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# Erosional Damages on Concave Banks of Directional Arcs in Natural Torrent Bed

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**ABSTRACT**

The article deals with the research of erosive damages of concave (outer) sides in directional circular arcs in the natural torrent bed. The research was carried out on 22 reference circular arcs on the Hučava torrent in the geomorphological unit of Poľana (Central Slovakia). The relation between $R/W_{bkf}$ ratio (radius of curvature R/torrent bed width inside the banks $W_{bkf}$) and the bank slope angle BA of the concave arc BA = $f(R/W_{bkf})$ was analyzed. The relationship between $R/W_{bkf}$ ratio and the percentage of vegetation cover VEG on the concave bank of the directional arc VEG = $f(R/W_{bkf})$ was analyzed as well. At the same time, the relation between ratio $R/W_{bkf}$ and the VEG/BA coefficient was studied, which simultaneously the influence of vegetation cover and bank slope in connection with its erosive damage VEG/BA = $f(R/W_{bkf})$. It was found that the determination index for the relation BA=$f(R/W_{bkf})$ has the value of $R^2 = 0.924$, for the relation VEG = $f(R/W_{bkf})$ the value of $R^2 = 0.953$ and for the relation VEG/BA = $f(R/W_{bkf})$ the value of $R^2 = 0.967$.

**Keywords:** erosion, natural torrents, simple circular arcs.

## INTRODUCTION

Torrents are characterized by significant erosive activity, especially during increased discharges after heavy rainfall in the watershed. During high discharges, the bottom and slopes of the torrent beds are eroded. Due to the streaming of water, significant erosive damage occurs, especially on the concave (outer) sides of the directional arches of the torrents. Collins et al. [2012], Kronvang et al. [2013], Neal and Andera [2015], Janes et al. [2017] state that channel bank erosion precesses represent a significant source of sediments in the waterhed. Simon et al. [2010] reported that the erosion losses from the banks of watercourses can account for up to 90 percent of the total volume of eroded material in a watercourse per year. Rosgen [2002] revealed that in some cases, soil losses due to watercourse erosion can account for up to 80 percent of total annual watershed soils losses. Pollen et al. [2004], state that this share represents more than 50 percent of the total annual land loss of the watershed. The concave sides of the arches are very significantly damaged by erosion in watercourses. The rates of torrent bank erosion are influenced by numerous factors [Janes et al., 2017]. These factors include the existence and influence of riparian vegetation, the effect of discharges, the composition of bank material, the slope and shape of the torrent bed etc. Erosion often occurs at the outer banks of a meander bends as a result of amplified velocities and shear stress. Uddin and Rahman [2012] noted that the causes of higher rate of erosion are as follows:

- oblique flow attacks the bankline,
- the velocity near the bankline is 1.1 to 1.3 times higher than the section average velocity,
- the shear velocity near the bankline is six times higher than the critical shear velocity etc.

Several authors [Hickin and Nanson, 1975, Wiliams, 1986, Begin, 1986, Hudson and Kesel, 2000, Larsen et al., 2006, Charlton, 2008, Blanckaert, 2011, Uddin et al., 2012, Constantinescu et al., 2013, Adib et al., 2018, Strick et al., 2018, Finotello et al., 2018, Sylvester et al., 2019, Liu et al., 2021, Donovan et al., 2021] have analyzed the effect of the ratio $R/W_{bkf}$, (it means the radius of the directional arc to width of the riverbed in the banks $W_{bkf}$) on the erosion of the concave arc. These authors analyzed the relationhip between the $R/W_{bkf}$ ratio and retreat of the concave banks of large rivers due to erosion or bed migration. Erosion or bed migration is expressed in meters or centimeters per year (m.year$^{-1}$ or cm.year$^{-1}$), especially in connection with the meandering of watercourses. Articles on the issue of erosion in connection with the directional arcs of small streams and torrents occur only rarely. The terrain conditions in the formation of meanders of large rivers differ significantly from the terrain conditions in which natural directional arches of torrents are formed. Rosgen [1994, 2008, 2009] dealt with this issue in detail in connection with the classification of watercourses, which also requires the calculation of sinusoity, that is the ratio of stream length to valley length. Sylvester et al. [2019] note that river bends with the highest curvature show the highest migration rates and erosion, exceptions with limited migration seem to by related to the low erodibility of the outer bank. The beds of natural torrents in mountain areas are a very important source of erosion products in the watersheds. For this reason, the torrent control has an important place in the erosion protection of the landscape. The activities of the modern integrated torrent control are based on design elements which follow each other. The design elements must take into account the proper justification of the specific torrent control and at the same time the need to apply nature-friendly measures. The design of the directional route is of great importance for the overall technical and ecological quality of the torrent conrol and its optimal functionality [Jakubis and Jakubisová, 2018]. The basic variant of the directional guidance of the modification is to maintain the longest possible length of the original route and the biocorridor of the torrent. Necessary route changes must always be justified with regard to the technical, environmental and economic consequences. The intervention must be appropriate to the nature of the environment, create the conditions for the subsequent maintenance of the torrent and must not restrict the management of coastal land. Another variant is the design of the route composed of geometric elements. Simple and compound circular arcs are most often used to round the route. The route should consist of alternating opposite curves, between which there are lines. The maximum length of lines in the extravillain should not exceed two to four times the width of the bed in the banks $W_{bkf}$. The length of the line between opposite arches should not be less than twice the width of the riverbed in banks $W_{bkf}$. It is recommended to design naturally stable sections of the torrent bed. In the case of suitable local conditions, it is possible to base the rounding designs only on an approximate geometric definition of the route by drawing it with the free hand. This procedure monitors:

- preservation of stable sections of the riverbed with suitable biocenoses;
- minimization of earthworks and interventions in the natural environment;
- consistent adaptation of the proposed elements to the natural conditions of the given locality;
- extension of the length of the jet, increase of the articulation of the bottom and slopes of the riverbed and roughness of the wetting circumference.

The aim of the work was to evaluate the influence of the $R/W_{bkf}$ ratio on the erosive damage of the concave side of a simple circular arc. The erosive damage was determined through:

- bank slope angle BA (large BA assumes greater erosion damage and vice versa),
- percentage of bank cover by protective vegetation VEG (higher VEG assumes less erosion and vice versa).

In addition, the VEG/BA ratio was derived, i.e. the ratio between the percentage of bank coverage by protective vegetation VEG (%) and the bank slope angle BA (°), to assess the erosive damage of the concave arch bank.

## MATERIAL AND METHODS

The research was carried out on 22 concave sides of reference circular arcs (RCA) of the Hučava torrent in the geomorphological unit of Poľana, Central Slovakia (Figure 1). The geological subsoil of the Hučava torrent watershed is formed

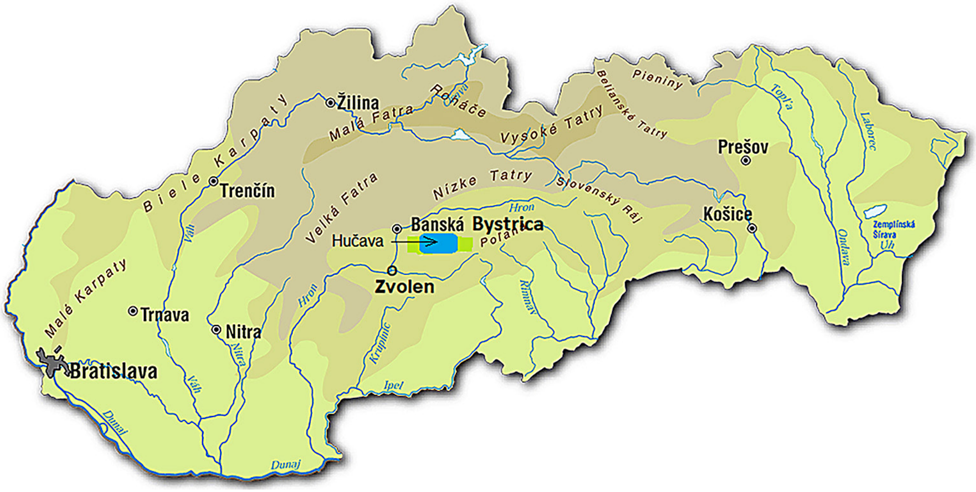


**Figure 1.** Research area – watershed of torrent Hučava

by neovolcanics, including pyroxene and pyroxene hornblende-andesites, andesite porphyry, rhyolites, rhyodacites, rhyolite tuffs and diorite porphyry. In the watershed and in the immediate vicinity of the stream, they occur from soil types Eutric and Distric Cambisoils, loamy, moderately graveled [Composite Authors, 2002]. The basic characteristics of the Hučava watershed and torrent include are presented in Table 1 and 2 [Jakubis and Jakubisová, 2019].

Geometric characteristics of directional arcs were delineated and focused in the field. After delineation of apex of the arc PTI, the inflection points of the arc were marked, it means the beginning of the arc BLA, end of the arc ELA (Figure 2). Then, the center of the arc CLA was determined. The main points of the circular arc were measured in the axis of the watercource. Individual distances were measured with a Leica DISTO A5 laser distance meter. According to the methodology proposed by [Rosgen, 2008, 2009], the authors geodetically focused the concave bank at the CLA point. From the plotted data, the angle of the bank and the percentage of its coverage by the vegetation cover was determined. The vegetation cover was expressed as a percentage of the total oblique length of the bank which was covered by vegetation. A schematic sketch of a simple circular arc with the marking of individual points is shown in Figure 2.

It was assumed that steep bank slopes mean greater erosive damage, small slopes mean less erosive damage. Similarly, it was assumed that higher vegetation coverage of the bank means greater protection of the bank from erosion and vice versa.

**Table 1.** Characteristics of watersheds and torrent Hučava (part 1)

| $A_w$ (km$^2$) | $H_{minw}$ (m a.s.l.) | $H_{maxw}$ (m a.s.l.) | $\Delta H_w$ (m) | $H_{øw}$ (m a.s.l.) | $L$ (km) | $L_{tr}$ (km) | $L_t$ (km) | $D_w$ (km.km$^2$) | $L_v$ (km) |
|---|---|---|---|---|---|---|---|---|---|
| 41.16 | 523 | 1457 | 934 | 929 | 14.20 | 33.63 | 47.82 | 0.861 | 14.52 |

**Note:** $A_w$ – watershed area; $H_{minw}$ – minimal altitude of the watershed; $H_{maxw}$ – maximal altitude of the watershed; $\Delta H_w$ – absolutne watershed heigth difference; $H_{øw}$ – mean altitude of the watershed; $L$ – length of main stream; $L_{tr}$ – total length of tributaries; $L_t$ – total length of watercourses in the watershed; $D_w$ – density of watercourses in the watershed; $L_v$ – length of thalweg.

**Table 2.** Characteristics of watersheds and torrent Hučava (part 2)

| $H_{mint}$ (m a.s.l.) | $H_{maxt}$ (m a.s.l.) | $\Delta H_t$ (m) | $A_f$ (km$^2$) | $f_{\%}$ | $L_d$ (km) | $S_{øt}$ (%) | $S_{øw}$ (%) | $B_w$ (km) | $w_w:\ell_w$ (-) |
|---|---|---|---|---|---|---|---|---|---|
| 523 | 1328 | 805 | 34.83 | 84.62 | 34.34 | 5.67 | 32.48 | 2.84 | 1:5.11 |

**Note:** $H_{mint}$ – minimal altitude of the torrent; $H_{maxt}$ – maximal altitude of the torrent – source; $\Delta H_t$ – absolute torrent height difference; $A_f$ – forested watershed area; $f_{\%}$ – percent of forest area of the watershed; $L_d$ – legth of the divide; $S_{øt}$ – mean gradient of the torrent; $S_{øw}$ – mean slopes gradient of the watershed; $B_w$ – mean width; $w_w:\ell_w$ – width/lenght ratio of the watershed.

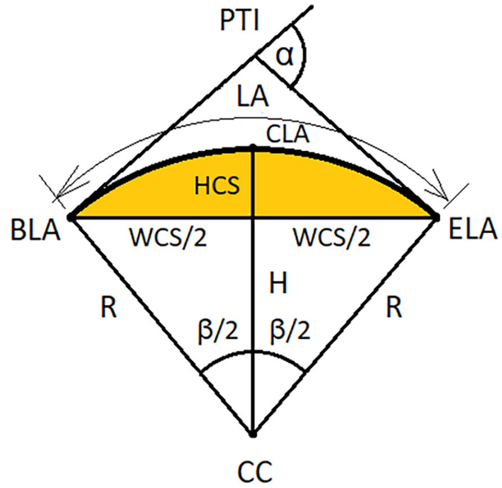


**Figure 2.** Symbols in simple circular arc; PTI – apex of the arc, LA – length of circular arc, BLA – beginning of circular arc – inflection point, CLA – center of circular arc, ELA – end of circular arc – inflection point, R – radius of curvature, CC – center of the circle, WCS – distance between BLA and ELA, HCS – heigth of circular segment, H – difference between R and HCS

From field measurements, calculations of individual quantities were performed according to equations 1–9. The radius of curvature was calculated by the equations 1–4:

$$R = \frac{WCS^2}{8\,HCS} + \frac{HCS}{2} \tag{1}$$

alternatively

$$R = \frac{(WCS/2)^2 + HCS^2}{2\,HCS} \tag{2}$$

possibly also

$$R = \frac{WCS/2}{\sin\left(2\,arctg\left(\frac{HCS}{WCS/2}\right)\right)} \tag{3}$$

or

$$R = \frac{WCS}{2\sin\left(2\,arctg\left(\frac{WCS}{2HCS}\right)\right)} \tag{4}$$

The lenght of circular arc we calculated by the equations 5 and 6:

$$LA = 2\,R\,arcsin\left(\frac{WCS}{2\,R}\right) \tag{5}$$

and

$$LA = 4\left(\frac{WCS^2}{8\,HCS} + \frac{HCS}{2}\right).arctg\left(\frac{HCS}{WCS/2}\right) \tag{6}$$

The value of H was calculated by equation (7):

$$H = \sqrt{R^2 - \left(\frac{WCS}{2}\right)^2} \tag{7}$$

The size of angle β/2 was calculated by the equations:

$$\cos\frac{\beta}{2} = \frac{H}{R} \tag{8}$$

and

$$\sin\frac{\beta}{2} = \frac{WCS/2}{R} \tag{9}$$

## RESULTS AND DISCUSSION

The measured and calculated characteristics of RCA are shown in Table 3. Detailed explanation of symbols in Table 3 are contained in Figure 2.

By analyzing the relation between bank angle BA (°) and vegetation coverage of the bank VEG (%) a strong correlation was found ($R = 0.980$ and $R^2 = 0.961$). The relation is shown in Figure 3. The bank angle BA (°) and vegetation coverage of the bank VEG (%) interact.

The values of the $R/W_{bkf}$ ratios range from 1.31 to 9.34 with an average value of 3.915 and median of 2.52. From Figure 4 it can be concluded that lower values of the $R/W_{bkf}$ ratio mean steeper – more erosively damaged concave bank in the arches. As the $R/W_{bkf}$ ratio decreases, the slopes of these banks decrease – they are less damaged by erosion. From Figure 5 it can be concluded that lower values of the $R/W_{bkf}$ ratio mean lower percentage coverage of concave banks and thus greater erosion.

Figure 6 shows relation between $R/W_{bkf}$ ratio and VEG/BA coefficient. Figure 7 shows a 3D graph of relations between the $R/W_{bkf}$ ratio, BA (°) and VEG (%). Wafer graph of relation BA = f($R/W_{bkf}$) contains Figure 8, wafer graph of relation VEG = f($R/W_{bkf}$) is found in Figure 9.

Regression equations of analyzed relations are contained in Table 4. Statistical characteristics and testing are contained in Table 5.

Rosgen [2008, 2009] based on the $R/W_{bkf}$ ratio created a scale for determining the value of Near Bank Stress (NBS) which is given in Table 6.

Williams [1986] used the $R/W_{bkf}$ ratio value to analyze 79 meanders from a large variety of physiographic environmants in various countries. The $R/W_{bkf}$ ratio values ranged from 1.02 to 6.97 with an average value of 2.43. The author has derived several equations that correspond to the relations

**Table 3.** Characteristics of reference simple circular arcs

| P No. | ST (km) | $W_{bkf}$ (m) | $D_{bkf}$ (m) | WCS (m) | HCS (m) | H (m) | R (m) | LA (m) | AB (°) | VEG (%) | β (°) | $R/W_{bf}$ (-) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.740 | 9.9 | 1.15 | 36.10 | 1.80 | 89.60 | 91.40 | 36.34 | 38 | 92 | 23.18 | 9.34 |
| 2 | 0.950 | 9.7 | 1.10 | 37.50 | 2.01 | 86.45 | 88.46 | 37.79 | 38 | 95 | 24.47 | 9.12 |
| 3 | 1.445 | 9.4 | 1.05 | 18.50 | 2.18 | 18.53 | 20.71 | 19.18 | 53 | 67 | 53.05 | 2.20 |
| 4 | 1.575 | 9.1 | 1.00 | 45.10 | 3.22 | 77.35 | 80.57 | 45.76 | 43 | 82 | 32.51 | 8.85 |
| 5 | 2.730 | 8.8 | 1.10 | 18.05 | 2.06 | 18.74 | 20.37 | 18.67 | 51 | 70 | 51.43 | 2.36 |
| 6 | 2.795 | 8.8 | 1.10 | 18.40 | 1.98 | 20.37 | 22.36 | 18.96 | 48 | 75 | 48.59 | 2.54 |
| 7 | 2.890 | 8.9 | 1.00 | 35.84 | 2.59 | 60.70 | 63.29 | 36.34 | 45 | 88 | 33.30 | 7.11 |
| 8 | 3.435 | 8.7 | 1.05 | 18.62 | 2.24 | 18.23 | 20.47 | 19.33 | 52 | 65 | 54.11 | 2.35 |
| 9 | 3.890 | 8.5 | 1.00 | 34.84 | 2.72 | 54.42 | 57.14 | 35.40 | 42 | 80 | 35.50 | 6.72 |
| 10 | 4.270 | 8.7 | 1.10 | 15.83 | 2.12 | 13.71 | 15.83 | 16.58 | 55 | 61 | 60.00 | 7.82 |
| 11 | 5.385 | 8.3 | 1.00 | 18.78 | 1.92 | 22.00 | 23.92 | 19.30 | 49 | 78 | 46.23 | 2.88 |
| 12 | 5.570 | 8.3 | 0.90 | 14.03 | 1.98 | 11.44 | 13.42 | 14.76 | 58 | 34 | 63.03 | 1.62 |
| 13 | 5.830 | 8.0 | 0.95 | 24.05 | 2.10 | 33.38 | 35.48 | 24.54 | 46 | 84 | 39.29 | 4.44 |
| 14 | 6.430 | 7.9 | 0.90 | 12.16 | 1.98 | 8.34 | 10.32 | 13.00 | 81 | 7 | 72.17 | 1.31 |
| 15 | 7.130 | 7.7 | 0.95 | 18.02 | 1.56 | 25.24 | 26.80 | 18.37 | 46 | 79 | 39.29 | 3.48 |
| 16 | 7.225 | 7.6 | 0.90 | 11.88 | 1.86 | 8.55 | 10.41 | 12.64 | 77 | 11 | 69.56 | 1.37 |
| 17 | 9.450 | 7.3 | 0.95 | 14.28 | 1.92 | 12.32 | 14.24 | 14.96 | 54 | 49 | 60.20 | 1.95 |
| 18 | 7.935 | 7.3 | 0.95 | 14.09 | 2.24 | 9.96 | 12.21 | 15.02 | 58 | 39 | 70.55 | 1.67 |
| 19 | 8.640 | 6.7 | 0.85 | 35.60 | 2.92 | 52.79 | 55.71 | 36.21 | 42 | 90 | 37.27 | 8.31 |
| 20 | 8.790 | 6.7 | 0.85 | 12.12 | 2.02 | 8.08 | 10.10 | 13.00 | 73 | 31 | 74.14 | 1.50 |
| 21 | 9.410 | 6.4 | 0.90 | 15.02 | 1.65 | 16.27 | 17.92 | 15.50 | 53 | 60 | 49.56 | 2.80 |
| 22 | 10.220 | 6.3 | 0.85 | 15.80 | 2.12 | 13.66 | 15.78 | 16.55 | 56 | 66 | 60.08 | 2.50 |

**Note:** ST – stationing (km), $W_{bkf}$ – bakfull width – width of the bed inside the banks (m), $D_{bkf}$ – mean bakfull depth (m).

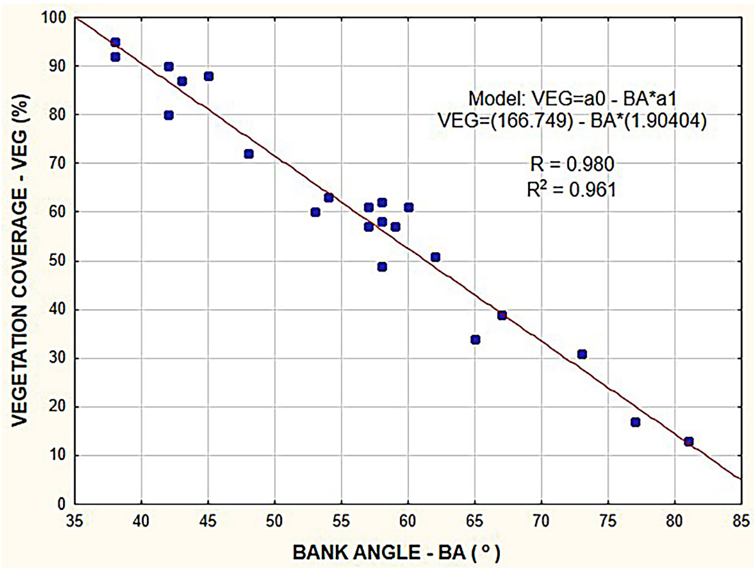


**Figure 3.** Relation between bank angle BA (°) and vegetation coverage of the bank VEG (%)

of channel sizes to river bends features. Larsen et al. [2006] studied 13 sections on the Sacramento River in California, USA. The authors found that the highest values of the mean erosion rate ranged from 7.0 m/year to 8.9 m/year for an $R/W_{bkf}$ ratio in the range of 2.0 to 2.9. As the $R/W_{bkf}$ value increased, the mean erosion rate decreased; for $R/W_{bkf}$ = 7.9 it was 0.4 m/ year. Liu et al. [2021] analyzed 9 river bends on Baihe River (China). The migration rates of river bends ranged from 0,38 to 6,10 m/year. The highest riverbed migration was recorded for the $R/W_{bkf}$ ratio of 2.31.

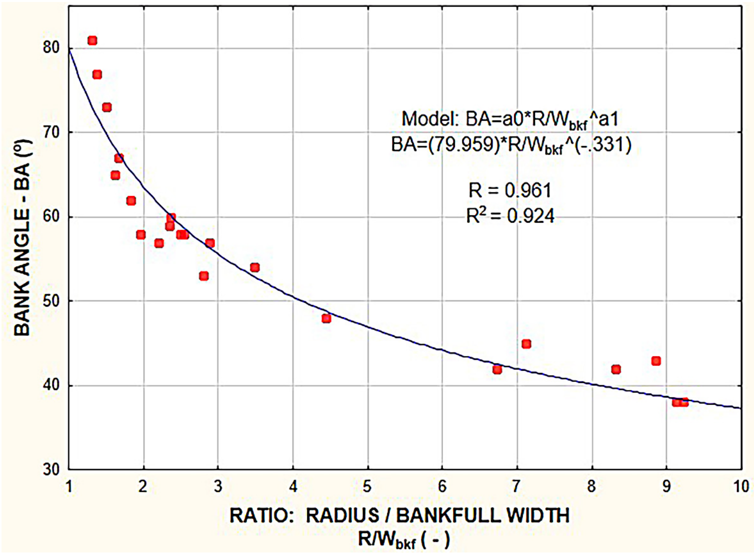


**Figure 4.** Relation between ratio $R/W_{bkf}$ and vegetation coverage of the bank angle BA (°)

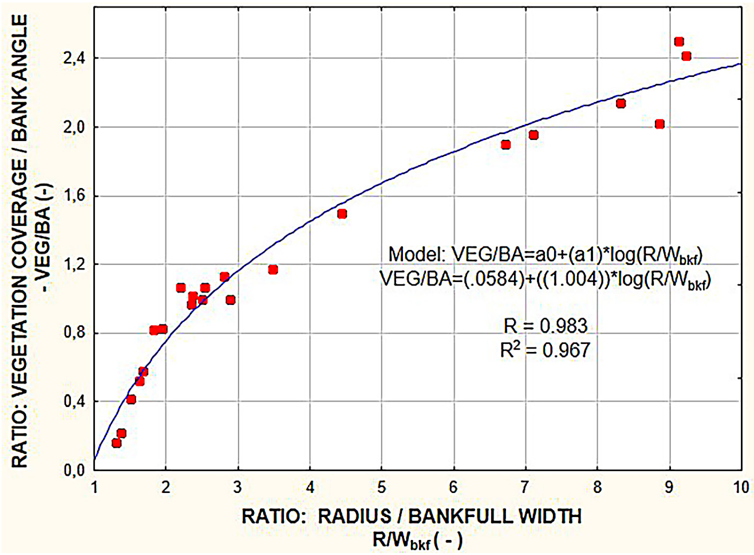


**Figure 5.** Relation between ratio $R/W_{bkf}$ and vegetation coverage of the bank VEG (%)

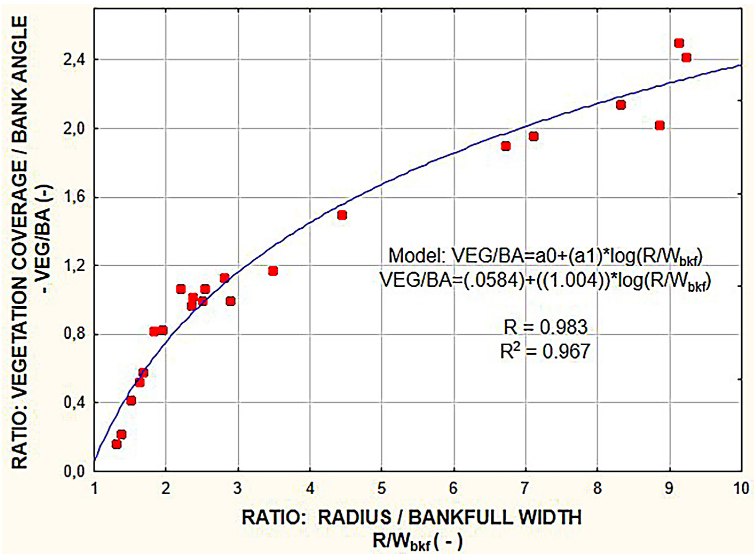


**Figure 6.** Relation between ratio $R/W_{bkf}$ and VEG/BA coefficient

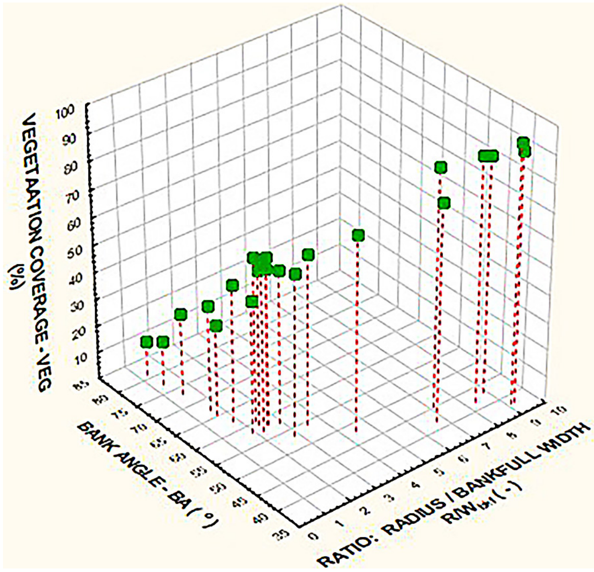


**Figure 7.** 3D graph of relations between $R/W_{bkf}$, BA and VEG

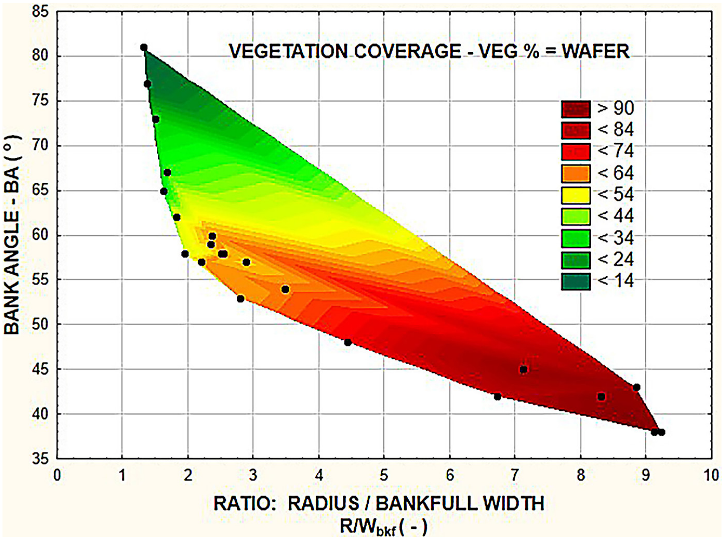


**Figure 8.** Wafer graph of relation BA = f($R/W_{bkf}$)

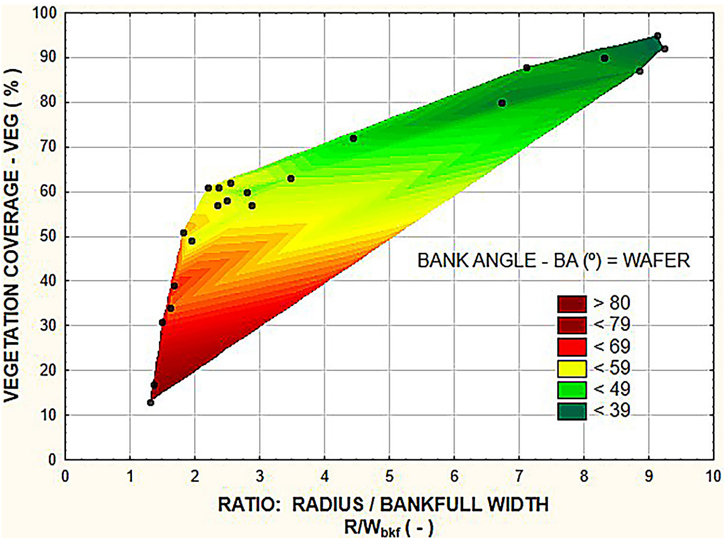


**Figure 9.** Wafer graph of relation VEG = f($R/W_{bkf}$)

**Table 4.** Regression equations od the analyzed relations

| Correlation relation | Regression equation |
|---|---|
| VEG = f(BA) | VEG = 166.749 – BA · 1.90404 |
| BA = f(R/$W_{bkf}$) | BA = 79.959 · (R/$W_{bkf}$)$^{-0.331}$ |
| VEG = f(R/$W_{bkf}$) | VEG = 101.531 – 107.926/ R/$W_{bkf}$ |
| VEG/BA= f(R/$W_{bkf}$) | VEGBA = 0.0584 + 1.004 · log(R/$W_{bkf}$) |

**Table 5.** Statistic characteristics for analyzed relations

| Correlation relation | R | $R^2$ | $S_R$ | t | > = < | $t_{0,01\ (20)}$ | RMSE |
|---|---|---|---|---|---|---|---|
| VEG = f(BA) | 0.980 | 0.961 | 0.044 | 22.27 | > | 2.845 | 4.71 |
| BA = f(R/$W_{bkf}$) | 0.961 | 0.924 | 0.062 | 15.50 | > | | 3.40 |
| VEG = f(R/$W_{bkf}$) | 0.978 | 0.953 | 0.048 | 20.38 | > | | 4.94 |
| VEG/BA= f(R/$W_{bkf}$) | 0.983 | 0.967 | 0.041 | 23.98 | > | | 0.13 |

**Note:** *R*: correlation coefficient; $R^2$: determination coefficient; $S_r$: $\sqrt{\frac{1-R^2}{n-2}}$; *t*: $\frac{R}{S_r}$ ; RMSE: root mean square error.

**Table 6.** Determination of near bank stress by ratio R/$W_{bkf}$

| NBS | Very low | Low | Mederate | High | Very high | Extreme |
|---|---|---|---|---|---|---|
| Value | > 3.00 | 2.21–3.00 | 2.01–2.20 | 1.81–2.00 | 1.50–1.80 | < 1.50 |

## CONCLUSIONS

Erosion on the banks of watercourses can have several negative consequences. These include, for example, deteriorating of water quality, siltation of water of reservoirs, endangering lands near watercourses, especially during floods, and also limiting use of these lands. The results of research of the erosion on the concave sides of torrent arcs can have both practical and theoretical significance. The practical point of view involves the use of knowledge in design of watercourses regulations, the prediction of the degree of endangerment of watercourses concave banks by erosion. Another possibility of use is the location and selection of longitudinal reinforcements on concave watercourse banks, the use of knowledge in the design and revitalization of torrents. From a theoretical point of view, this is an extension of knowledge about the optimization of habitat conditions for the design of anti-erosion effective vegetation on the banks of riverbeds.

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