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Predicting the annual erosion rates on a small stream by the BANCS model

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Abstract: The erosion of streambanks causes soil loss and degrades the stream habitat. To optimize the prevention of bank erosion, we first need to determine the most vulnerable places on banks. This can be done by the BANCS model. However, data are still missing on its accuracy in small streams. We measured the real annual erosion rates on 18 experimental sections established on the Lomnická stream. Using the Near Bank Stress (NBS) and Bank Erosion Hazard Index (BEHI) we developed the erosion prediction curves and evaluated the relationship between these two indices and the real annual erosion rates. We found a strong relationship between BEHI and real annual erosion rates, with R^2 = 0.72. The relationship between the NBS index and real annual erosion rates was also strong, with R^2 = 0.53. Then we constructed erosion prediction curves for very high and extreme BEHI and for moderate and high BEHI. Despite the strong correlation between BEHI and annual erosion rates, the prediction curves had no real relationship with real annual erosion rates, with R^2= 0.004 and 0.15, respectively.

Keywords: Bank Erosion Hazard Index (BEHI); erosion model; Near Bank Stress (NBS) index; prediction curves; streambank erosion

Erosion is a natural process that occurs on streambanks of every river (McQueen *et al.* 2013). There is a consensus that streambank erosion is one of the greatest sources of sedimentation in watersheds and that bank erosion is a major source of sediment pollution (Rosgen 1976; Prosser *et al.* 2000; Laubel *et al.* 2003; Simon & Klimetz 2008; McQueen *et al.* 2013). Sediment loads pollute the surface water with trace metals and other pollutants, increase water turbidity (Chen *et al.* 2005; McMillan & Hu 2017), and can be an important source of phosphorus in watersheds (Zaimes *et al.* 2008). The USACE (1983) estimated that about 220 000 km of streambanks are in need of erosion protection in the United States.

We can solve the problems caused by sedimentation stabilizing the stream channels. Although the stabilization measures are costly, we can reduce their costs by intervening only in the parts of streams that are the most prone to erosion. We can conveniently identify these parts of streams by the Bank Assessment for Non-point Source Consequences of Sediment (BANCS) model (Rosgen 1997, 1998,

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2001). The BANCS model is an empirical model that evaluates the erodibility potential of a stream. It predicts streambank erosion using two separate indices to calculate potential erosion rates – Bank Erosion Hazard Index (BEHI) and Near-Bank Stress (NBS) index. Higher scores of these indices indicated higher predicted erosion rates. Rosgen developed the BANCS model for rivers in Colorado, USA, but we should be able to apply it to any stream.

Rosgen (1996, 2001, 2006, 2008) based the model on both measured and visual assessment of a streambank and its NBS and BEHI incorporate the physical characteristics of a streambank that work to resist both the gravitational and hydraulic forces applied to a streambank (Bigham 2016). To create a BANCS model for a particular stream, we need to measure the real annual bank erosion (RABE) rates from parts of streambanks at different NBS/BEHI.

We hypothesize that the BEHI and NBS indices correlate positively with the RABE rates we measured on the Lomnická stream and that we will be able to explain a significant part of the variability of the real annual erosion rates by the prediction curves of the BANCS model on the Lomnická stream. This will provide information on the erodibility of particular parts of the banks of the river, and can be used to optimize the placement of erosion prevention measures.

MATERIAL AND METHODS

Study area. We established 18 experimental sections (ES) on the Lomnická stream in May 2014. To determine the placement of the ES, we used the riffle-pool method, as shown by Rosgen (1996). This system is based on the information that the geometric parameters of natural channels mostly change in curves. On the outer side of the curve, the channel profile is deeper (pools) and on the inner side it is shallower. The geometric parameters of the channel profile before and after the curve gradually change. Between two opposing curves lays a shallower straight section called riffle. This is why we set up approximately the same number of the ES in curves and in riffles, to gain variability of the NBS and BEHI indices. The total length of 306 m of the ES represents 4.34% of the total length of main channel (Table 1) (Figure 1). Lomnická stream springs on the northern slope of Ihla Mt, elevated 1145 m a.s.l., and joins the Kolačkovský creek south-west of the village of Kolačkov, at the elevation of 708 m a.s.l.

Lomnická stream is located in the area of the Levočské vrchy mountain ridge. Intensive gully erosion and landslides affect the area along with the erosion-accumulation processes of the watercourses. Due to the lengthwise slope of the channels, kinetic

Table 1. Information about the experimental sections (ES) laid out on the Lomnická stream

ES	Distance from the mouth of the watershed (km)	Altitude (m a.s.l.)	GPS coordinates	Length of ES (m)
1	0.28	718	49°14'63.1"N, 20°37'34.4“E	16
2	0.46	728	49°14'53.3"N, 20°37'34.6“E	15
3	0.56	738	49°14'48.7"N, 20°37'31.3"E	15
4	1.14	744	49°14'23.4"N, 20°37'07.3"E	20
5	1.20	747	49°14'20.1"N, 20°37'05.2"E	20
6	1.92	774	49°13'88.4"N, 20°36'94.9"E	15
7	1.98	775	49°13'86.8"N, 20°36'88.0"E	15
8	2.73	805	49°13'51.6"N, 20°36'69.1"E	20
9	2.95	817	49°13'42.4"N, 20°36'59.8"E	15
10	3.19	822	49°13'31.5"N, 20°36'51.5"E	15
11	3.29	825	49°13'28.3"N, 20°36'48.3"E	20
12	3.51	840	49°13'17.3"N, 20°36'41.9"E	15
13	3.70	849	49°13'07.4"N, 20°36'46.5"E	20
14	4.00	868	49°12'93.5"N, 20°36'54.1"E	20
15	4.18	873	49°12'85.6"N, 20°36'51.0"E	20
16	4.36	878	49°12'76.8"N, 20°36'43.5"E	15
17	4.49	885	49°12'71.0"N, 20°36'38.7"E	15
18	5.08	903	49°12'42.1"N, 20°36'21.3"E	15

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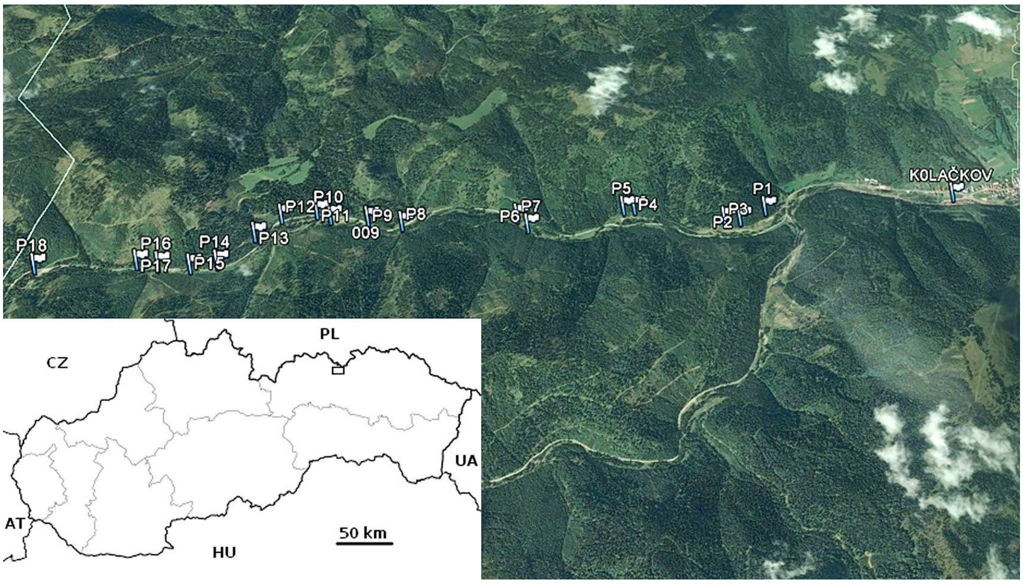

Figure 1. Localization of the Lomnická stream watershed and established experimental sections

energy, instability of flows, geology, and the resulting amount of bed loads, intensive gully formation processes affect the channels.

Geologically, the watershed is mostly composed of flysches alternating with siltstone. The high content of clay within the watershed results in a subsurface soil layer through which water does not easily pass. This causes quick and long-lasting saturation of top soil layers by precipitation. It also causes high levels of surface runoff and generally increased bank erodibility (Rinaldi & Casagli 1999). Regarding soil types, the most abundant are Cambisols covering about two thirds of the watershed area. Cambic Podzols cover the remaining third of the area, and they mostly occur in the upper part of the watershed.

The whole watershed of the Lomnická stream is located in the cold climate zone (mean temperature between 4 and 6°C). The mean annual precipitation is 800 to 900 mm, reaching a maximum in June (110 to 130 mm) and minimum in February (30–40 mm). The monthly rainfall in the Lomnická stream watershed is shown in Table 2. Information on the rainfall was taken from measurements from the village of Kolačkov, upstream of which the Lomnická stream mouths to the Kolačkovský brook. The elevation of the weather station was 650 m a.s.l.

Basic morphological characteristics of the watershed. We calculated the following characteristics for the Lomnická stream watershed: watershed area Sp = 10.94 km^2, forest cover of the basin 10.72 km^2 (ℓ = 97.93%), length of the main stream L = 7.05 km, length of tributaries L_p= 5.37 km, stream network density r = 1.13 km/km^2, length of the watershed divide O = 16.06 km, thalweg length L_u = 7.34 km, mean width of the basin B_p = 1.49 km, absolute gradient of the stream ΔH_t = 472.67 m, absolute gradient of the basin ΔH_{pov} = 582.14 m, slope of the thalweg I_u = 7.87%, mean slope of the basin I_s= 17.59%, average slope of the stream It = 6.70%, average altitude of the watershed $ØH_{pov}$ = 990.9 m above sea level. Discharges are as follows: Q_{100} = 19.69 m^3/s, Q_{50} = 14.76 m^3/s, Q_1 = 2.17 m^3/s. We also determined the long-term mean discharge – Q_a= 0.15 m^3/s.

The rainfalls occurring in the observed period and their duration were acquired from the Slovak Hydrometeorological Institute (SHMÚ). The data on

Table 2. Monthly rainfall and the number of days with rainfall from the Kolačkov weather station, 650 m a.s.l. (Žoldák 2018) (http://meteoinfo.sk/stanice/590kolackov/statistiky/datum-5-2014)

Year	2014								2015				
Month	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	I.	II.	III.	IV.	V.
Rainfall (mm)	160	50	185	150	50	60	2	–	15	36	16	25	80
No. of rainfall days	16	2	15	13	5	7	1	–	3	1	2	1	7

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Table 3. Flow rates in the Lomnicka stream determined by the CN method after the most important rainfalls during the observed period

Date	Rainfall (mm)	Rainfall duration (min)	5-day antecedent rainfall (mm)	CN forest/meadow/road	Direct runoff (mm)	Watershed drainage (m^3)	Peak discharge (m^3/s)	% of the bankfull
14. 5. 2014	68.81	664	36.9	73/71/95	17.4	190230	5.8	84.7
15. 5. 2014	166.3	1019	105.7	87/86/98	127.9	1398946	28.8	418.4
17. 5. 2014	34.4	745	263.1	87/86/98	11.1	121383	3.4	48.7
2. 7. 2014	36.6	271	101.0	87/86/98	12.6	137778	9.2	134.2
11. 7. 2014	62.0	524	54.8	87/86/98	32.0	349960	13.3	193.3
17. 7. 2014	77.5	309	24.9	54/52/87	4.7	51531	3.1	45.1
21. 7. 2014	31.1	378	77.5	87/86/98	8.4	114619	5.8	84.7
13. 8. 2014	56.6	1023	68.7	87/86/98	27.6	301836	6.2	89.9

the rainfalls were interpolated for the mean elevation of the watershed (990.9 m a.s.l.) from four weather stations: Podolínec (563 m a.s.l.), Ihľany – Majerka (680 m a.s.l.), Nižné Ružbachy (555 m a.s.l.), and Stará Ľubovňa (535 m a.s.l.). There is no SHMÚ weather station that could provide precise 24-h data on rainfalls and their duration in the watershed itself. Using the Curve number (CN) method, we determined the peak discharge (m^3/s) in the channel. We selected the days during which the rainfalls resulted in a peak flow of at least 40% of the bankfull stage during the observed period (1. 5. 2014–31. 5. 2015). An overview of the most important rainfall events, the related curve numbers, as well as the peak discharge and the following shares of the bankfull stage are available in Table 3. We compared the flow stage with the mean capacity of the Lomnická stream channel, which was Q = 6.88 m^3/s. We found that in the observed period eight important rainfall events occurred, during which the erosion we measured was to occur. It is also apparent from the table that water exceeded the bankfull stage during three rainfall events. One situation was extreme (15. 5.2014) when the bankfull stage was exceeded four times. We also created a model of peak discharge in the channel after 10 to 200 mm rainfalls of various durations (1, 2, 3, 6, 12, 24 h). When we created the CN curves, we assumed 0 mm rainfall in the preceding five days. The CN curve models are shown in Figure 2. In the model construction, we therefore used the following CN numbers: (10.72 km^2 of forest – 54CN; 0.211 km^2 of grassland – 52CN; 0.009 km^2 of roads – 87CN).

BANCS model. We evaluated each ES by the BEHI and NBS and measured the RABE rate. We deter-

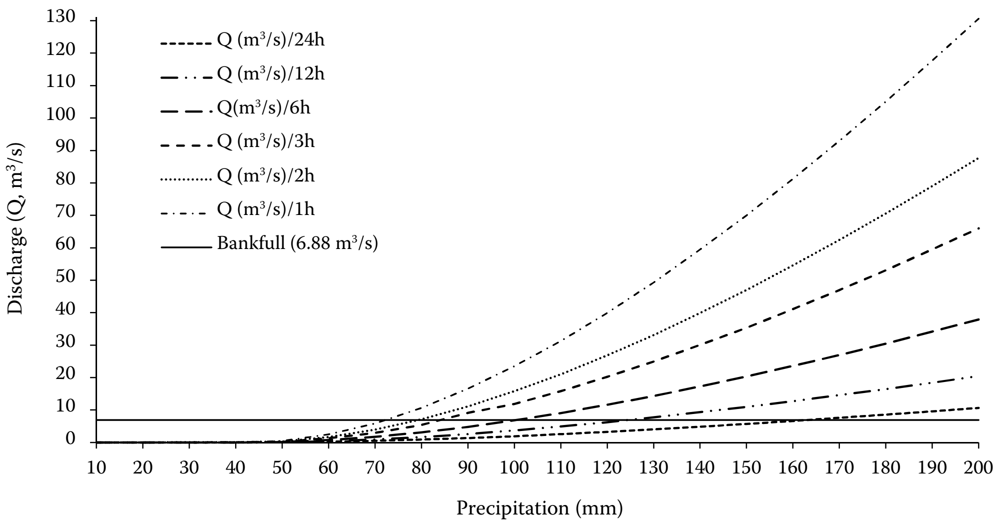

Figure 2. Determined flow rates using the Curve number method for specific precipitation and its duration in the Lomnická stream

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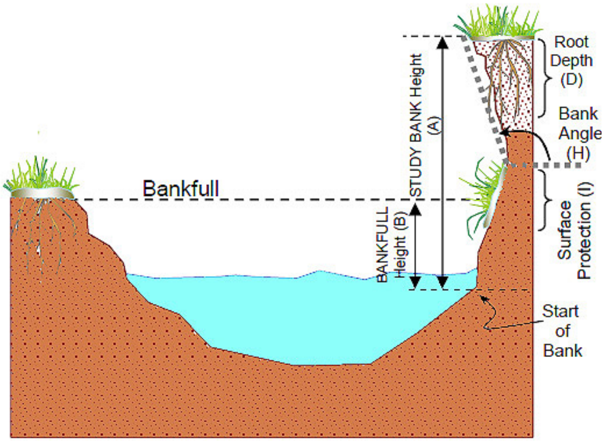

Figure 3. Variables for Bank Erosion Hazard Index

mined the BEHI score according to Rosgen (2006). We evaluated seven parameters on each ES: (a) the ratio of the height of the studied bank (BH) to the bankfull height (BFH); (b) the ratio of the root depth (RD) to BH; (c) weighed root density (WR); (d) bank angle (BA); (e) surface protection (SP); (f) bank material (BM); and (g) stratification of the bank material (SBM). Bank height (BH) is the height from the bank toe (a point where the steel pin is set into the bed) to the top of the bank; bankfull height (BFH) is the height from the bank toe to the bankfull position; surface protection (SP) is visually estimated as a percentage of the bank covered by plants, trees, shrubs or woody debris, boulders or other objects that can help protect the bank against erosion; root density (RD) is the visually assessed density of vegetation roots growing on banks (Figure 3).

We measured BH, BFH, RD, and BA and evaluated BM by the sieve and densimetric tests of soil samples we took from the bank at each ES. The assessments of WR and SP were visual as well as the assessment of SBM. To stratify the bank material, we assessed the bank layers.

To obtain the total BEHI index, we used BEHI worksheet (Rosgen 2008). We converted measured variables to partial indices through the nomograms (Rosgen 2006). Variables (a) to (e) could reach one of the six ratings: very low (0–2 points), low (2–4 points), moderate (4–6 points), high (6–8 points), very high (8–9 points), and extreme (9–10 points). Based on the grain size of bank material (f), we subtracted or added 5–10 points to the total BEHI (Rosgen 2008). Stratification of bank material (g) according to this parameter, we can add five or ten points to the BEHI score. We added five points to the total BEHI score if: (*i*) the bank is composed of two separate layers; (*ii*) layers are situated in a part of the bank between bank toe and bankfull height; (*iii*) one of the layers is composed of erosion-prone material (such as sand, gravel or their combination). We added ten points to the BEHI score if more than two layers were present and conditions (*ii*) and (*iii*) were applicable (Rosgen 2008). To obtain the total BEHI score for experimental sections we summed the points for each parameter. Then we determined the erodibility potential of each experimental section — very low (< 9.9 points), low (10–19.9), moderate (20–29.9), high (30–39.9), very high (40–45), and extreme (45.1–50 points).

Using the NBS, we assessed the energy acting upon the streambanks (Presnail 2013). Seven methods for NBS determination are available according to Rosgen (2006). We used method no. 5 – the ratio of the near-bank maximum depth to the bankfull mean depth available in the NBS rating worksheet (Rosgen 2008). We measured the depth of the channel for the bankfull stage each 0.5 m of the channel's width to

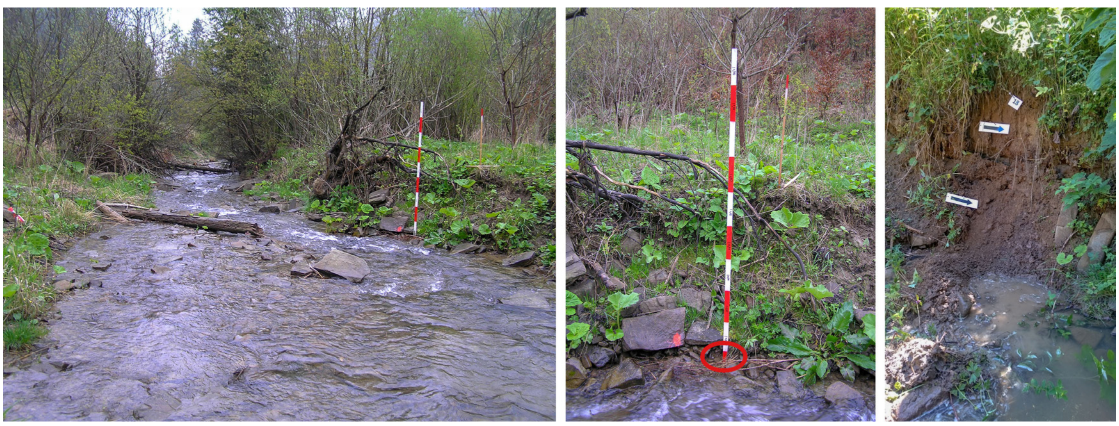

Figure 4. Experimental section 16 (whole section, position of the pin, bank soil probe)

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establish H_{max} and $H_ø$ at the bankfull stage. The NBS can reach the following levels: very low (< 1.00), low (1.00–1.50), moderate (1.51–1.80), high (1.81–2.50), very high (2.51–3.00), extreme (> 3.00) (Rosgen 1996, 2001, 2006, 2008).

We measured the RABE rates using 50-cm steel toe pins. We set one toe pin as a control point in each ES (Figure 4). Then we placed a plumb survey rod on the top of the toe pin and measured the horizontal distances from the rod to the bank face at various height levels. We recorded the height level of the measurements and the horizontal distances. We recorded the location of the pin using a GARMIN Colorado 300 GPS device. After one year, we re-measured the horizontal distances at the same height levels. We drew the initial shape of the area and subsequently calculated the real annual erosion rates per one meter of the ES (in m^3/m/year).

We studied the relationship between BEHI and RABE by regression and correlation analyses. In a similar manner, we studied the relationship between the NBS and RABE rates. After verifying the relationships between both indices and the RABE rates, we constructed prediction curves. During the construction of prediction curves, we classified the ES according to their BEHI category. Due to insufficient data in individual categories, we merged the neighbouring BEHI categories. Other authors similarly combined neighbouring BEHI categories (Harmel *et al.* 1999; Sass 2011; Coryat 2014; Kwan & Swanson 2014). We conducted all statistical analyses in the STATISTICA 10.0 program.

RESULTS AND DISCUSSION

We measured the input characteristics needed to calculate the BEHI (Table 4), determined the BEHI for individual ES (Table 5), measured the characteristics needed to calculate the NBS index (Table 6), and determined the NBS index. We then started the statistical analyses.

Regression and correlation analyses proved a statistically significant relationship between the BEHI and RABE rates. The relationship between the two variables was strong, with the coefficient of determination at 0.72 (P = 0.00001). Figure 5 shows the positive correlation. Other authors obtained mixed results when studying the relationship between the BEHI and RABE rates. Ghosh *et al.* (2016) conducted their research in the West Bengal region and the $R^2$of 0.28 shows only a weak relationship. Coryat (2014) reached similar results. On the banks of the Stony Clove Creek (New York) a weak relationship existed between the BEHI and RABE rates, with R^2 = 0.23. Saha & Mukhopadhyay (2014) also reported a weak relationship between the variables on the banks of the Kunur river in India, with R^2 = 0.14. However, Coryat (2014) explained the weak relationship by flood discharges during Hurricane Irene.

On the other hand, Markowitz & Newton (2011) reported a moderately strong relationship, at R^2= 0.53 on the Birch Creek (New York). Dick *et al.* (2014) reported an even stronger relationship, with R^2 = 0.67 for several watercourses in Michigan. The differences in the results indicate that the BANCS model is not universally applicable to any given stream. Before predicting the RABE rates in a particular stream, one has to conduct a survey on it. Once they proved a strong relationship between BEHI and RABE on a sufficiently large sample, then they can use the BEHI to predict the RABE rates. We can obtain a better relationship between BEHI and RABE by determining the parameters (f) bank material and (g) stratification of bank material. Instead of the ocular estimate we used the sieve and densimetric test. This procedure allowed us to accurately determine the index compared to other authors who used visual assessment (Harmel *et al.* 1999; Ghosh *et al.* 2016).

We tested the relationship between the NBS index and the RABE rates in a similar manner like the relationship between the BEHI and the RABE rates (Figure 6). The relationship was moderately strong, with a coefficient of determination at R^2 = 0.53 (P = 0.0005). Ghosh *et al.* (2016) reported a weaker relationship, with R^2 at 0.28. Markowitz & Newton (2011) reported similar results to Ghosh *et al.* (2016) with R^2 at 0.20 on the Birch Creek (New York). Harmel *et al.* (1999) studied the watershed of the Illinois River and found that there was virtually no relationship between the NBS index and the RABE rates on the banks of this stream, with R^2 at 0.17. On the other hand, a moderately strong relationship between the NBS index and the RABE rates was reported by Coryat (2014) with R^2 at 0.37. When we compare the methods for determining the NBS index, we can see that the best results were reported by authors who used all seven methods to determine the NBS index and then used the one that provided the highest NBS index. Coryat (2014) addressed the problem in this way, as well as Sass and Keane (2012). Coryat (2014) reached a coefficient of determination between the NBS index

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and RABE of only 0.37. However, after modifying the BANCS model Sass and Keane (2012) were able to reach much stronger relationships of R^2 in the range of 0.7 to 0.75. The authors such as Kwan and Swanson (2014), Markowitz and Newton (2011) or Ghosh *et al.* (2016) used the same method of determining the NBS index (method no. five). Out of these authors, only Kwan and Swanson (2011) reported the nature of the relationship between the variables, reaching mixed results (R^2 in the range

Table 4. Assessment of individual experimental sections (ES) by the Bank Erosion Hazard Index (BEHI)

ES		BH	BFH	BH/BFH	RD	RD/BH	R	WR	SP	BA	Partial BEHI score
				(m)				(%)		(°)	
1	value	0.88	0.42	2.10	0.10	0.1	38	3.8	50	30	
	index			8.1		8.2		9.1	4.3	2.3	32.0
2	value	0.89	0.76	1.17	0.28	0.31	41	12.8	60	82	
	index			3.9		5.9		8.1	3.9	7.1	28.9
3	value	1.85	0.86	2.10	0.29	0.15	25	3.9	15	58	
	index			8.1		7.9		9.2	7.6	3.8	36.6
4	value	1.04	0.47	2.21	0.35	0.33	51	17.1	65	68	
	index			8.2		5.5		7.7	3.2	4.7	29.3
5	value	1.70	0.35	4.80	0.32	0.18	36	6.7	20	71	
	index			10		7.2		8.8	7.0	5.0	38.0
6	value	1.97	0.64	3.07	0.40	0.20	35	7.1	45	57	
	index			10		7.0		8.8	4.6	3.7	34.1
7	value	2.70	0.78	3.46	0.21	0.07	28	2.17	5	59	
	index			10		9.0		9.4	10	3.9	42.3
8	value	1.07	0.48	2.29	0.57	0.53	50	26.6	55	42	
	index			8.2		3.6		6.2	4.0	3.0	25.0
9	value	1.65	0.42	3.90	0.64	0.38	39	15.1	60	47	
	index			10		5.0		8.0	3.9	3.2	30.1
10	value	0.96	0.58	1.65	0.46	0.48	50	23.9	85	73	
	index			6.6		3.9		6.3	1.5	5.2	23.5
11	value	1.40	0.68	2.05	0.34	0.24	35	8.5	30	69	
	index			8.1		6.8		8.7	5.8	4.7	34.1
12	value	0.65	0.42	1.54	0.20	0.30	30	9.0	55	41	
	index			5.9		6.0		8.4	4.0	2.9	27.2
13	value	1.04	0.83	1.25	0.22	0.21	45	9.5	45	48	
	index			4.1		6.8		8.4	4.6	3.3	27.2
14	value	1.08	0.57	1.90	0.48	0.40	40	17.7	55	51	
	index			7.5		4.8		7.7	4.0	3.4	27.4
15	value	1.03	0.34	3.02	0.53	0.51	40	20.5	65	88	
	index			9.2		3.8		7.1	3.2	7.9	31.2
16	value	1.18	0.36	3.20	0.48	0.40	45	18.3	65	69	
	index			9.6		4.8		7.5	3.2	4.7	29.8
17	value	0.55	0.47	1.17	0.31	0.56	65	36.6	75	48	
	index			3.9		3.6		5.3	2.2	3.3	18.3
18	value	1.12	0.51	2.19	0.53	0.47	35	16.5	45	83	
	index			8.1		3.9		8.0	4.6	7.2	31.8

BH – bank height; BFH – bankfull height; RD – root depth; R – root density; WR – weighted root density; SP – surface protection; BA – bank angle

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Table 5. Determination of bank material and stratification of bank material on each experimental section (ES)

ES	Skeleton	Clay	Silt	Sand	BEHI index		Overall BEHI score
	(%)				material adjustment	stratification adjustment	
1	41.58	2.21	1.61	54.6	5	0	37.0
2	40.63	0.61	2.76	56.0	6	0	34.9
3	34.91	1.06	9.64	54.39	5	0	41.6
4	43.12	2.08	7.15	47.65	5	0	34.3
5	42.5	0.29	7.13	50.08	5	0	43.0
6	41.31	3.06	11.76	43.87	5	0	39.1
7	68.6	0.91	6.24	24.25	5	0	47.3
8	61.92	0.78	6.22	31.08	5	0	30.0
9	52.22	0.44	11.49	35.85	5	0	35.1
10	12.3	1.54	18.57	67.59	8	0	31.5
11	19.31	2.21	16.18	62.3	7	0	41.1
12	67.21	0.97	6.63	25.19	5	0	32.2
13	29.6	1.44	11.64	57.33	6	0	33.2
14	16.5	1.71	16.38	65.41	8	0	35.4
15	8.72	0.96	21.89	68.43	8	0	39.2
16	29.6	2.23	25.46	42.71	0	0	29.8
17	70.01	0.73	3.58	25.68	5	0	23.3
18	7.65	2.96	23.73	65.66	7.5	0	39.3

BEHI – Bank Erosion Hazard Index

of 0.37 to 0.77). However, the strongest results are obtained when the "Velocity gradients" method is used to determine the NBS index, as reported by Rosgen (1996, 2001, 2006).

We created two erosion prediction curves for the Lomnická stream (Figure 7): one for moderate and high BEHI categories and the other for very high and extreme BEHI categories. Subsequently we used the curves to predict the erosion rates on particular ES and studied the relationship between the predicted erosion and the RABE (Table 7). We found no statistical significance of the relationship between predicted erosion and RABE for moderate and high BEHI. The relationship was also very weak, with R^2 at 0.15 (P = 0.1673). As for the relationship between predicted erosion and RABE for very high and extreme BEHI, this was also statistically insignificant and practically non-existent, with R^2 at 0.004 (P = 0.9316). Therefore,

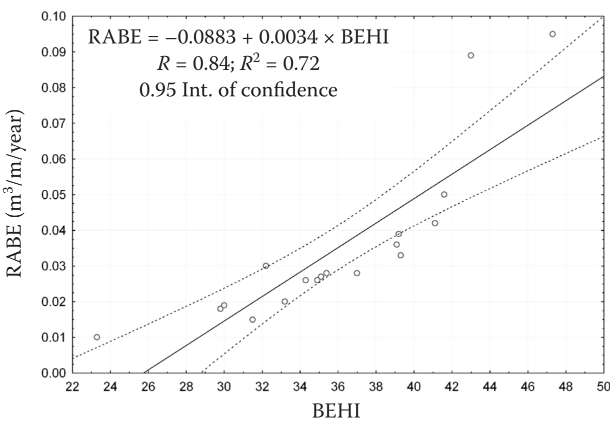

Figure 5. Relationship between Bank Erosion Hazard Index (BEHI) and the real annual bank erosion (RABE)

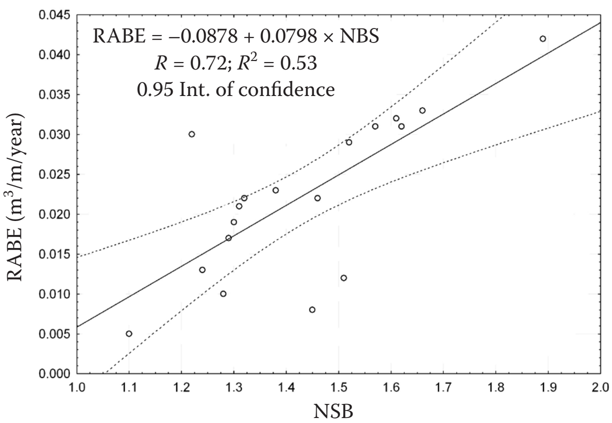

Figure 6. Relationship between the Near Bank Stress (NBS) index and the real annual bank erosion (RABE)

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Table 6. Assessment of individual experimental sections (ES) by the NBS index

ES	H_{max}	$H_{ø}$	$H_{max}/H_{ø}$	NBS index
1	0.50	0.39	1.28	L
2	1.15	0.76	1.51	M
3	0.95	0.51	1.86	H
4	0.85	0.57	1.63	M
5	0.57	0.29	1.96	H
6	1.30	0.75	1.73	M
7	1.05	0.60	1.75	M
8	0.65	0.43	1.51	M
9	0.68	0.45	1.51	M
10	0.85	0.60	1.40	L
11	1.0	0.55	1.81	H
12	0.58	0.42	1.38	L
13	1.05	0.76	1.38	L
14	0.90	0.63	1.42	L
15	0.65	0.46	1.41	L
16	0.55	0.45	1.20	L
17	0.55	0.39	1.41	L
18	0.75	0.48	1.56	M

H_{max} – near-bank maximum depth; $H_{ø}$ – bankfull mean depth; L – low; M – moderate; H – high

Table 7. Real annual bank erosion (RABE) vs. predicted bank erosion (PBE)

	RABE	PBE	Difference
	(m³/m/year)		
ES1	0.028	0.021	+0.007
ES2	0.026	0.027	–0.001
ES3	0.05	0.070	–0.02
ES4	0.026	0.029	–0.003
ES5	0.089	0.065	+0.024
ES6	0.036	0.032	+0.004
ES7	0.095	0.067	+0.028
ES8	0.019	0.027	–0.008
ES9	0.027	0.027	0
ES10	0.015	0.024	–0.009
ES11	0.042	0.068	–0.026
ES12	0.03	0.024	+0.006
ES13	0.02	0.024	–0.004
ES14	0.028	0.025	+0.003
ES15	0.039	0.024	+0.015
ES16	0.018	0.019	–0.001
ES17	0.01	0.024	–0.014
ES18	0.033	0.023	–0.001

we cannot use the BANCS model to predict erosion on the Lomnická stream. Even if the relationships proved to be statistically significant (but they were not), we could not sufficiently explain the variability of RABE by the predicted erosion, so the predictions would be inaccurate.

Our results are backed by multiple studies where the authors reported an inability to create sufficiently precise prediction curves. Jennings and Harman (2001) and Patterson *et al.* (1999) in North Carolina reported their predicted erosions had only a weak correlation with RABE, with coefficients of determination in the interval of 0.05 to 0.17. A weak relationship between predicted erosion and RABE was also reported by Harmel *et al.* (1999), who conducted their study in Oklahoma. They were able to reach a coefficient of determination of only 0.15 for the extreme BEHI, and 0.09 for the high and very high categories. Coryat (2014), who studied the Stony Clove Creek, reported a moderately strong relationship between predicted erosion and RABE, with R^2 at 0.35 for high and very high BEHI.

However, there are studies which prove the BANCS model can be used to predict erosion and pinpoint the most vulnerable sections of banks. Sass (2011) and Sass and Keane (2012) studied the watershed of the Black Vermillion River in Kansas. Their prediction curves were able to predict erosion with better accuracy for moderate BEHI as the coefficient of determination reached 0.80, as well as for high

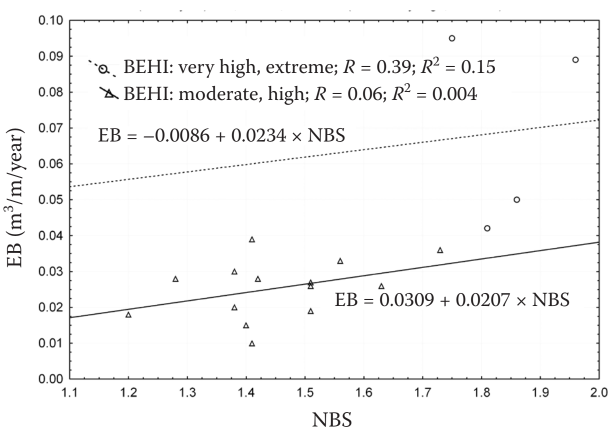

Figure 7. Erosion prediction curves for the Lomnická stream BEHI – Bank Erosion Hazard Index; NBS – Near Bank Stress; EB – annual bank erosion

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and very high BEHI, although here we would predict erosion with considerably lower accuracy, on the margin of advisability, because R^2 is 0.42. The authors worked further with the data and modified the original model. They were able to strengthen the relationship between the predicted erosion and RABE for the high and very high BEHI to a more manageable coefficient of determination of 0.77, thus improving the prediction accuracy. Kwan and Swanson (2014) studied the Sequoia National Forest in California. They constructed prediction curves with sufficient precision for extreme BEHI (R^2 = 0.76) and for low BEHI (R^2 = 0.70), but not for moderate BEHI (R^2 = 0.49) or for high and very high BEHI (R^2 = 0.37). North Carolina State University was able to construct suitable prediction curves in the Piedmont region of North Carolina for moderate BEHI (R^2 = 0.92), extreme BEHI (R^2 = 0.91) and for very high BEHI (R^2 = 0.66), but the results for other categories were less precise, e.g. high BEHI (R^2 = 0.53) (NCSU 1989). The model's creator Rosgen (1996, 2001, 2006) was able to successfully construct the prediction curves for

Table 8. Comparison of methods and factors utilized in the bank assessment for non-point source consequences of sediment (BANCS) models (edited), Bigham (2016)

Author	Model accuracy	Years of data	Method of NBS	Method of estimation of bank erosion	Discharge	Area
Rosgen (1996, 2001, 2008)	R^2 = 0.92 (BANCS)	1	velocity isovels	bank profiles	60–70% below bankfull	Colorado
Rosgen (1996, 2001, 2008)	R^2 = 0.84 (BANCS)	1	velocity isovels	bank profiles	60–70% below bankfull	Wyoming
Patterson *et al.* (1999)	R^2 = 0.17 (BEHI)	1	near-bank area/ total bkf area	bank pins	not reported	North Carolina
Harmel *et al.* (1999)	R^2 = –0.32–0.15 (BANCS)	1	near-bank area/ total bkf area	bank pins	4× greater than bankfull	Oklahoma
Markowitz and Newton (2011)	no relationship (BANCS), R^2 = 0.53 (BEHI), R^2 = 0.20 (NBS)	1	near-bank max depth/bkf mean depth	cross sections	9× greater than bankfull	New York
Sass and Keane (2012)	R^2 = 0.75–0.77 (BANCS, pre-modification)	4	nbs method selection*	bank profiles	at bankfull to 2.5× greater than bankfull	Kansas
Kwan and Swanson (2014)	R^2 = 0.37–0.77 (BANCS)	1	near-bank max depth/bkf mean depth	bank profiles	65% below bankfull to 1.5× greater than bankfull	California
Coryat (2014)	BANCS not developed, R^2 = 0.23 (BEHI), R^2 = 0.37 (NBS)	11	nbs method selection*	bank profiles	8× greater than bankfull	New York
Ghosh *et al.* (2016)	BANCS not developed, R^2 = 0.28 (BEHI), R^2 = 0.28 (NBS)	5	near-bank max depth/bkf mean depth	cross sections	not reported	West Bengal
Dick *et al.* (2014)	R^2 = 0.37–0.67 (BEHI)	2	near-bank max depth/bkf mean depth	bank pins	not reported	Michigan

*Near Bank Stress (NBS) method selection: all available NBS methods were employed at the time of development and the highest was used; BEHI – Bank Erosion Hazard Index

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the Front Range area in Colorado (R^2= 0.92) and the Yellowstone area in Wyoming (R^2 = 0.84). Comparing the results obtained in other studies discharges in the channel are also an important factor. The best results for the BANCS model were obtained by the authors who reported discharges lower than the bankfull stage (Markowitz and Newton, 2011 or Dick *et al.* 2014). Rosgen (1996) reached the highest correlation of prediction curves and experienced discharges that were at most at 60–70% of the bankfull stage. On the other hand, the authors who recorded a discharge greater than the bankfull stage or high flood discharge obtained much worse results (Coryat 2014). To summarize the results of other authors we attach Table 8.

CONCLUSION

In our case, the BEHI proved to be a good predictor of bank erodibility on the Lomnická stream. On the other hand, the NBS index proved less efficient as a predictor of this phenomenon. The relationships between the constructed erosion prediction curves and high BEHI were weak and insignificant, as well as those for very high and extreme BEHI. The weak relationships showed that the prediction curves constructed from our data were not suitable for predicting RABE of the Lomnická stream. The weak relationships could be due to the fact that flood discharges occurred on the stream in May 2014, shortly after the erosion pins were installed. This, along with the research of other authors, shows that the prediction curves constructed by the BANCS model should be adapted for such high flow rates to increase their accuracy in non-standard conditions.

On the other hand, there is sufficient data that proves the BANCS model can be a helpful tool when managing erosion-prone watercourses. We shall continue verifying its potential in the Central European conditions until we can, with confidence, advise practitioners whether or not to use this model when implementing channel stabilisation measures.

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