

1 **Is sinuosity a function of slope and bankfull discharge? – A**
2 **case study of the meandering rivers in the Pannonian**
3 **Basin**

4
5 **J. Petrovszki** ^{1,2}, **G. Timár** ², **G. Molnár** ^{2,3}

6 [1] {Water Management Research Group of the Hungarian Academy of Sciences, Budapest,
7 Hungary }

8 [2] {Department of Geophysics and Space Science, Eötvös Loránd University, Budapest,
9 Hungary }

10 [3] {Geological, Geophysical and Space Science Research Group of the Hungarian Academy
11 of Sciences, Eötvös University, Budapest, Hungary }

12 Correspondence to: J. Petrovszki (geojudit@gmail.com)

13
14
15 **Abstract**

16 The multi-variable connection between the channel slope, bankfull discharge and sinuosity
17 values were analysed in the Pannonian Basin to get a mathematical formula, which predicts a
18 sinuosity value for varying slope and discharge values.

19 The above mentioned relations were studied over the last few decades, but mainly focused on
20 slope and sinuosity or river pattern changes according to the slope and discharge values.
21 Furthermore, in some cases artificial (scaled analogue model) channels were used, instead of
22 natural rivers. With merging the diagrams of these relations, the resulting quasi 3Dimensional
23 graph suggests, that the slope-sinuosity connection works for a wide range of discharge
24 values. The aim of this work is to prove this relation, and describe it numerically.

25 The sinuosity, slope and discharge values of the meandering rivers of the Pannonian Basin
26 (last natural, uncontrolled state, 19th century) were used as a case-study area, to fill in the
27 quasi 3Dimensional graph. A quadratic polynomial surface was fitted onto these points with
28 least squares regression. The average RMS error of this estimation is around 15% on this
29 dataset and believed to be the effect of the non-analysed changes in the sediment discharge
30 and size distribution.

1 **1 Introduction**

2 The morphology of a river is affected by many parameters (e.g. water and sediment discharge,
3 sediment grain size, channel slope, vegetation, tectonics, climate, tributaries ...; e.g.: see
4 Schumm, 2005 for a comprehensive review). The natural, uncontrolled rivers respond to such
5 impacts by changing their shape and pattern. The sinuosity (the ratio of channel length to
6 valley length; Schumm, 1963) is a very useful parameter to uncover the changes. The
7 connection between the slope and sinuosity was studied in flume experiments (analogue
8 model channels) by Schumm & Khan (1972). Leopold & Wolman (1957) and Ackers &
9 Charlton (1970a, 1970b) defined border lines between the different river patterns, according
10 to the channel slope and water discharge values. Timár (2003) merged their results into a
11 quasi-3D diagram (Fig.1.a), which suggests that the results of the flume experiments (with
12 very low water discharge) correlate with observations along natural rivers, independently of
13 the discharge values. In this study, we test this theoretical connection for the rivers of the
14 Pannonian Basin with the aim of describing it numerically.

15 The rivers are bedrock controlled in the mountain regions, and after getting to the plain, they
16 became alluvial rivers. Depending on the main river parameters (especially the valley slope,
17 the bankfull-discharge and the sediment load), they belong to the straight, meandering,
18 braided or anastomosed river patterns. This study is focusing on the meandering alluvial
19 rivers. The rivers, unless their river beds are controlled, chose an optimal channel, depending
20 on the slope, the water discharge and the transported sediment (Leopold and Wolman, 1960).
21 The formation of meanders increases the length of the river, while simultaneously decreasing
22 the channel slope and the velocity (Whitten and Brooks, 1972).

23 **1.1 Slope and sinuosity**

24 Schumm & Khan (1972) carried out flume experiments to detect the effects of the changing
25 slope and sediment discharge on river patterns. They found, that the slope related to the
26 sediment discharge and they proceeded to determine threshold values separating the river
27 different patterns. The river will be straight if the slope and sediment discharge is low.
28 Increasing the slope, the water- and sediment discharge, the river starts meandering then
29 becomes braided (Fig.1.b). It is not so easy to extend the results of the flume experiments to
30 real channels; during the modelling not all parameters can be analysed. But the results of Lane
31 (1957), Ackers (1982) and Ackers & Charlton (1970b) fit to the model of Schumm & Khan
32 (1972).

1 At a given valley slope, the sinuosity is in inverse proportion to the sediment load (Schumm,
2 1963). At given water discharge and valley slope, if the sediment load is constant, a
3 “calculated” sinuosity can be estimated. If the valley becomes steeper, the sinuosity is
4 increasing (self-organising meandering), until a maximum value, but after reaching a certain
5 threshold, any further increase in the slope will result in a decrease of sinuosity (wandering,
6 Miall, 1977; unorganised meandering, Timár, 2003; Fig.1.a).

7 **1.2 How the river patterns depend on slope and discharge?**

8 Leopold & Wolman (1957) analysed the connection between the channel slope and bankfull-
9 discharge along the rivers of the United States, and separated the meandering and braided
10 channels (Fig.1.a horizontal graph). They noted that their results are derived from natural
11 channels, where there are a number of other factors that can affect their behaviour.

12 Ackers & Charlton (1970b) defined the border lines between the meandering and straight pat-
13 terns (Fig.1.a horizontal graph). They found two lines: the upper limit of the straight pattern
14 and the lower limit of the meandering pattern; with a mixed type appearing in between: a
15 straight channel with bars.

16 Knighton & Nanson (1993) extended this original diagram to include anastomosing channels
17 which occur at low slopes. According to Henderson (1966), Carson (1984) and Fergusson
18 (1987) the braiding depends on the grain size of the bed-load sediments: the larger the grain
19 size, the greater will be the slope limit. According to van den Berg (1995), the channel slope
20 is partly dependent on river sinuosity, so he proposed to use the valley slope (which is pattern-
21 independent) instead. This way, the meandering and braided points overlapped. He found the
22 meandering-braided transition is less dependent on the bankfull-discharge than in the original
23 graph. Because of this he introduced the average of the annual floods, which is of the order of
24 the bankfull discharge, but less dependent on the channel pattern.

25 Schumm (1967) proposed that the sediment load determines the meander dimensions. On the
26 other hand, Parker (1976) derived a relation differentiating between the meandering and
27 braided pattern, which was independent of sediment transport.

28 Edgar (1984) analysed the channel formations and thresholds in flume experiments,
29 demonstrating the presence of thresholds. Chang (1985) also classified the rivers into four
30 regions based upon the bankfull discharge, channel slope and median grain size of bed
31 sediment.

1 The above mentioned works concern only the sediment discharge, which is also an important
2 factor of the river planform (Leopold & Wolman, 1957; Schumm, 1960). It was more
3 involved in the work of Simpson & Smith (2001): they suggested studying the silt-clay
4 content, too.

5 **1.3 The quasi 3D-graph**

6 Timár (2003) merged the slope vs. sinuosity (based on flume experiments; Schumm & Khan,
7 1972) and the slope vs. discharge (based on natural rivers; Leopold & Wolman, 1957; Ackers
8 & Charlton, 1970b) graphs. Based on the resulting quasi 3D graphs Timár (2003) argued that
9 the slope-sinuosity graph works for a wide range of discharge values (Fig.1.a). The increasing
10 slope increases the sinuosity until the sinuosity reaches a maximum value for the given
11 discharge. This value is the border of the self-organised and the unorganised meandering
12 pattern (Timár, 2003).

13 Using the sinuosity values along the rivers of the Pannonian Basin (Fig.2.a; Petrovszki &
14 Timár, 2010; Petrovszki et al., 2012), the graph developed by Timár (2003) was filled in with
15 points, to create a real 3D graph.

16 **2 Data and method**

17 As our study aims to define a function of the channel sinuosity vs. the channel slope and the
18 water discharge, we need to gather data for all of the above factors. As the rivers of the study
19 area were subjects of extensive water control works, we need the data, concerning the original
20 status of our streams.

21 **2.1 Sinuosity**

22 The sinuosity values are read from the digitized river thalweg lines. The maps, showing the
23 original river courses, prior to the water control works, are the Second (mainly around 1860;
24 Timár et al., 2006) and the Third (around 1880; Molnár & Timár, 2009) Military Surveys of
25 the Habsburg Empire.

26 The channels were digitized (Fig.2.a), and the resulting polyline was divided into equal length
27 segments (50 m). Along these point series, the sinuosity values were calculated using the
28 definition of Schumm (1963). In our work, the channel length was the window-size, which
29 was changed successively from 5 km to 50 km, with a step of 5 km (Fig.1.c). The valley
30 length was the distance between the two endpoints of the window, along a straight line. Using

1 this method, sinuosity values were calculated for all point of the channel (van Balen et al.,
2 2008; Petrovszki & Timár, 2010; Petrovszki et al., 2012; Fig.1.c).

3 To create the 3D surface, the average sinuosity values calculated with 10 different window-
4 sizes were used. Sinuosity values were available for every 50 m.

5 **2.2 Slope and discharge values**

6 For the water discharge and the channel slope, our initial dataset was the one presented by
7 Viczián (1905). In his book, Viczián (1905) gives an overview of the hydraulic energy
8 potential of the discussed rivers, so water discharge values are given at gauge points (20-30
9 kilometres from each other). Additionally, the heights of the gauges are given, according to
10 the precise levelling works provided by a geodetic survey at the end of the 19th century.
11 Unfortunately, the survey and the published dataset of Viczián (1905) were limited to the
12 higher-slope sections of the rivers. The sections in the Great Hungarian Plain are missing
13 from this data set. Therefore, we completed the initial data set by additional values, provided
14 by the hydrographical survey in the second part of the 20th century (Lászlóffy et al., 1965).

15 The points along the incised valleys are not alluvial but bedrock controlled, so these points
16 were deleted from the data set.

17 Note, that the slope and discharge values derived from the work of Viczián (1905) are
18 spatially more scattered than the sinuosity values calculated from the digitized river thalweg
19 lines.

20 **2.3 Calculating the bankfull discharge**

21 On the original graphs (Leopold & Wolman, 1957; Ackers & Charlton, 1970b) the bankfull
22 discharge was displayed (Fig.1.a). However, the dataset assembled for this study used mean
23 water discharge. Williams (1978) reported 16 ways of determining the bankfull discharge, but
24 none of them used the mean discharge. Williams (1978) compared the calculated bankfull
25 discharges to the flow frequency, and defined their recurrence interval. Depending on the
26 methods, it was between 1 and 5 years.

27 Viczián (1905) did not measure long time series of water discharges, or the maps did not
28 display the cross sectional areas. So, these methods could not be used. Van der Berg (1995)
29 did not analyse the connection between the mean and bankfull discharge. He compared the
30 properties of the different water discharges (mean annual discharge, mean annual flood and

1 bankfull discharge) and their dependence of the channel pattern. However, in the appendix of
2 his paper, he gives the mean and bankfull discharges of many rivers (Fig.2.b). Using the
3 meandering ones, we fitted a line to them (on a log-log scale). Along the small rivers the rate
4 of the mean and bankfull discharge can change on a wide range. For the 1 m³/s mean
5 discharge, 10 and 1000 m³/s bankfull discharge also appeared. Finally, the line was fitted for
6 the rivers with minimum 10 m³/s mean discharge (Fig.2.b). For the lower discharges, no other
7 line was fitted, because of the high deviation. The regression was made for 24 points, and its
8 equation is: $\ln Q_{bf} = 0.692 \ln Q_m + 3.282$, where Q_{bf} is the bankfull discharge, Q_m is the mean
9 discharge ($R^2=0.727$). However, we must note, that the line was fitted onto the points of
10 natural rivers, which were affected by other parameters, too. We used the above fitting
11 equation to generate bankfull discharges from the mean discharges.

12 Despite, that this is not a commonly used method to generate the bankfull discharge, the
13 resulting values are about the same order of magnitude as the bankfull discharge values
14 estimated by other, more established methods. To prove this statement, our results were
15 compared to the graph of Chang (1979), which also demonstrate the relationship between the
16 mean annual and bankfull discharge (using the river data by Carlestone, 1965; and Schumm,
17 1968; $\ln Q_{bf} = 0.756 \ln Q_m + 2.802$). The fitted lines (on log-log scale) are quite similar on the
18 two graphs (Fig.2.b).

19 **2.4 Calculating the natural slope**

20 During the main river control works in the 19th century the meandering rivers became
21 straighter, their lengths shortened so their slope increased. Viczián (1905) measured the new
22 slope values but for this present work, the original values were needed. To correct these
23 slopes, the notes of the river regulations were analysed.

24 The natural slope of the river Tisza was published by Lászlóffy (1982). Along the rivers,
25 surveyed by Viczián (1905) and Lászlóffy et al. (1965) the slope corrections were made for
26 every measured section of the rivers. The river courses, however, were taken from the above
27 mentioned, historical cartographic sources. Using, that majority of the original gauge points
28 were in the same geographic position before and after the control works, their elevation could
29 have been taken from the 'modern' dataset and the channel slopes were computed using these
30 elevations and the 'original' channel length. On the contrary, the discharge values were taken
31 exclusively from the 'modern' data source. This source mismatch is definitely an error source;
32 however these are the only available data for the investigated rivers.

1 In the area of the Great Hungarian Plain, the shortening could be about 40-50%, while along
2 the upper parts of the rivers, it often stayed under 10%.

3 **2.6 Interpolation methods**

4 The results can be displayed for every point (Fig.2.c). However, the aim of the analysis was to
5 verify the slope-sinuosity connection for a wide range of water-discharge, so a surface was
6 fitted onto them.

7 First, different interpolation methods were tested (Kriging, Triangulation with Linear
8 Interpolation, Nearest Neighbour, Local Polynomial), as they tend to highlight different
9 features of the data. While all of the parameters affect the behaviour of the rivers could not be
10 analysed quantitatively (this was not the aim of this study), the slope-discharge-sinuosity
11 connection was approached with a smoothed surface, using Local Polynomial regression
12 (Fig.2.d). In natural rivers, sediment types vary together with sediment discharge regimes.
13 The slope – bankfull discharge – sinuosity connection could be improved analysing the
14 changing sediment discharge.

15 **2.7. Least Squares regression**

16 While testing the different fitting methods, we tried to find the optimal parameter setting
17 which provides the best fit between the model and the original data. In our work, the result
18 surface was composed from several surfaces (for every river pattern), using constrains
19 (continuous surface) at the margins. This problem is formulated in an array-matrix form.

20 In our approach the sinuosity is approximated with a bivariate function of channel slope and
21 discharge. So the sinuosity (P) is z-coordinate and the discharge (Q_{bf}) and channel slope (S_c)
22 are x and y coordinates respectively (Fig.3.a). The model was chose as a quadratic (second
23 order polynomial) function of x and y coordinates (a surface), that fits to the z coordinates.

$$24 \quad P^{\text{model}} = a_0 + a_1 \lg Q_{bf} + a_2 \lg S_c + a_3 \lg Q_{bf}^2 + a_4 \lg Q_{bf} \lg S_c + a_5 \lg S_c^2 \quad (1)$$

25 According to the theory of least squares, the sum of the square of the residuals should be
26 minimized:

$$27 \quad \sum (P_i^{\text{original}} - P_i^{\text{model}})^2 := \text{minimum} \quad (2)$$

1 **3 Results and discussion**

2 According to Stølum (1996) the expected sinuosity value is the π (3.14). Along the rivers of
3 the Pannonian Basin, such high sinuosity value appears, if the bankfull discharge is high
4 enough (Fig.2.c), however it is far from a general value, or even from a most probable figure.
5 Also, as early as in the flume experiments of Schumm and Khan (1972) the maximum
6 sinuosity occurred at the value of 1.3 (Fig.1.b).

7 In this study, the sinuosity values of the smallest rivers were around this value. At higher
8 discharge values, the maximum sinuosity values were also higher. However, not only the
9 higher discharge causes this, because it just affects the size of the bends. But more water can
10 transport more sediment, which can affect the river pattern.

11 Fig.2.c shows the place of the points which were used to create the surface, on the bankfull-
12 discharge – channel slope graph. Fig.2.d was created from these points, using local
13 polynomial regression. Table1 shows a brief statistic of the key variables (channel slope,
14 bankfull discharge and sinuosity). This bankfull discharge – sinuosity relation probably works
15 only in the Pannonian Basin, but in other areas, the graph should be somewhat similar. At a
16 given discharge, if there are enough points, the cross section is similar to the graph of
17 Schumm and Khan (1972). The resulted graph verifies the theory: after a given slope the
18 sinuosity started to decrease.

19 Using linear slope-scale, the curve of Schumm and Khan (1972) is rather a parabola (Fig.1.b).
20 This similarity gives the idea to try to describe the slope-discharge-sinuosity connection with
21 fitting parabolas, at every discharge value. In the zone of the straight pattern, the sinuosity
22 was set to unity by definition. At given discharges, the maximum sinuosity was chosen from
23 the original data. At the braided pattern, the sinuosity was set to 1.3 (the average of the
24 sinuosity values of this area). Comparing the original data to this parabolic model-surface, at
25 lower discharges, the fitting is quite good, but high discharges the model is overestimated.

26 Using the least squares regression (Equation 1 and 2) a mathematical model was created to
27 estimate the sinuosity values at given slope and discharge values (Fig.3.a; Table2). The
28 channel slope – bankfull discharge plain was divided into 4 regions, and for every region a
29 simple surface was fitted on the sinuosity values. In the straight pattern region, a horizontal
30 plain was chosen with the sinuosity set to 1. In the other three pattern regions (self-organised
31 meandering, unorganised meandering and braided patterns) three quadratic surfaces were fit.

1 The parameters of these three surfaces (Table2) were computed with constrains: the fitted
2 surfaces at the margins of the regions have to be continuous.

3 The difference between the model-surface and the original dataset was calculated and
4 displayed. (Fig.3.b and c). Using the quadratic surface fitting method, no overestimation
5 appeared at high discharges (Fig.3.c). The resulted graph is a basic model: however in case of
6 real rivers more or less difference occurs in any case (Fig.3.b). According to our opinion
7 (which was not yet tested or analysed) the main cause of these differences is the effect by the
8 sediment discharge and size distribution. Furthermore, the effect of the sediment load were
9 confirmed in several works (e.g. Leopold and Wolman, 1957; Schumm, 1967; Schumm and
10 Khan, 1972; Chang, 1985)

11 **4 Conclusions**

12 Using the slope, discharge and sinuosity values of the rivers of the Pannonian Basin a model
13 surface can be declared (Fig.3; Table2). This surface estimates the sinuosity at given slope
14 and discharge values. Equations (1) and (2) gives the general form of the fitting (second order
15 polynomial with least squares regression), and its parameters were summarized in Table 2
16 (concern to the Pannonian Basin).

17 According to our results, the sinuosity depends on the slope and discharge values. However,
18 there are some differences between the model and the original datasets, so other river
19 parameters (e.g. sediment load) may also affect the sinuosity. The maximum RMS error
20 remains under 15%. The best fitting appears along the unorganized meandering sections, at
21 steeper channel slopes. (Fig.3.c)

22 The highest differences can be found along the rivers of the Great Hungarian Plain, mainly in
23 the Körös River Basin (Fig. 3.b). Here, the area is very flat, but the water discharge is quite
24 big. According to Ackers and Charlton (1970b), these points should belong to the straight
25 pattern, but their sinuosity is around 3 (these points were not used during the fitting). In this
26 area, neotectonically active faults can be found (Petrovszki & Timár, 2010;), which can
27 locally change the channel slopes. However, the sediment discharge is also differing from the
28 steeper, hilly areas.

29 Along the natural channels, the variations in slope change the sinuosity similarly to what is
30 observed in the flume experiments. The differences between the original data and the model
31 surface are believed to be caused by the sediment load.

1 **Acknowledgements**

2 This study was supported by the project OTKA-NK83400 (SourceSink Hungary); Water
3 Management Research Group of the Hungarian Academy of Sciences. The European Union
4 and the European Social Fund have also provided financial support to the project under the
5 grant agreement no. TÁMOP 4.2.1./B-09/1/KMR-2010-0003.

6 Thanks for Jeff Warburton and Tomaž Podobnikar for detailed comprehensive reviews, and
7 for Zoltán Erdős for the linguistic review.

8 **References**

9 Ackers, P.: Meandering Channels and the Influence of Bed Material, Gavel Bed Rivers,
10 Fluvial Processes, Engineering and Management, edited by: Hey, R. D., Bathurst, J. C., and
11 Thorne, C. R., John Wiley & Sons Ltd., Chichester, 389–414, 1982.

12 Ackers, P. and Charlton, F. G.: Meander geometry arising from varying flows, *J. Hydrol.*, 11,
13 230–252, 1970a.

14 Ackers, P. and Charlton, F. G.: The slope and resistance of small meandering channels, *ICE*
15 *Proceedings*, 47, 388, doi:10.1680/iicep.1970.6579, 1970b.

16 Carlestone, C.W.: The relation of free meander geometry to stream discharge and its
17 geomorphic implications. *Am. J. Sci.*, 263: 864–885, 1965.

18 Carson, M. A.: The meandering-braided river threshold: a reappraisal, *J. Hydrol.*, 73, 315–
19 334, 1984.

20 Chang, H.H.: Minimum stream power and river channel patterns. *Journal of Hydrology*, 41,
21 303–327, 1979.

22 Chang, H.H.: River morphology and thresholds. *Journal of Hydraulic Engineering* 111, 503–
23 519.6, 1985

24 Edgar, D.E.: The role of geomorphic thresholds in determining alluvial channel morphology.
25 In Elliot, C.M. (ed.) *River meandering*. New Orleans, American Society of Civil Engineers,
26 44-54, 1984.

27 Ferguson, R. I.: Hydraulic and sedimentary controls of river pattern, in: *River channels:*
28 *environment and process*, edited by: Richards K. S., Blackwell, Oxford, 129–158, 1987.

- 1 Henderson, F. M.: Stability of alluvial channels, *J. Hydraul. Div. Amer. Soc. Civil Eng.*, 87,
2 109–138, 1961.
- 3 Knighton, A. D. and Nanson, G. C.: Anastomosis and the continuum of channel pattern, *Earth*
4 *Surf. Proc. Land.*, 18, 613–625, doi:10.1002/esp.3290180705, 1993.
- 5 Lane, E. W.: A study of the shape of channels formed by natural streams flowing in erodible
6 material, MRD Sediment Series 9, US Army Corps Eng., Missouri River Div., Omaha, Nebr.,
7 1–106, 1957.
- 8 Lászlóffy, W.: A Tisza – vízi munkálatok és vízgazdálkodás a tiszai vízrendszerben,
9 Akadémiai Kiadó, Budapest, p. 610, 1982.
- 10 Lászlóffy, W., Szesztay, K., Károlyi, Z., Zsuffa, I., Szabó, S., and Kárpátiné, R. D.:
11 Magyarország vízvidékeinek hidrológiai viszonyai, edited by: Goda, L., VITUKI, Budapest,
12 1965.
- 13 Leopold, L. B. and Wolman, M. G.: River channel patterns: braided, meandering and straight,
14 *Physiographic and hydraulic studies of rivers*, US Geological Survey Professional Paper 282-
15 B, US Geological Survey, Washington, 1957.
- 16 Leopold, L. B. and Wolman, M. G.: River meanders, *Bull. Geol. Soc. Am.*, 71, 769–794,
17 1960.
- 18 Miall, A. D.: A review of the braided river depositional environment, *Earth-Sci. Rev.*, 13, 1–
19 62, 1977.
- 20 Molnár, G. and Timár, G.: Mosaicking of the 1:75,000 sheets of the Third Military Survey of
21 the Habsburg Empire. *Acta Geod. et Geophys. Hung.* 44(1), 2009
- 22 Parker, G.: On the cause and characteristic scales of meandering and braiding. *Journal of*
23 *Fluid Mechanics*, 76, 457-480, 1976.
- 24 Petrovski, J. and Timár, G.: Channel sinuosity of the Körös River system,
25 Hungary/Romania, as possible indicator of the neotectonic activity, *Geomorphology*, 122,
26 223–230, 2010.
- 27 Petrovski, J., Székely, B., and Timár, G.: A systematic overview of the coincidences of river
28 sinuosity changes and tectonically active structures in the Pannonian Basin, *Global Planet.*
29 *Change*, 98–99, 109–121, 2012.

- 1 Schumm, S. A.: The shape of alluvial channels in relation to sediment type, Erosion and
2 sedimentation in a semiarid environment, US Geological Survey Professional Paper 352-B,
3 US Geological Survey, Washington, 1960.
- 4 Schumm, S. A.: A tentative classification of alluvial river channels, US Geol. Surv. Circ.,
5 477, p. 10, 1963.
- 6 Schumm, S. A.: Meander wavelength of alluvial rivers. *Science*, 157, 1549-50, 1967.
- 7 Schumm, S. A.: River adjustment to altered hydrologic regimen -- Murrumbidgee River and
8 paleochannels, Australia. U.S. Geol. Surv., Prof. Pap. 598, 65 pp., 1968.
- 9 Schumm, S. A.: *River Variability and Complexity*. Cambridge University Press, New York,
10 ISBN: 978-0-521-04099-0, p.220, 2005
- 11 Schumm, S. A. and Khan, H. R.: Experimental study of channel patterns, *Geol. Soc. Am.*
12 *Bull.*, 83, 1755–1770, 1972.
- 13 Simpson, C. J. and Smith, D. G.: The braided Milk River, northern Montana, fails the
14 Leopold-Wolman discharge gradient test, *Geomorphology*, 41, 337–353, 2001.
- 15 Stølum, H.-H.: River meandering as a self-organization process, *Science*, 271, 1710–1713,
16 1996.
- 17 Timár, G.: Controls on channel sinuosity changes: a case study of the Tisza River, the Great
18 Hungarian Plain, *Quaternary Sci. Rev.*, 22, 2199–2207, 2003.
- 19 Timár, G., Molnár, G., Székely, B., Biszak, S., Varga, J. and Jankó, A.: Digitized maps of the
20 Habsburg Empire – The map sheets of the second military survey and their georeferenced
21 version. Arcanum, Budapest, 59 p. 2006
- 22 van Balen, R. T., Kasse, C., and Moor, J.: Impact of groundwater flow on meandering:
23 example from the Geul river, the Netherlands, *Earth Surf. Proc. Land.*, 33, 2010–2028, 2008.
- 24 van den Berg, J. H.: Prediction of alluvial channel pattern of perennial rivers,
25 *Geomorphology*, 12, 259–279, 1995.
- 26 Viczián, E.: *Magyarország vízierói, Általános fölvétel*, Pallas Részvénytársaság Nyomdája,
27 Budapest, 1905.
- 28 Whitten, D. G. A. and Brooks, J. R. V.: *Dictionary of Geology*, Penguin Books, London, p.
29 516, 1972.
- 30 Williams, G. P.: Bankfull discharge of rivers, *Water Resour. Res.*, 14, 1141–1154, 1978.

1 **Tables and Figures:**

2 Table 1. A brief statistic of the key variables:

	S_c	Q_{bf}	P^{original}
Minimum	0.000052	11.03	1.11
Maximum	0.0058	2216.28	2.50
Mean	0.0013	245.53	1.54
Median	0.00081	131.06	1.48
Dispersion	0.0012	310.52	0.24

3

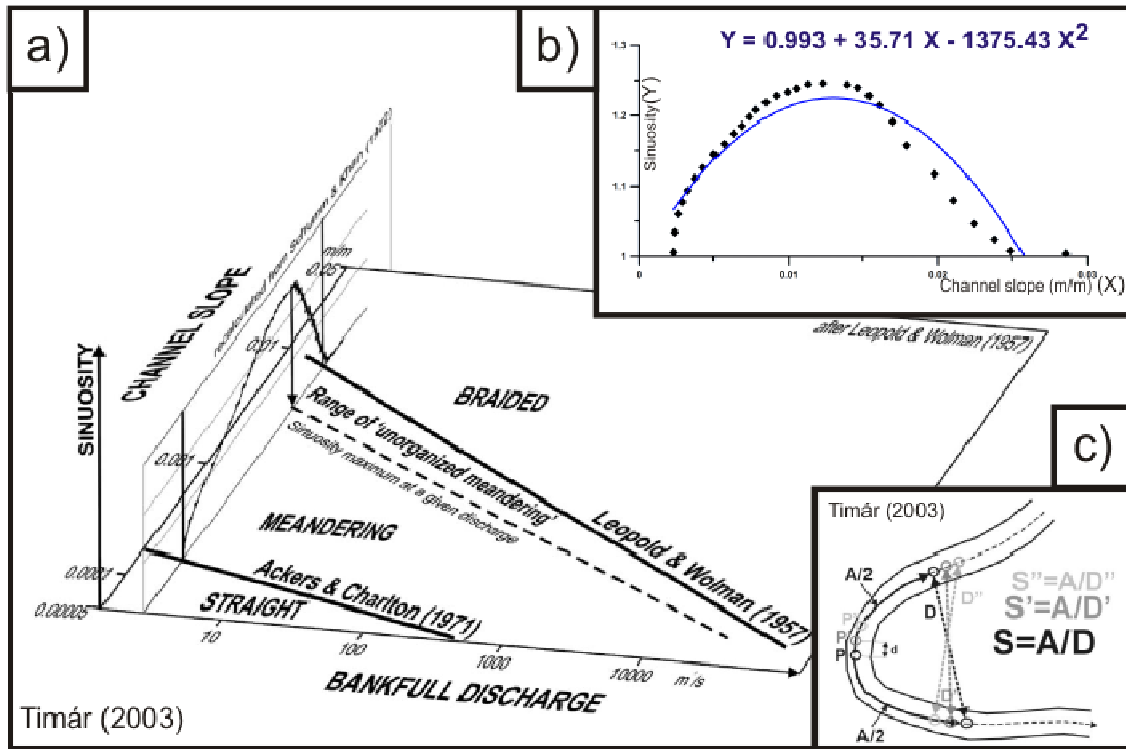
4

5 Table 2. The parameters of the polynomial regression, along the rivers of the Pannonian Basin

	Straight	Self-organised meandering	Unorganised meandering	Braided
a0	1	-6.6945	1.3977	-2.3876
a1	0	0.2345	2.8787	0.3347
a2	0	-4.9453	2.4406	-2.2767
a3	0	0.0337	-0.0802	-0.4646
a4	0	0.0181	0.9156	-0.5851
a5	0	-0.7715	0.8414	-0.5869

6

7

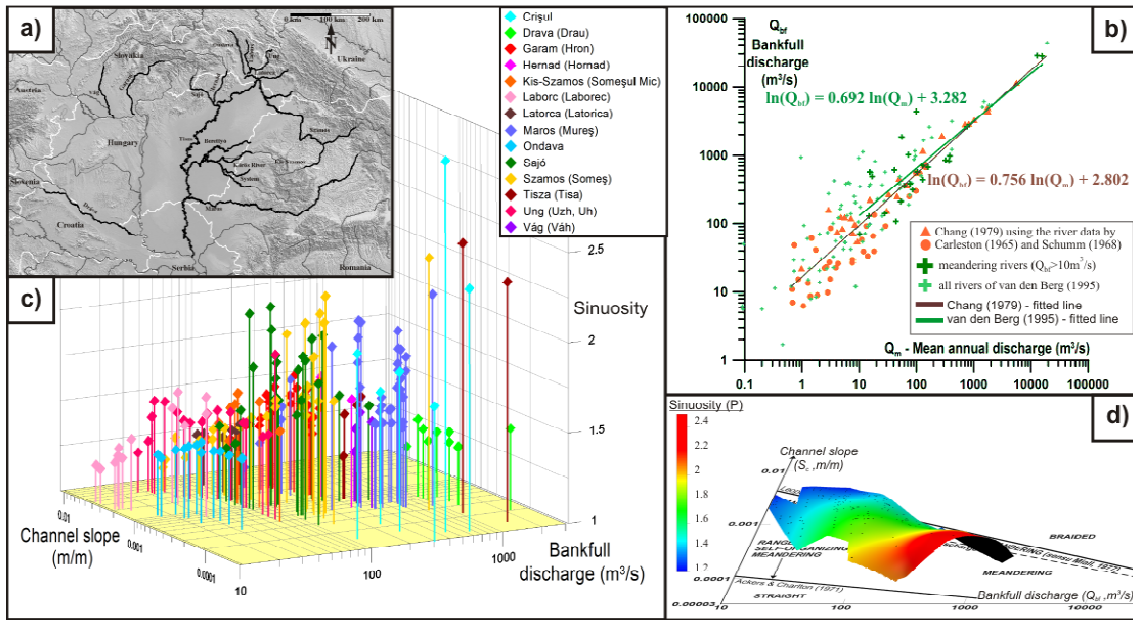


1

2 **Figure 1.** a) The quasi 3D graph of Timár (2003) suggests that the relation between the slope
 3 and sinuosity works for wide range of discharge. b) Using linear slope-scale, the curve of
 4 Schumm and Khan (1972) is rather a parabola. c) We calculated the sinuosity values using a
 5 moving window method. Consequently, sinuosity values were available for every 50 m.

6

7

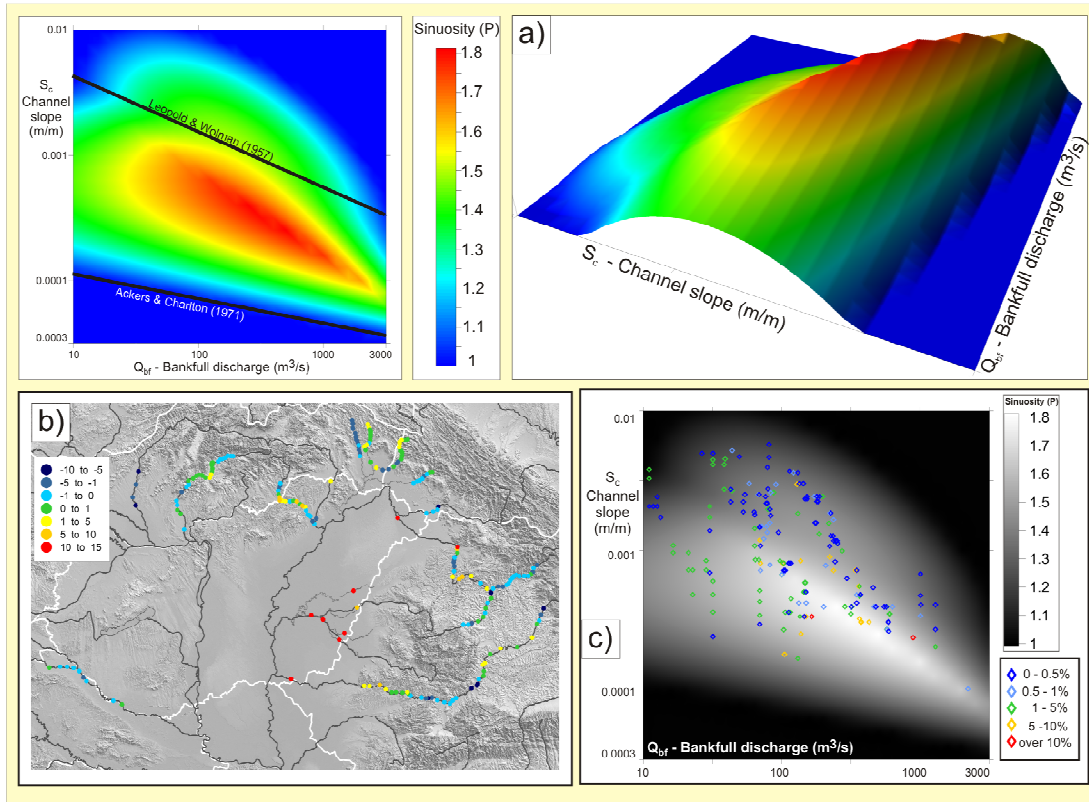


1

2

3 **Figure 2.** a) The study area. b) The connection between the mean annual discharge (Q_m) and
 4 the bankfull discharge (Q_{bf}), using the dataset of Chang (1979) and van den Berg (1995). c)
 5 The slope-discharge-sinuosity values along the studied river sections. d) The fitted surface
 6 shows the estimated sinuosity along the rivers of the Pannonian Basin depending on their
 7 slope and bankfull discharge values, using local polynomial regression.

8



1

2 **Figure 3.** A quadratic surface was fitted to estimate the most probable sinuosity values. Along
 3 the straight patterns, a constant value was used, along the other patterns, different parameters
 4 were calculated, using the least squares regression. The differences (in %) between the model
 5 surface and the original data along the studied rivers (b) and in the different patterns (c).