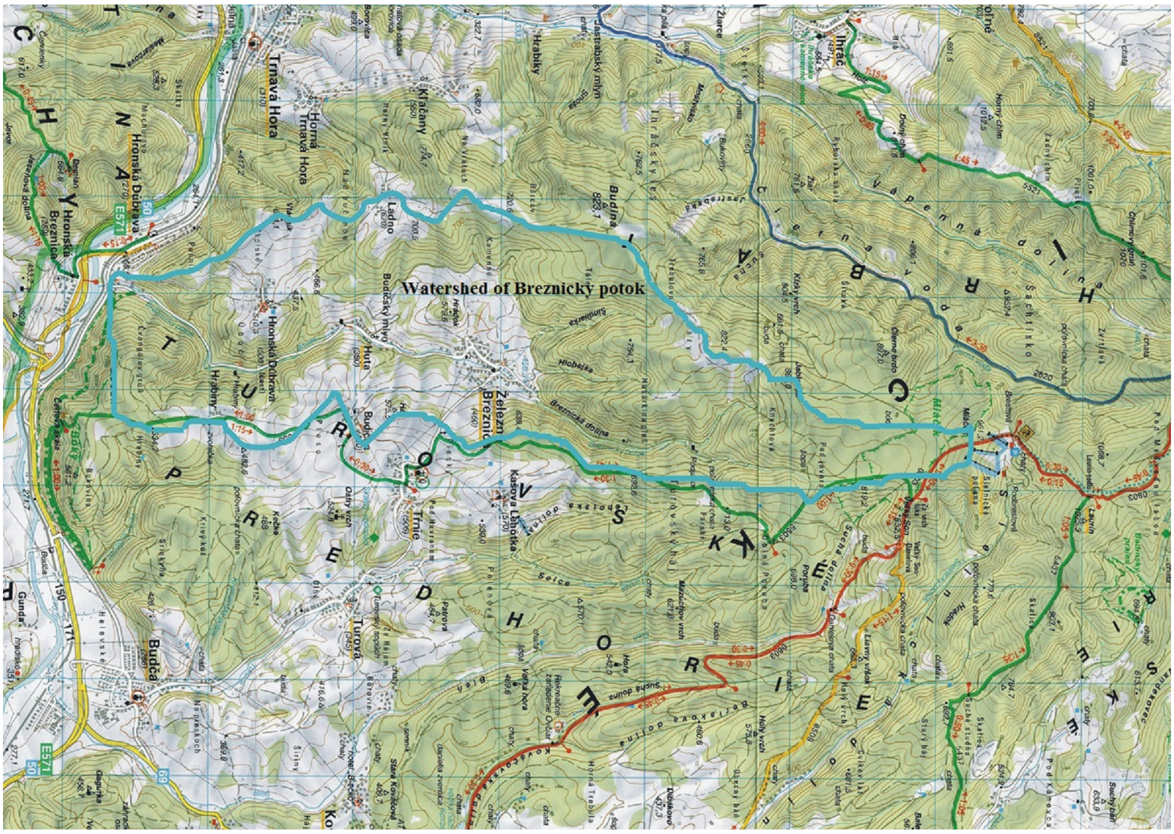
$$\xi = \tan^{-1}\left(\frac{1}{\tan\theta+\cot\chi}\right) \quad (2)$$

where:
θ........ angle of shear distortion (°);
χ........ initial orientation angle of fiber relative to the failure plane (°).

Pollen *et al.* (2004), Pollen and Simon (2005) found that models based on Equation (1) tend to overestimate root reinforcement because it is assumed that the full tensile strength of each root is mobilized during soil shearing and that the roots all break simultaneously. This overestimation was largely corrected by Pollen and Simon (2005) by developing a fiber-bundle model (RipRoot) to account for progressive breaking during mass failure. Validation of RipRoot versus the perpendicular model of Wu *et al.* (1979) was carried out by comparing results of root-permeated and non-root-permeated direct-shear tests. These tests revealed that accuracy was improved by an order of magnitude by using RipRoot estimates, but some error still exists by the authors Pollen and Simon (2005).

Characteristic of experimental watershed and torrent of Breznický potok, the field measurements

The research was conducted on torrent of Breznický potok in geomorphological unit Kremnické vrchy, subunits Flochovský chrbát and Turovské predhorie (in Central Slovakia, watershed



1: *Watershed boundary of Breznický potok*
Source: own elaborate

boundary see Fig. 1). The experimental watershed of Breznický potok belongs to the main basin of river Hron. Breznický potok has the hydrologic number of 4-23-04-026; the coefficient of torrent activity 0.191; the catchment area 23.50 km^2; the forest area in the watershed 16.92 km^2; the forest coverage in the watershed 72.00 %; the average annual precipitation in the watershed 905 mm; the average annual evaporation 448 mm; the average annual temperature 5.9 °C; the length of the main watercourse (from the riverhead to the closed discharge profile) 12,500 km; the length of the tributaries 17,280 km; density of the watercourses in watershed 1.27 km/km^2; maximum altitude of the watercourse 819 m a. s. l.; maximum altitude of the watershed 960 m a.s.l.; minimum altitude of the watershed and watercourse 275 m a.s.l.; the mean altitude of the watershed 595 m a.s.l.; the absolute difference of altitudes of the watercourse 544 m; the absolute difference of altitudes 685 m in watershed; the mean longitudinal gradient of the watercourse 4.35 %; the mean gradient of the thalweg 5.11 %; the mean slope of the banks in the watershed 27.11 %; the ratio of tree species is 75 % deciduous and 25 % coniferous in the basin.

We have established 20 experimental sections (ES) with 20 experimental discharge profiles (EP) in a straight sections on the banks with various characteristics of slopes and with various coverage grass – herbaceous vegetation. We obtained the necessary data through geodetic measurements (leveling) for delineation of geometric characteristics of the experimental dicharge profiles (EP) and ES on the slopes of banks. We also delineated the ground plan of EP with dimensionals: LES x Y (m); where LES – 10 m (length of ES); Y – total inclined width of the bank with delineation of vegetation surface coverage to determination of percentage cover by vegetation (VEG %). There were identified the species of herb and grass for every EP subsequently.

In office were delineated the EP to scale 1:100. From a graphic materials we have set gradients of slopes and hights for all of EP . All of the geometric characteristics were determined in relation to bankfull discharge.

The measured, calculated and determined characteristics have been used as an input data for the calculation of the stability factor (F_s) by BSTEM (see Tab. I) and additional cohesion (c_r) by RipRoot of model taking into account the identified hydrophilic communities with following representation: *Chaerophyllum hirsutum, Caltha palustris, Brachypodium sylvaticum, Rubus hirtus, Crepis paludosa, Galeobdolon luteum, Ajuga reptans, Oxalis acetosela, Impatiens noli-tangere, Galeopsis speciosa, Stachys sylvatica, Stelaria nemorum, Aegopodium podagraria, Rubus fruticosus, Lysimachia vulgaris, Urtica dioica, Chrysosplenium alternifolium, Glechoma hederacea,* I: *Classification of stability factor (F_s) according to BSTEM*

F_s	>1.3	1.0–1.3	<1.0
Degree of bank stability	S	RS	U

Explanatory notes to Tab. 1: F_s – factor of stability, Degree of stability: S – Stable, RS – Relatively Stable, U – Unstable

II: *Terrain Classification (TC) to quantification of degrees stream-bank erosion damages*

Degree of erosion	Terrain Classification (TC), scale to quantify of degree of erosion damages on the watercourse banks
S [1]	The banks of watercourse without visible erosive faults and damages, the toe of the bank is stable, significant stabilizing effect of riparian vegetation on the whole area.
VL [1.5]	Less erosive faults and damages on the slope, up to 15 % mainly in the toe; above the toe the significant stabilizing effect riparian vegetation.
L [2]	Erosive faults and damages on the slope 16–30 %; slight erosive-damages on longitudinal slope of the bank, without signs of lateral erosion; on the most part of slope the reinforcing effect of riparian vegetation.
M [2.5]	Erosive faults and damages on the slope 31–50 %; clear signs of longitudinal and lateral erosion; on the toe clear signs of erosion and temporarily accumulated the material at the bottom of the bed; vegetation more prevalent in the upper parts; the average (medium) reinforcement of riparian vegetation.
H [3]	Erosive faults and damages on the slope 51–70 %; clear signs of longitudinal and lateral erosion; on the toe the clear signs of intensive erosion and temporarily accumulated material at the bottom and over it; without retreating of basal layer, without the undermined upper layer; with low anti-erosion effect of bank vegetation.
VH [3.5]	Erosive faults and damages on the slope 71–90 %; predominant erosion in longitudinal and lateral direction on the bank; riparian erosive faults with of undermined upper layer; without the upper layer fall; slope of the bank < 90°; the bank vegetation with a very low anti-erosion effect.
E [4]	Erosive faults and damages on the bank more than 90 %, visible riparian erosive faults and damages; rotational failure of surface, overhang generated on upper bank; slope of the bank > 90°; the extremly erosion in longitudinal and lateral direction; without occurrence of vegetation protection

Explanatory notes to Tab. 2: Degree of erosion: S – stable, VL – very low, L – low, M – middle, H – high, VH – very high, E – extreme, TC – terrain classification
Source: own elaborate

III: *Classification scale of BEHI by* Rosgen *(1996)*

BEHI (Scale)	Degree of erosion
5–9.5	VL
10–19.5	L
20–29.5	M
30–39.5	H
40–45.0	VH
46–50.0	E

Explanatory notes to Tab. III: BEHI – Bank Erosion Hazard Index, D_{sBEHI} – degrees of bank stability by classification BEHI: VL – very low, L – low, M – middle, H – high, VH – very high, E – extreme

Filipendula ulmaria, Solanum dulcamara, Geum rivale, Stelaria holostea, Poa nemoralis, Daucus carota, Juncus conglomeratus, Scirpus sylvaticus.

For the clarification is noted that all of these and similar species are in the RipRoot model summarized as under the name wet meadow vegetation. We have determined the actual degree of erosion damages on the experimental banks (see Tab. II) according to our "Terrain Classification (TC) to quantification of degrees stream-bank erosion damages".

The following values were quantified by the software: additional cohesion (c_r) through RipRoot model, factor of stability (F_s) by BSTEM and real degree of damage through visual assessment in terrain (see TC in Tab. IV. of Results and

IV: *Data of grass-herbaceous vegetation coverage, additional cohesion, factor of stability, degrees of erosion according to BEHI, BSTEM and TC*

No. RS	RL [km]	$VEG_{\%}/B_S$ [%]	D_{root} [m]	BEHI [-]	c_r [kPa]	BSTEM [-]	TC [-]
1P	1.97	77/23	0.50	20.3/M	0.9	4.35/S	2/L
2L	1.97	72/28	0.50	20.5/M	0.8	3.81/S	2/L
3L	2.20	68/32	0.50	18.2/L	0.8	3.22/S	2.5/M
4L	2.30	64/36	0.50	23.4/M	1.0	3.32/S	2.5/M
5P	2.50	70/30	0.50	21.1/M	0.8	3.25/S	2/L
6L	2.55	61/39	0.40	24.5/M	0.7	2.91/S	2.5/M
7L	2.60	60/40	0.40	21.5/M	0.7	2.83/S	2.5/M
8L	2.78	45/55	0.50	26.3/M	0.9	1.85/S	3/H
9L	2.85	47/53	0.30	27.7/M	1.3	1.97/S	3/H
10P	2.95	41/59	0.30	27.7/M	1.5	1.61/S	3/H
11P	3.15	40/60	0.65	27.8/M	0.1	1.95/S	3/H
12L	3.15	30/70	0.45	29.1/M	0.1	0.98/U	3/H
13P	3.35	23/77	0.20	32.9/H	0.0	0.95/U	3.5/VH
14L	3.35	20/80	0.30	31.5/H	0.0	0.62/U	3.5/VH
15L	3.65	20/80	0.25	32.5/H	0.0	0.55/U	3.5/VH
16P	3.65	14/86	0.20	37.0/H	0.0	0.81/U	3.5/VH
17L	3.80	13/87	0.20	34.7/H	0.0	0.63/U	3.5/VH
18P	3.80	10/90	0.10	40.7/VH	0.0	0.72/U	3.5/VH
19L	4.05	9/91	0.20	40.6/VH	0.0	0.55/U	4/E
20P	4.05	8/92	0.10	42.7/VH	0.0	0.46/U	4/E

Explanatory notes to Tab. IV: No. RS – number of the reference section, L – left bank, P – right bank, RL – river log [km], $VEG_{\%}$ – banks with cover vegetation [%], B_S – banks without cover vegetation [%], D_{root} – depth of roots [m], c_r – additional cohesion [kPa], BEHI – index of erosion by BEHI (Bank Erosion Hazard Index), BSTEM – value of stability factor by BSTEM (Bank Stability and Toe Erosion Model), TC – degree of erosion by classification in terrain, Degree of stability: S – Stable, U – Unstable, Degree of erosion: VL – Very Low, L – Low , M – Middle, H – High, VH – Very High, Extreme (E), [-] – dimensionless number

Discussion). The results of F_s calculated by BSTEM were compared according to methodology of Bank Erosion Hazard Index – BEHI by the author Rosgen (1996), see Tab. III.

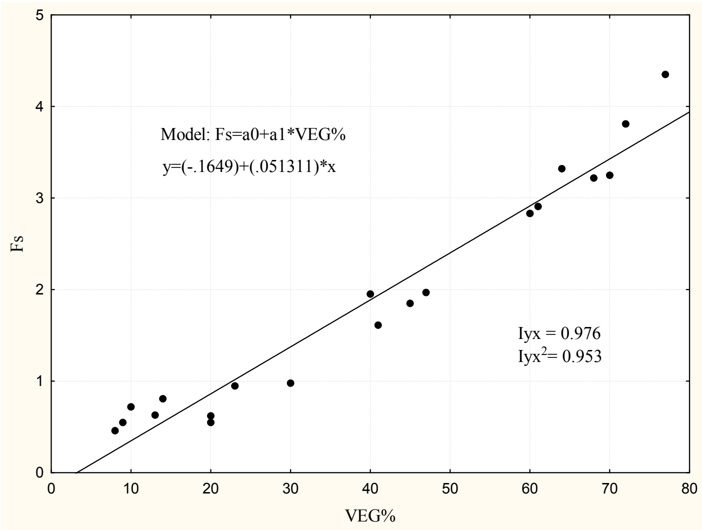
Data and methodology of BEHI have been published in a separate work by the author Jakubisová (2011). The results of each method are shown in Tab. IV.

RESULTS AND DISCUSSION

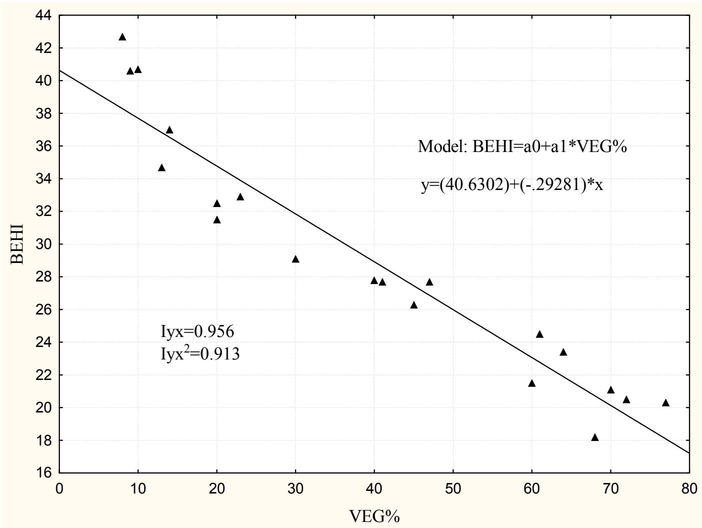
According to our results, we can confirm that the grass-herbaceous community limits the degree of bank erosion in terms of increasing compactness of bank material through root systems, reduces the bank damages and also decreases the system of bank failures. We confirmed that with increasing density of grass-herbaceous vegetation on the banks of WTC, also with increases the percentage coverage increases the stability factor Fs, and thus increases the stabilizing effect of riparian vegetation through „wet meadow“ communities. The results are clearly documented in Tab. IV.

Calculated results of F_s according to BSTEM were compared with results of BEHI and TC (according to a new original visual classification). We have done a following graphical comparisons: relations between VEG % and Fs (see Fig. 2), VEG % and BEHI (see Fig. 3), VEG % and TC values (see Fig. 4), BEHI and Fs (see Fig. 5), TC values and Fs (see Fig. 6). The research showed a strong correlation between the range of surface coverage of the watercourse banks by vegetation and their following strengthening what show calculated values of additional cohesion cr (see Tab. IV) and the increasing factor of stability F_{sv} (see Fig. 2). The determined degrees of stability taking account vegetation coverage VEG %, corresponds very well with real state of erosion on ES which was found on the banks of WTC. It has been found the following statistical relationships: Fs = f (VEG %) with Iyx = 0.976 (correlation coefficient), BEHI = f (VEG %) with Iyx = 0.956, TC = f (VEG %) with Iyx = 0.967. At the same were for comparison analyzed relationships Fs = f (BEHI) and Fs = f (TC). Graphical representations of the relationships are in the Figs. 2–6.

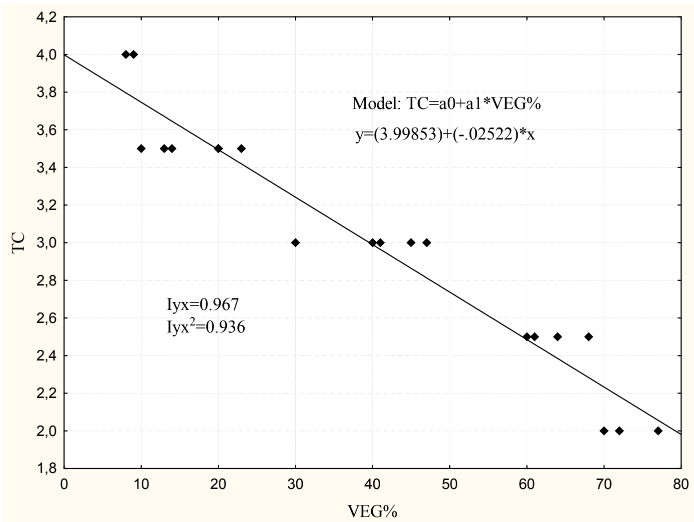
Correlation relationships were statistically tested (see Tab. V).



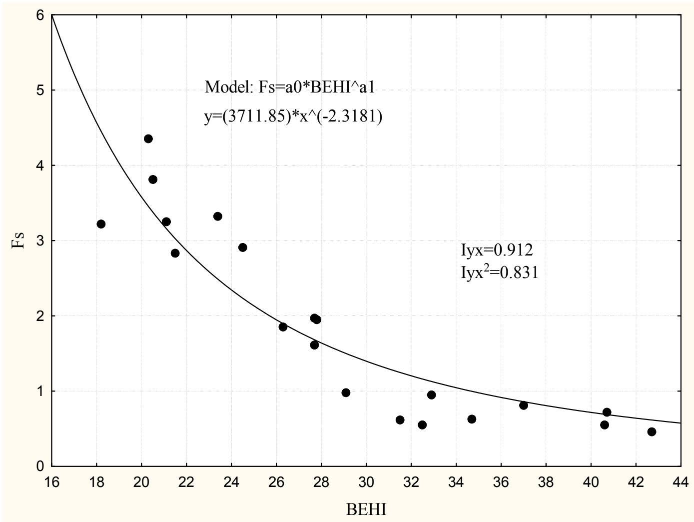
2: *Relation between VEG % and F_s*



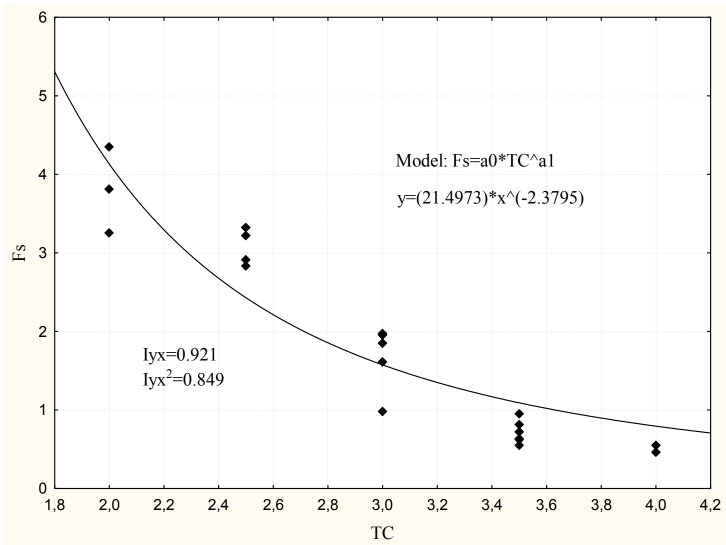
3: *Relation between VEG % and BEHI*



4: *Relation between VEG % and TC*



5: *Relation between BEHI and F_s*



6: *Relation between TC and F_s*

V: *Regression equations and statistical testing of examined relations*

Correlation relation	Regression equation	Iyx	Iyx²	S_R	t	> = <	$t_{0,01(18)}$
Fs = f (VEG %)	Fs = $a_{01} + a_1$*(VEG %) Fs = –0.1649 + 0.5131*(VEG %)	0.976	0.953	0.0511	19.10	>	2.878
BEHI=f(VEG %)	BEHI = $a_{02} + a_2$*(VEG %) BEHI = 40.6302 + 0.2928*(VEG %)	0.956	0.913	0.0695	13.76	>	2.878
TC=f (VEG %)	TC = $a_{03} + a_3$*(VEG %) TC = 3.9958 + (–0.0252)*(VEG %)	0.967	0.936	0.0596	16.22	>	2.878
Fs=f (BEHI)	$Q_K = a_{04}*(BEHI)^{a4}$ $Q_K = 3711.85*(BEHI)^{-2.3181}$	0.912	0.831	0.0969	9.41	>	2.878
Fs = f (TC)	$B = a_{05}*(TC)^{a5}$ $B = 21.4973*(TC)^{-2.3795}$	0.921	0.849	0.0916	10.05	>	2.878

I_{yx} – coefficient (index) of correlation, I_{yx}^2 – coefficient (index) of determination

$$SR = \sqrt{\frac{1 - I_{yx^2}}{n-2}}, \; t = \frac{I_{yx}}{s_R}$$

The measurements show that strength of the herbs vegetation on the streambank is correlated with vegetation density indicators, including stem counts, standing biomass per unit area, and the ratio of root mass to soil mass by the Micheli and Kirchner (2002b). They found wet meadow vegetation were on average five times stronger than those colonized by dry Xeric meadow and schrubs vegetation. Simon and Collison (2002) investigated the mechanical and hydrological impact of herbs riparian vegetation in connection with riverside reinforcement. They state that the mechanical effects of grassy-herbaceous community increases the level security of the banks up to 70 %. Yang and Duan (2014) tested the effect of herbs vegetation reinforcement on the banks in relation to discharge and sediment transport. They state that the resistance of soil particles in the sediment transport is a function of the density of vegetation on the streambank. A very important factor for the stability of the streambank has also the transverse slope which is also important foor the existence of riparian vegetation. Small transverse slope allows good growth of riparian vegetation. Existing vegetation has effects on gradient of the slope and through the root system increases resistance of banks against the erosion by the authors Valtýni *et al.* (1990). We took thoroughly into account the transverse slope in our calculations by methods BSTEM and BEHI.

In the USA, Markowitz, Newton (2011) and Dick *et al.* (2014) confirmed the relationship between annual erosion and BEHI index of the banks with natural riparian vegetation. Allmanová (2016) used the BEHI index of the banks with natural riparian vegetation to estimate the erosion rate on three watercourses in the Slovak Republic: Sestrč (Chočské vrchy mesoregion) the watershed area 25.68 km^2 (BEHI values ranged from 13.1 to 35.7), Lomnická rieka (Levočské vrchy mesoregion) the watershed area 10.94 km^2, (BEHI values ranged from 18.3 to 42.3) and Tŕstie (Biele Karpaty and Myjavská pahorkatina mesoregions) the watershed area 41.55 km^2 (BEHI values ranged from 11.1 to 40.7). Authoress confirmed correlation between annual erosion and BEHI index of the banks with natural riparian vegetation in investigated watercourses.

CONCLUSION

Importance of riparian vegetation in the countryside increases with regard to ecological solutions of strengthening the banks watercourses, also in the context of erodibility control, the sediments formation, their transport and accumulation. An essential component of a balanced countryside is the natural riparian vegetation, also perceived as a natural stabilizing linear corridor along the watercourses and other water areas. Through field research, we confirmed that the quantified results which were calculated considering methodology BSTEM and BEHI correspond with an actual erosion damages on the banks of watercourse Breznický potok. The research confirmed that herbal communities decreases the riparian erosion. At present the exploitation of riparian vegetation focused on a practical use of mitigation of deleterious influence of erosion, especially during of extreme hydrological situations, floods. Beside that the correct selection of stabilization measures with using herbal vegetation supports in riparian areas their stability and strengthens the natural habitat of countryside.

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