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IS THE BEHI INDEX (PART OF THE BANCS MODEL) GOOD FOR PREDICTION OF STREAMBANK EROSION?

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Abstract

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Sedimentation of waterways and reservoirs, decreasing quality of drinking water and costs necessary for maintenance of these objects directly related to streambank erosion. This study provides a tool for water management that can help with estimation parts of a streambank which are prone to erosion. The Bank erosion hazard index (BEHI) part of the BANCS (Bank Assessment for Non-point source Consequences of Sediment) model is one of the several procedures for assessing streambank erosion condition and potential (Rosgen, 2001). On May 15th 2014 a high precipitation occurred in the watershed of Sestrč torrent, in the eastern part of Chočské vrchy (Sp = 27.64 km^2). It reached 102.7 mm per 24 hours. The rainfall resulted in extreme streambank erosion. We started the research of annual stream bank erosion on Sestrč in the beginning of May 2014 and we established 19 experimental sections on the stream. Occurrence of heavy rainfall allowed us to erosion rates after flash flood. The aim of this paper was to verify, if BEHI index can really determine the most vulnerable parts of a banks to erosion. We measured erosion rates Eb (m^3/m) using a bank pins and toe pin (Sass, 2011) on each experimental section and evaluated each section by BEHI index (Rosgen, 2001, 2008). The results were statistically verified and confirmed a strong relationship between BEHI and real damage of banks Eb (m^3/m) (R: 0.88, R^2: 0.78).

Keywords: bank erosion, flood discharge, BANCS model, BEHI index

INTRODUCTION

The water flowing in a stream channel causes gradual separation of soil particles from the bank and their subsequent transport downstream. Intensity of bank erosion in natural (unpaved) streams depends on various factors, e.g. The type of bank material, bank slope, discharge level, presence or absence of vegetation on the bank, etc. Processes of erosion in torrent channels are the natural events connected with long-time development (morphogenesis) of such streams (Grešková, Lehotský 2006). According to Jakubis (2007), widening of scientific knowledge about morphogenesis of natural water streams is important because of two contradictory reasons: (i) importance of torrents for man, stability of adjacent ecosystems, natural and living environment, and as a source of drinking water; (ii) the possibility of flash floods and erosion processes adjacent to the torrent.

Previous studies indicate that bank erosion rates may exceed 50 % (Pollen *et al.* 2004) and sometimes reach 80 % (Rosgen 2002) from total annual soil erosion rates in watershed. Monitoring and modeling techniques to assess the contribution of channel sediment to overall sediment load are needed to determine the reductions necessary to meet water quaity standards (Ramírez – Avilla, *et al.*, 2010). Results of monitoring can help with evaluation and prediction of channel stability, provide information for riparian habitat management and assess priorities for restoration of channels (Kwan & Swanson, 2013).

The phenomenon of stream bank erosion was surveyed by many authors (Lawer *et al.*, 1999; Laubel *et al.*, 1999; Haniman 2009; Midgley *et al.*, 2012). One of the possible approaches to estimation or prediction of the erosion of stream banks is through the BANCS model. the model allows to create erosion prediction curves and to predict annual erosion rates of the banks. Rosgen (2001, 2006) developed these curves for the Colorado and Yellowstone regions. Van Eps *et al.* (2004) and Sass, Keane (2012) developed prediction curves for other regions on the basis of the BANCS model. The model consists of two indexes – the BEHI (Bank Erodibility Hazard Index) and the NBS (Near Bank Stress). Calculation of BEHI is a process of evaluation the susceptibility of a bank to erosion, using known variables that affect bank erosion rates. The BANCS model and the BEHI index and their use for estimation of the erosion were investigated by Rosgen (1996, 2001, 2006, 2008), Van Eps *et al.* (2005), Sass, Keane (2012), McQueen *et al.* (2013), Bandyopadhyay *et al.* (2013), and by Jakubis (2010) or Jakubisová (2009, 2010, 2014) in Slovakia. Their research was focused mainly on the sedimentation processes in drinking water reservoirs and the water quality. This study was focused on evaluating the suitability of the BEHI index for torrents on limestone bedrock, loamy soils, slope, and mode of use of the area of the watershed.

MATERIALS AND METHODS

On 15th of May 2014 a high precipitation occurred in the watershed of Sestrč torrent. The precipitation reached 102.7 mm per 24 hours, affected whole watershed area and resulted to discharges which caused extreme bank erosion. We estimated rainfall using the data about the 24 h precipitation on 15th of May 2014 from six nearest precipitation gauge stations. We calculated precipitation for Sestrč torrent watershed according the relation between altitude of gauge station and recorded precipitation in these stations. We created the equation for average altitude of Sestrč watershed:

$$Z = -19.273 + 0.132 \times 924 = 102.69 \text{ mm} \quad (1)$$

Heinige *et al.*, (1995) published maximum daily precipitation values which occurrence probability in average is once per every N years. We chose four nearest places to the watershed and estimated N = 100 precipitation for average altitude of watershed (924 m.n m) and calculated following equation:

$$N_{100} \text{ daily precipitation} = 67.5309 + 0.0307 \times 924 = 95.87 \text{ mm} \quad (2)$$

The real precipitation which occurred on May 15th was 102.7 mm. Hence it is possible to state, that it was an extreme precipitation, which occurrence probability in average is lower than 1 time per 100 years.

Study area

The watershed of Sestrč torrent is situated in the eastern part of Chočské vrchy mountain ridge, between Sielnické vrchy and Prosečné crests.

Sestrč torrent stems near Malatiná village under Grúň hill, with elevation of 896 m. The most important data about the stream are as follows: watershed area Sp = 27.64 km^2, forest cover of basin 15.13 km^2 (l = 54.76 %), grassland and shrubs: 5.89 km^2, meadows: 4.05 km^2, cultivated land: 1.75 km^2, urban areas: 0.57 km^2, other: 0.27 km^2, length of main channel L = 12.7 km, length of tributaries L_p = 20.1 km, stream network density r = 1.18 km.km^{-2}. Sestrč torrent flows into Liptovská Mara reservoir near Bobrovník village. The most important left side tributary, Annin potok, flows into the Sestrč near Liptovská Anna village. Geologically the watershed consist of limestone strata and grey dolomites. In terms of soil texture, the most frequent are loamy soils (80 %), clay-loam

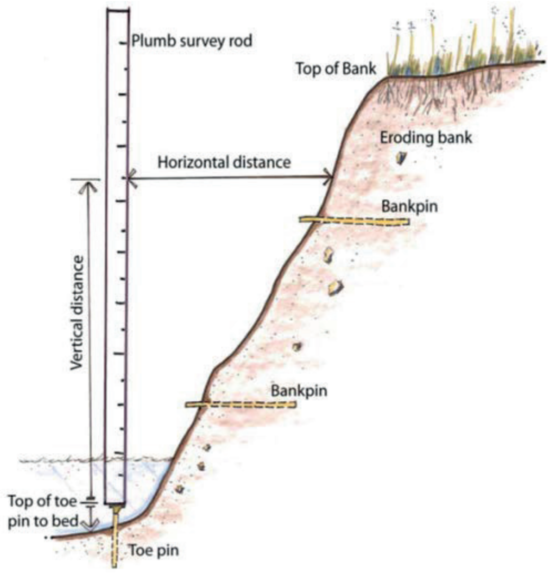
1: *Localization of the experimental sections on Sestrč stream* soils (20 %) with medium permeability and medium retention capacity. The most frequent soil types are Rendzic, Eutric Cambisols, Distric Cambisols, Stagni Cambisols and the Rendzic Leptosols. The watershed is situated in cold climate area (C) and subarea (C_1), moderately cold and moderately wet. Temperatures in January vary between -3 and -6 °C and between 12 to 16 °C in July. Average annual precipitation is 800 to 1000 mm, calculated torrent coefficient $K_b = 0.31$, meaning a moderately strong torrent. Length of the watershed divide O = 26.75 km, length of thalweg L_u =12.96 km, mean width of the basin B_p = 2.14 km, absolute gradient of stream ΔH_t = 326.6 m, absolute gradient of basin ΔH_{pov} = 708 m, slope of the thalweg I_u = 2.94 %, the mean slope of basin I_s = 13.47 %, average slope of the stream It= 2.57 %, average altitude of watershed $ØH_{pov}$ = 924 m above the sea level. Discharges are as follows: Q_{100} = 15.05 $m^3.s^{-1}$, Q_{50} = 12.64 $m^3.s^{-1}$ and Q_1 = 2.26 $m^3.s^{-1}$, Q_a = 0.39 $m^3.s^{-1}$. The above mentioned discharges were calculated according to regional dependence and maximal specific runoff - $q_{max \times 100}$ (2), where we used regional coefficients (B = 2.20, n = 0.409) and watershed area a (km^2). Then we calculated $Q_{max \times 100}$ multiplying $q_{max \times 100}$ by watershed area a (km^2) (OTN ŽP 3112-1:0). Calculated $Q_{max \times 100}$ was modified according to forest cover of watershed and shape of the watershed, where we used correction coefficients (o_1 and o_2) from Otto Dub (Binder, 1969). We calculated Q_a = 0.39 $m^3.s^{-1}$ according (Szologay *et al.*, 1997).

$$q_{max \times 100} = B\,(A + 1)^{-n}\ (m^3 \times s^{-1} \times km^{-2}) \quad (3)$$

Experimental design

In May 2014, we established 19 experimental sections (ES) of Sestrč torrent (Fig.1, Tab.I) in order to quantify the annual erosion rate using the BEHI index of the BANCS model and tested its accuracy. a few days after established experimental sections heavy rainfall in watershed occurred. The rainfall resulted in extreme streambank erosion and we verified, if BEHI index can really determine the most vulnerable parts of a banks to erosion an if the highest values of BEHI index indicate highest erosion rates. The total length of the ES was 312 m (2.46 % of the total length of the main channel). We selected the locality of the ES so that the ES length distribution in bent and straight sections was roughly the same. The total length of ES in bends was 142 m (1.12 % of the length of the main channel) and the total length of the straight sections was 170 m (1.34 % of the length of the main channel).

On the established ES, we chose and localized cross sections (CS), where we inserted steel pin (length 500 mm; diameter 20 mm) vertically into the stream bed at the toe of the bank (toe pin). Two other pins were inserted horizontally into the banks (bank pins) according to Sass (2011). The toe pin was localized with a GPS device. We placed the plumb survey rod vertically on the top of the toe pin and measured horizontal distances from the rod to the surface of the bank (Fig. 2) in various vertical distances from the top of the toe pin. Repeated measurements (after the heavy precipitation) of the horizontal distances in the same heights allowed us to quantify the erosion rates through the calculation of the eroded area in the cross section of the channel (S_E) We used the Home Plane software to determine the area of S_E. Subsequently we calculated the volume of eroded soil per 1 m (E_b) of length of the experimental section. The data we gathered enabled verification of the ability of BEHI index to predict bank erosion in given natural conditions.



2: *Bank profile example and measures. Toe pin is used as a control point at the bottom of the bank, vertical and horizontal distances are taken from toe pin to face of bank (Sass & Keane, 2012).*

The methodology of BEHI calculation was published in detail by Rosgen (1996, 2001, 2008, 2009). For calculation of BEHI, we measured the following variables: bank height (H), bankfull height (h), rooting depth (Hk), bank angle (α). We assessed visually the: surface protection (P_{VEG}) as a percentage of ES covered by vegetation or material which can protect bank before erosion (boulders, woody debris) and rooting density (K) according to (Rosgen, 2008, 2009). This procedure is described in detail in U.S: Fish & Wildlife Service.

(http://dnr2.maryland.gov/streams/Documents/ /2013TFTraining_BANCS_Davis.pdf).

To determine the BEHI score, we calculated five ratios of the measured variables: Bank height/ Bankfull height, Root depth/Bank height, Weighted root density, Bank angle, and Surface protection (marked as **value** in Tab. II). We assigned mark in range of 1 to 10 for every ratio using a nomograms

I: *Basic information about the experimental sections (ES) and measured erosion Eb*

	Distance from the mouth of the watershed(km)	Altitude(m.n.m)	GPS coordinates	Length of ES(m)	ES localization
ES1	1,23	579	49°07′72.0″N, 19°28′59.7″E	15	P
ES2	1,39	583	49°07′80.2″N, 19°28′59.1″E	15	O
ES3	1,45	586	49°07′84.0″N, 19°28′61.1″E	15	P
ES4	2,98	613	49°08′41.1″N, 19°27′74.1″E	15	P
ES5	3,05	617	49°08′41.0″N, 19°27′67.7″E	15	O
ES6	3,12	618	49°08′42.7″N, 19°27′62.5″E	20	O
ES7	3,28	624	49°08′43.8″N, 19°27′49.9″E	20	O
ES8	3,40	625	49°08′45.1″N, 19°27′40.3″E	20	O
ES9	3,43	626	49°08′44.4″N, 19°27′37.4″E	15	P
ES10	3,51	627	49°08′47.0″N, 19°27′21.1″E	20	O
ES11	3,59	627	49°08′46.4″N, 19°27′26.1″E	15	P
ES12	3,74	629	49°08′48.3″N, 19°27′13.6″E	15	P
ES13	3,90	635	49°08′51.8″N, 19°26′93.9″E	15	P
ES14	4,0	635	49°08′51.7″N, 19°26′93.9″E	16	O
ES15	4,11	636	49°08′56.4″N, 19°26′87.7″E	15	P
ES16	4,18	639	49°08′51.9″N, 19°26′93.7″E	15	P
ES17	4,35	655	49°08′62.6″N, 19°26′71.9″E	16	O
ES18	4,58	668	49°08′70.9″N, 19°26′58.7″E	15	P
ES19	4,63	676	49°08′73.3″N, 19°26′56.5″E	20	P

ES = experimental section, L_{ES} = length of experimental section, P = straight section, O = bend

II: *General estimation of the BEHI index for all water streams (Rosgen 2001, 2008, 2009)*

		Category of BEHI index					
Input data		**Very Low**	**Low**	**Medium**	**High**	**Very High**	**Extreme**
Bank height/ Bankfull height	Value	1.0–1.1	1.11–1.19	1.2–1.5	1.6–2.0	2.1–2.8	> 2.8
	Index	1.0–1.9	2.0–3.9	4.0–5.9	6.0–7.9	8.0–9.0	10
Root depth/ Bank height	Value	1.0–0.9	0.89–0.5	0.49–0.3	0.29–0.15	0.14–0.05	< 0.05
	Index	1.0–1.9	2.0–3.9	4.0–5.9	6.0–7.9	8.0–9.0	10
Weighted root density	Value	100–80	79–55	54–30	29–15	14–5.0	< 5.0
	Index	1.0–1.9	2.0–3.9	4.0–5.9	6.0–7.9	8.0–9.0	10
Bank angle	Value	0–20	21–60	61–80	81–90	91–119	> 119
	Index	1.0–1.9	2.0–3.9	4.0–5.9	6.0–7.9	8.0–9.0	10
Surface protection	Value	100–80	79–55	54–30	29–15	14–10	< 10
	Index	1.0–1.9	2.0–3.9	4.0–5.9	6.0–7.9	8.0–9.0	10

III: *Category of BEHI index according to the BEHI score (Rosgen 2001, 2008, 2009)*

Total BEHI score	**Very Low**	**Low**	**Medium**	**High**	**Very High**	**Extreme**
	5–9.9	10–19.9	20–29.9	30–39.9	40–45	45.1–50

IV: *Assessment of individual experimental sections through the BEHI index*

ES	H (m)	h (m)	H/h (m)	Hk (m)	Hk/H (m)	K (%)	WK (%)	PVEG (%)	α(°)	BEHI score	Eb (m3×m−1)
1	0.75	0.54	1.38	0.58	0.77	58	44.7	78	52	16.7	0.138
2	0.75	0.38	1.97	0.58	0.77	47	36.2	52	43	22.8	0.205
3	0.72	0.72	1.0	0.29	0.40	26	10.4	23	64	22.8	0.121
4	0.52	0.52	1.0	0.46	0.88	63	55.4	81	90	15.6	0.287
5	0.59	0.59	1.0	0.37	0.63	45	28.3	45	54	16.6	0.047
6	1.06	0.95	1.12	0.80	0.75	48	36.0	60	64	17.6	0.174
7	1.43	0.60	2.38	1.0	0.69	60	41.4	35	105	29.7	0.157
8	0.95	0.95	1.0	0.60	0.63	45	28.4	25	53	18.6	0.398
9	0.47	0.34	1.38	0.22	0.46	52	24.4	83	75	21.8	0.024
10	1.18	0.33	3.57	0.37	0.31	35	10.85	25	64	34.6	0.321
11	0.60	0.21	2.86	0.43	0.71	55	39	88	90	26	0.02
12	1.91	0.44	4.3	0.45	0.23	40	9.2	25	63	36.3	0.128
13	1.88	0.36	5.2	1.24	0.65	40	26.0	36	78	29	0.115
14	0.88	0.34	2.58	0.59	0.67	42	28.14	35	85	30.5	0.072
15	0.84	0.40	2.1	0.78	0.92	56	52.0	58	90	24.8	0.008
16	0.87	0.20	4.35	0.35	0.4	35	14.0	31	61	32.3	0.024
17	0.46	0.34	1.35	0.40	0.86	49	42.6	77	90	21.5	0.019
18	0.82	0.60	1.36	0.61	0.74	40	29.7	35	90	26.7	0.045
19	0.37	0.24	1.54	0.30	0.81	48	38.8	72	58	19.6	0.041

H = bank height, h = bankfull height, Hk = root depth, K = root density, WK = weighted root density, P_{VEG} = surface protection, α = bank angle, E_b= volume of eroded soil per 1 m of E.

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

No.	Function	Regression equation	R	R^2	$\hat{s}_R$	t	> = <	$t_{0,01\,(17)}$
1	Eb = f (BEHI)	$E_b = a_0 + a_1 \times$ BEHI Eb = −0.21192 + 0.013863 × BEHI ($m^3.m^{-1}$)	0.884	0.781	0.1135	7.789	>	2.898

published by Rosgen (2008). The marks were presented as **index** in (Tab. II). After the calculations, we compared the outcomes with the general estimation table (Tab. III), we determined the total BEHI score by summing the indexes of all (Tab. III). We did not adjust the overall index, regarding to character of bank material and absence of layers.

Statistical analyses

In order to verify the suitability of the BEHI index as a predictor of bank erosion, we observed the relationship between the total BEHI score (BEHI) and bank erosion (E_b). We used a linear regression to study the relationship. The significance of the relationship was tested through Student's T-test.

RESULTS AND DISCUSSION

Recorded data (Tab. IV) presents a review of measured variables, which describes the parameters of the banks. These variables were used to calculate the BEHI index and give information about the total volume of eroded soil per 1 m from the observed ES of the stream.

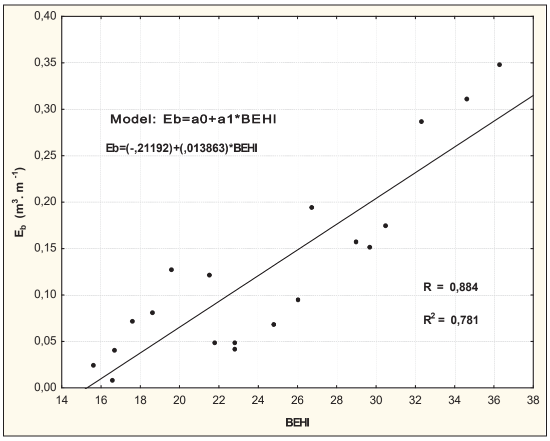
We used linear regression model to describe the relationship between BEHI and the E_b:

$$E_b = a_0 + a_1 \times \text{BEHI}\ (m^3 \times m^{-1}) \quad (4)$$

The final shape of the model is as follows:

$$E_b = -0{,}21192 + 0{,}013863 \times \text{BEHI}\ (m^3 \times m^{-1}) \quad (5)$$

The relationship between BEHI and E_b, proven by the value of the coefficient of correlation (R=0.884), coefficient of determination R^2 = 0,781 (Fig. 3) shows that more than three quarters of the variability of bank erosion can be explained through BEHI.



3: *Relationship between the BEHI indexes and the E_b values ($m^3 \times m^{-1}$)*

We subsequently tested if the correlation coefficient is significantly different from 0, i. e. whether the relationship between the BEHI and Eb ($m^3 . m^{-1}$) is significant or not. We stated the null hyphotesis that the correlation coefficient in statistical population $\delta_{xy} = 0$ (Šmelko 1991) and tested the hypothesis using the following test:

$$t = \frac{R}{s_R}, \text{where } S_R = \sqrt{\frac{1-R^2}{n-2}} \qquad (6)$$

The t value would follow Student´s t distribution with $f = n - 2$ degree of freedom, if the sample data set follows at least approximately the normal distribution. In our case the calculated testing criterion t was 7.789, which was higher than the necessary value $t_{\alpha;f} = t_{0,01\ (17)} = 2.898$, so we rejected the null hypothesis (Tab. V) and concluded that the relationship was significant. We can say that BEHI index is suitable for prediction of streambank erosion in Sestrč torrent conditions.

Jakubisová (2011) used the BEHI index to estimate the erosion rate of the banks of Železnobreznický potok torrent (S_p=23.50 km²), located in Kremnické vrchy mesoregion (30 ES) and of Hučava torent (S_p=41.16 km²), located in Poľana mesoregion (30 ES). The BEHI values for Železnobreznický potok torrent ranged from 15.2 to 32.8 and from 15.6 to 42.7 for the Hučava torrent. The author focused her study to erosion rates of banks with different shares of vegetation cover and bank angles and confirmed their significant influence on bank erosion rates. She recommended to use the BEHI method, because it enables precise evaluations and predictions of erosion rates compared to other methods.

Markowitz & Newton (2011) studied the relationship between BEHI index and annual erosion rates on Birch Creek in New York state. They confirmed the existence of the relationship between the examined characteristics and coefficient of determination $R^2 = 0.52$. Another study (Bandyopadhyay *et al.*, 2013) was carried out along the Haora river in India, where authors established 30 experimental sections for BEHI index and bank erosion evaluation. They confirmed that 75 % of the banks had erosion rates close to BEHI index category. Dick *et al.* (2014) confirmed coefficient of determination $R^2 = 0.67$ between annual erosion rates and BEHI index. They conducted their research in water streams in Michigan. These studies confirmed the possibility of using the BEHI index as a good predictor of streambank erosion.

CONCLUSION

The research of erosion in Sestrč torrent is a part of wider research taking place in various geomorphological units of Slovakia. Studies of other authors confirmed that this methodology offers acceptable estimation and prediction data. The results of this study confirmed correlation between BEHI index and Eb, $R^2 = 0.78$ and we can say that BEHI index can determine sections of the streambanks prone to erosion and can be useful for prioritization of erosion control and restoration of channels. This is very important especially in streams, which are tributaries of reservoirs of drinking water and in places where we must decide which part of streams needs some erosion control measurements. Our future research will be focused on comparison of real annual erosion rates with model erosion rates estimated by the BANCS model.

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