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MORPHOLOGICAL AND HYDROLOGICAL CHARACTERISTICS OF PALEO-CHANNELS ON THE ALLUVIAL FAN OF THE MAROS RIVER, HUNGARY

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Abstract

The aim of our research was to identify and map the paleo-channel systems on the alluvial fan of the Maros River and to analyse their spatial characteristics. The study on flow directions, horizontal channel parameters and paleo-discharge of the channels can help to forecast the maximum flood discharge and channel changes influenced by climate variations. The paleo-channel generations on the Maros alluvial fan form 13 zones with well defined boundaries. These zones can be either dominated by meandering (5), braided (2), or the mixture of meandering and braided patterns (3). The remaining three paleo-channel zones exhibit an anastomosing pattern but they were not analysed in this study. The horizontal morphological parameters of the braided, the meandering and the misfit channels were measured. Based on these morphometric parameters and regional discharge equations the bankfull discharge of the meandering zones was calculated. The greatest discharge was around 2655 m^3/s while the smallest was 27 m^3/s in case of a misfit paleo-channel. Based on the slope conditions the alluvial fan was divided into three parts. The greatest slope (31.0 cm/km) was found in the central part of the alluvial fan, whilst slightly lower slopes (23.8 cm/km and 24.9 cm/km) characterise its axial and distal parts. These parameters refer to a normal radial profile of an alluvial fan. The channel pattern changes are in close relation with differences in slope. This is the most obvious in zone No. IX, where braided channels transform into meandering and then braided again from east to west in accordance with slope conditions.

Keywords: paleo-channel, paleo-discharge, morphometric parameters, slope conditions

INTRODUCTION

Paleo-hydrological data play an important role in understanding the response of rivers to climate change. For example precipitation and runoff conditions can be reconstructed by calculating paleo-discharge data. There are several methods to reconstruct the hydrological conditions of the past. Some studies use proxy data, for example the ratio of stable oxygen isotopes or the rate of the high-resolution magnetic susceptibility, but morphometric parameters of alluvial channels can provide more precise data (Stein et al., 2004; Carson and Munroe 2005; Scheurle et al., 2005; Saenger et al., 2006).

Scheurle et al. (2005) applied paleo-oceanographic stable oxygen isotope ($\delta^{18}O$) to determine paleo-discharge of the Elbe River. They analysed the rate of isotopes in calcareous shells of marine animals and correlated it to salinity, thus the ratio of salty- and freshwater (referring to paleo-discharge) were estimated. Saenger et al., (2006) applied the same method, but besides they modelled the precipitation conditions of the drainage area too.

Sedimentological, geochemical and micro-paleontological proxy data of surface sediments also allow the reconstruction of paleo-climatic conditions. High-resolution magnetic susceptibility record was used to estimate sediment fluxes and their relationship to paleo-environmental changes by Stein et al. (2004). The variability of sediment fluxes during the Holocene was related to the changes in discharge and coastal erosion input.

Carson and Munroe (2005) applied dendro-hydrology to reconstruct mean annual discharge and precipitation data. The width of an annual tree ring reflects the yearly hydrological conditions and also refers to the near-surface temperature, evapo-transpiration and precipitation (Werritty and Leys, 2001).

Since there is a close relationship between discharge and different channel parameters, a wide range of paleo-discharge calculations exist (Gábris, 1970, 1986; Sylvia and Galloway, 2006; Timár and Gábris, 2008). For example Sylvia and Galloway (2006) reconstructed Late Pleistocene discharge mostly based on horizontal channel parameters of the paleo-channels, whilst Lauriol et al. (2002) beside morphometry also analysed fluvial deposits to study paleo-climatic conditions. The most frequently studied channel parameters in paleo-discharge calculations are radius of curvature, wavelength, channel width and depth. Williams (1984) emphasized the regional validity of these equations, thus the equations can be used only in the same geographical environment and for the same river dimensions the equations were derived from.

In the Carpathian Basin Gábris (1986, 1995) and Timár and Gábris (2008) made paleo-discharge calculations using meander wavelength to study Holocene climate change and the discharge of scour-channels.

On the Hungarian part of the Maros alluvial fan dense paleo-channel systems can be identified, but their flow directions and pattern have not been studied in detail before, though they can provide useful information on Late Pleistocene and Holocene climate changes. The aim of the present study was to identify the abandoned channels and to determine their horizontal morphometric parameters on the Hungarian part of the alluvial fan. Our further goal was to calculate paleo-discharges using existing equations. Meanwhile, slope conditions, being potential causes of longitudinal pattern change on the alluvial fan were also investigated.

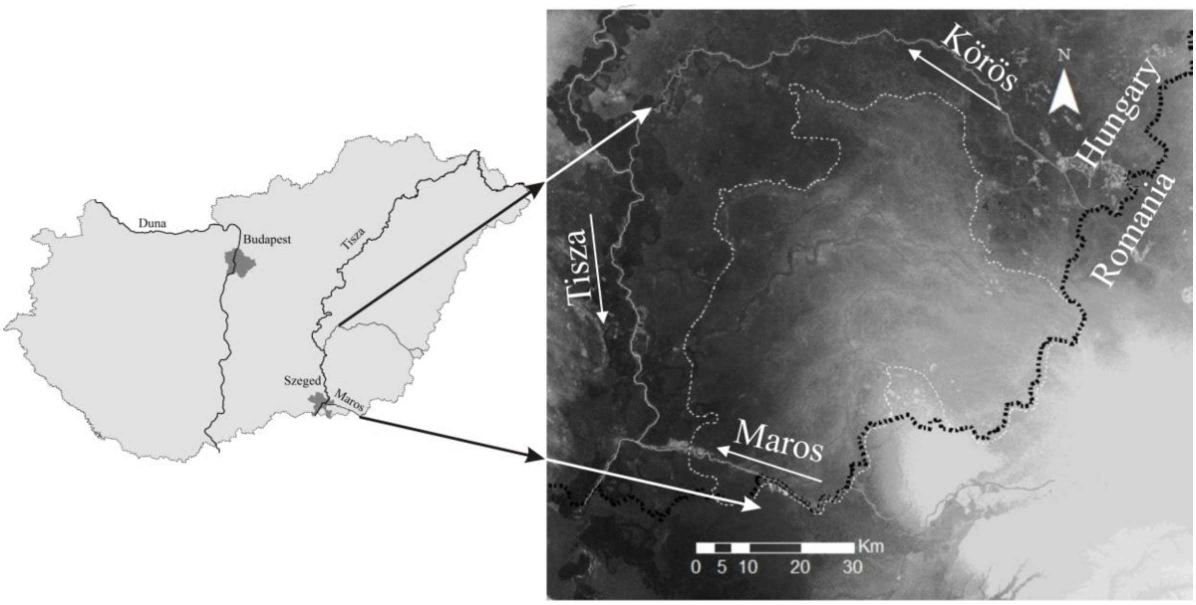

Fig. 1 The study area is on the Hungarian part of the Maros alluvial fan (SRTM model)

STUDY AREA

The alluvial fan of the Maros River has a semi-circular form with a 80-100 km radius (Mike, 1991). It is bordered by the Körös River and its floodplain in north and by the Tisza River and its incised floodplain in west. The alluvial fan stretches also to Romania and Serbia, but in the present study only the Hungarian part (3640 km^2) was studied (*Fig. 1*).

The area of the alluvial fan is affected by tectonic movements (Nádor et al., 2005, 2007). Certain parts are characterised by intensive subsidence, e.g. the Békés Basin or the Makó–Hódmezővásárhely Graben, while others are sinking more slowly, thus exhibit a relative uplifting, e.g. the Battonya–Pusztaföldvár Horst (Joó et al. 2000; Dövényi 2010). Throughout the Quaternary the direction of channels was controlled by the different tectonic activity of the above mentioned areas. The channels slid down from the rising areas and changed their directions towards the sinking basins frequently (Nádor et al., 2005), thus the body of the fan is characterised by intercalated sediment layers (Molnár, 2007). However, the history of the alluvial fan has not been cleared yet. According to Mike (1991) the evolution of the alluvial fan started in the Late Pliocene when the South Transylvanian Basin was drained by the Maros (Somogyi, 1961). However, based on the sedimentary sequences of the alluvial fan Molnár (2007) concluded that the development of the alluvial fan started just in the Early Pleistocene. According to Andó (1976) and Borsy (1989) the formation of the youngest parts started in the Late Pleistocene or in the Early Holocene. It was supported by the measurements of Gábris (1986), who revealed that the Száraz Brook was an active Maros channel or tributary channel in the Boreal Phase. According to Nádor et al. (2007) the Maros River turned to its present direction during the Middle or Late Holocene, as it is reflected by a gravel layer in the sedimentary structure of the alluvial fan. The reconstruction of the development of the alluvial fan is especially questionable along its boundaries, where the sediments of the Maros are intercalated with that of the neighbouring rivers (Molnár, 2007). The flow directions of the paleo-channels are not well known either. According to Márton (1914) the Maros had no well-defined channel until the Pleistocene, as it was split into several secondary channels. The frequent changes of river course were also emphasized by Andó (2002), who mentioned four main flow directions during the Pleistocene. According to Mike (1991), the Holocene Maros channel shifted on the alluvial fan frequently, but in each case at first it turned to north-east then towards to the south. However, Somogyi (1961) supposed a similar drainage network like nowadays at the end of the Pleistocene. The paleo-discharge was determined just for a limited number of paleo-channels (Gábris, 1986) and it showed that in the Boreal Phase mean discharge was similar (160 m^3/s) to the present-day discharge of the Maros (Fiala et al., 2006).

The surface of the alluvial fan is covered by loess, sandy loess sand fluvial sediments containing silt and clay (Dövényi, 2010). The alluvial fan is rich in fluvial forms, dominated by paleo-channels, scour-channels and cut-offs, though in some places sand deposits were blown out and dunes were formed. The Battonya Horst is poor in fluvial forms, as it lies more than 3 meters above the alluvial fan surface and is mostly covered by loess.

METHODS

To identify the fluvial forms on the Maros alluvial fan a digital elevation model (DEM) was created using 1:10,000 scale topographical maps under ArcGIS 10. software with a horizontal resolution of 2 m. Based on the DEM, the paleo-channels, mid-channel bars and point-bars were identified and used for determining channel patterns (braided, meandering, anastomosing and misfit) following the classification of Leopold and Wolman (1957) and the definitions of Rosgen (1996). Considering the pattern and the spatial distribution of forms on the surface the alluvial fan was divided into 13 paleo-channel zones. In case of the braided paleo-channels their width (W), channel length (L_c) and valley length (L_v) were measured, and their sinuosity (S) (channel length / valley length) was calculated. In case of the meandering and misfit paleo-channels the radius of curvature, (R_c), half-wavelength (L) and chord-length (H) were determined. The radius of curvature was deriveted from the largest circle fitting at least at three points to the centre-line of the meander. Half-wavelength was measured between two inflection points along the centre-line (the inflection point was understood as the mid point of the straight section between two bends). Chord-length was equal to the straight distance between two inflection points. Laczay (1982) classified river bends based on the ratio of half-wavelength and chord-length (β = L/H), and defined various development phases. Gábris (1986) suggested that from Laczay's classes only the so called developed and well-developed meanders should be used in paleo-discharge calculations. Finally, palaeo-discharges were calculated applying the regional equations developed by Sümeghy and Kiss (2011).

During the research we were regularly faced to the problem of sudden pattern changes along the paleo-channel zones. To resolve this phenomenon, the slope conditions of the alluvial fan were also studied. The alluvial fan was divided into three belts (axial, central and distal) according to the basic morphological units of such forms (see Rachocki, 1981). The slope of belts was determined along radial lines following the paleo-channel zones. To study slope variations in detail, the slopes of the floodplain and the channel were also measured. Floodplain slope was determined along the paleo-channels, ca. 10 m away from banklines, whilst channel slope was defined along the centre-line of the paleo-channel. The entrenchment ratio was calculated by dividing the floodplain slope with the channel slope.

RESULTS AND DISCUSSION

Morphology of the paleo-channels

Paleo-channels appear in almost continuous zones (13) with well-defined boundaries (*Fig. 2)*. The mean length of paleo-channel zones is 42 km and the adjacent floodplain sections are 4.1-8.7 km wide in average. Zone No. IX has the largest territory (474 km^2), while zones No. II and VI are the smallest (ca. 99 km^2). Each paleo-channel within a zone has a typical channel pattern, though in some cases pattern-changes could also be detected (*Table 1-2)*. Two of the 13 zones (No. III and IX) are dominated by braided channels, though occasionally meandering sections do also appear. Five zones have only meandering paleo-channels, two of them are misfit (No. I and V). Three zones (No. XI, XII and XIII) are dominated by meandering channels with short braided sections. The remaining three zones (No. II, VII and X) exhibit an anastomosing pattern (although sub-channels are meandering, due to uncertain bifurcation points these were not analysed further on).

Table1 Morphometric parameters of braided paleo-channels
(A: area, W: channel width, L_c: channel length, L_v: valley length, S: sinuosity)

Zone		A (km^2)	Channel pattern	W (km)		L_c (km)	L_v (km)	S
				Min	Max			
III.	a	164	dominantly braided	2.3	4.4	62.2	50.2	1.24
	b	146		1.8	3.5			
IX.		474	dominantly braided	1.1	3.4	51.1	43.5	1.17
XI.		452	dominantly meandering	0.8	3.0	13.0	11.8	1.10
XII.		213	dominantly meandering	0.8	5.1	20.4	18.0	1.10
XIII.		375	dominantly meandering	1.6	2.5	12.0	11.6	1.04

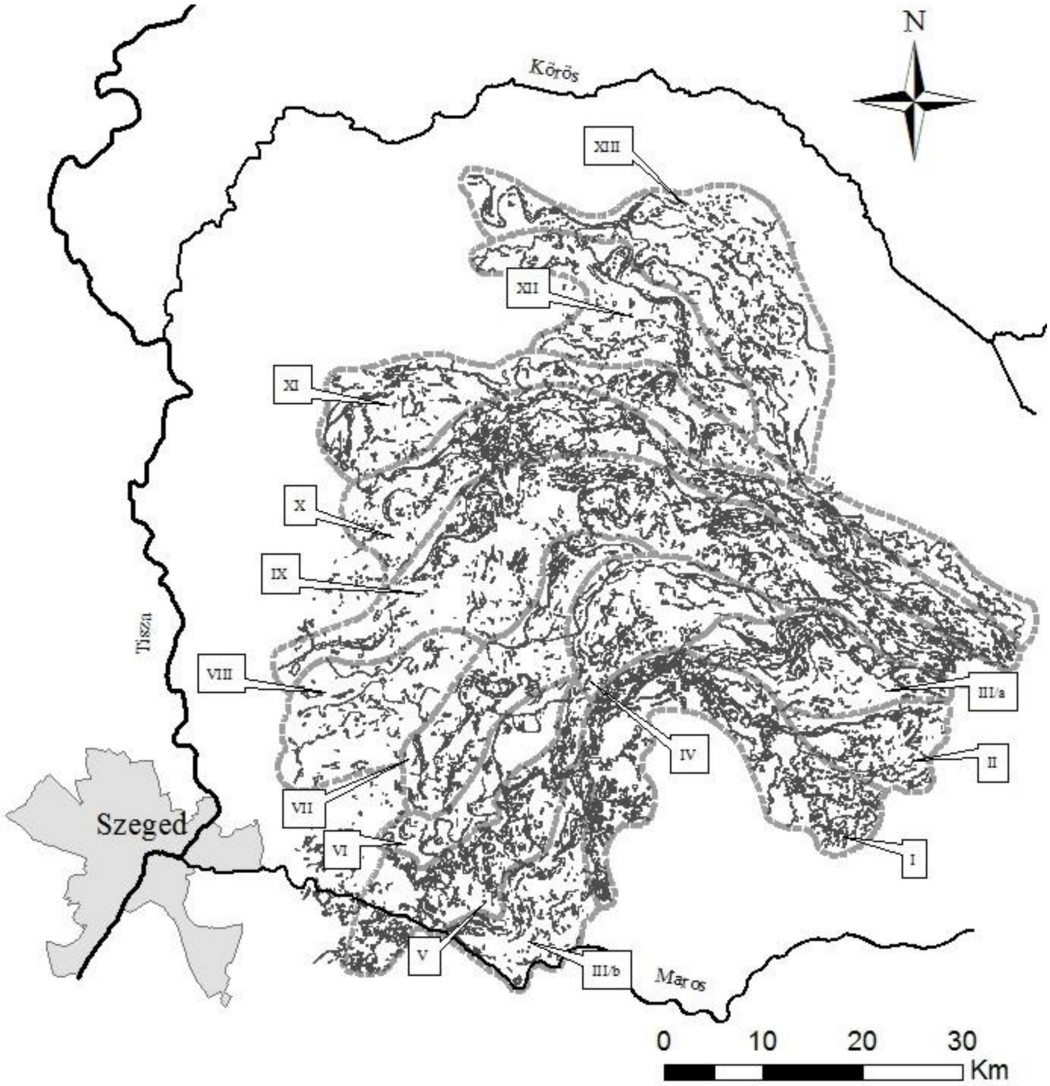

Fig. 2 Paleo-channel network on the Maros alluvial fan. The paleo-channel zones are indicated by Roman numbers (I-XIII). In the lack of absolute age data, at the present stage of the research numbering is based on the morphologically presumed succession of channels

Table 2 Mean values of horizontal channel parameters in the meandering paleo-channel zones and at subordinate meandering sections (R_c: radius of curvature, L: half-wavelength, H: chord-length)

Zone	Area (km^2)	Zone pattern	Number of analysed meanders	Horizontal parameters (m)		
				R_c	L	H
I.	296	meandering	42	202	845	519
		misfit	81	106	340	229
IV.	164	meandering	15	312	1201	710
V.	207	meandering	30	208	1008	435
		misfit	137	67	228	147
VI.	99	meandering	14	528	2175	1246
VIII.	187	meandering	13	478	1472	1113
IX.	452	dominantly braided	14	587	2394	1402
XI.	348	dominantly meandering	55	349	1331	807
XII.	213	dominantly meandering	18	297	958	712
XIII.	375	dominantly meandering	32	656	1775	1390

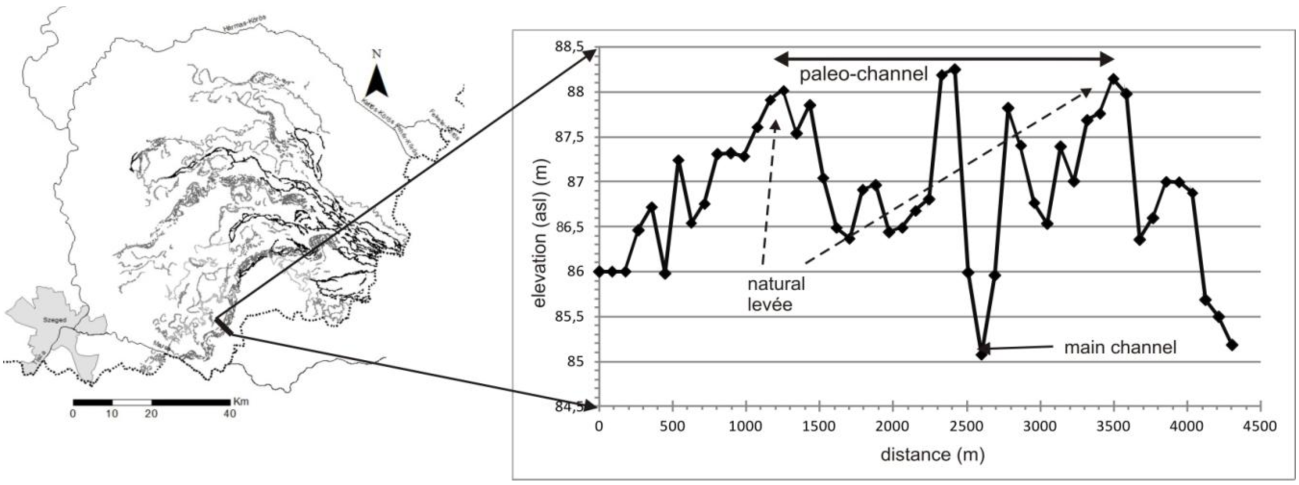

Fig. 3 Cross-section of a braided channel in zone No. III/b

The minimal width of ***braided channels*** varies between 0.8 and 2.3 km, while their maximal width is between 2.5 and 5.1 km *(Table 1)*. The two dominantly braided channel zones (No. III and IX) stretch from the apex of the alluvial fan to its distal, western border, therefore their channel length is between 51.1 and 62.2 km, whilst the length of their valley is 43.5 and 50.2 km respectively. The sinuosity of the braided channels is between 1.0 and 1.2, which fits well to the Leopold and Wolman's classification (1957), having a 1.5 value as a threshold. The forms of the two dominantly braided channels are almost entirely recognisable, though some sections have been reworked by younger meandering and misfit channels. Their natural levees are approximately 1.0-1.5 m higher than the surrounding floodplain surface *(Fig. 3)*.

On the northern part of the alluvial fan, which is dominated by meandering zones, three braided paleo-channel remnants were found. They are only 12.0-20.4 km long and their valley length is 11.6-18.0 km. Certain sections were reworked by meandering channels, thus the banks and the bars partially disappeared.

Meandering channels occupy the southern and western parts of the alluvial fan. Concerning the meandering zones the value of mean R_c varies between 202 and 656 m, L is 845-2394 m, while H is between 435 and 1402 m (*Table 2*). However, the number of the analysed bends was quite different in each zone. The fewest developed and well-developed meanders (in all 13) were identified in paleo-channel zone No. VIII, while there were 55 such meanders in the zone No. XI. The greatest horizontal channel parameters were measured in zone No. XIII (R_c=656 m), and in zone No. IX (L=2394 m, H=1402 m). The smallest mean ratio of curvature (R_c=202 m) and half-wavelength (L=845 m) was measured in zone No. I, while the smallest chord-length (H=435 m) was in zone No. V *(Fig. 4)*. Thus, in case of each parameters the difference in mean values is almost threefold (2.8-3.2).

Decreasing discharge resulted the development of ***misfit channels*** (zone No. I and V), which then reworked the material of the original channel. The mean half-wavelength of misfit paleo-channels is 228-340 m, while the mean chord-length is 147-229 m. The mean value of the radius of curvature is varying between 67-106 m. Values related to the original meanders are 2-4.5 times greater than that of the misfit bends *(Table 2)*.

As according to Gábris (1986) developed (β=1.1-1.4) and well-developed (β=1.4-3.5) meanders are the most appropriate for paleo-discharge calculations, the development phase of the bends was also calculated. Concerning mean values two out of the nine meandering paleo-channel zones (No. XII and XIII) fall into the developed class, while the remaining seven zones are well-developed *(Table 3)*. For all zones the paleo-discharge calculations were carried out using the mean horizontal channel parameters and the formerly created regional equations (Sümeghy and Kiss, 2011).

The greatest mean bankfull discharge was calculated for paleo-channel zone No. IX (2655 m^3/s). This value equals to the present day flood discharge (2400-3200 m^3/s) of the Tisza River (Sándor, 2011) and slightly higher than the present day peak discharge (2420 m^3/s) of the Maros River (Sipos, 2006). On the alluvial fan there are two other paleo-channels with bankfull discharges above 2000 m^3/s (zone No. VI and XIII). Four paleo-channels (No. IV, VIII, XI and XII) have a mean bankfull discharge around 800-2000 m^3/s, which is similar to the mean discharge of the Tisza (800 m^3/s, Tímár, 2003). In zone No. I. original meanders could have four times greater bankfull discharge (493 m^3/s) than younger, misfit channels (119 m^3/s). The difference is even greater in case of zone No.

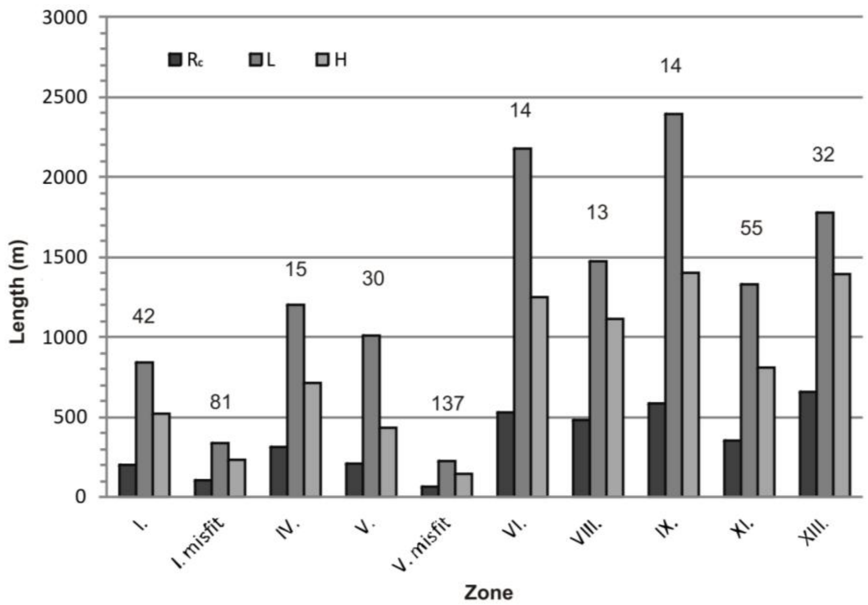

Fig. 4 Mean radius of curvature (R_c,), half-wavelength (L) and chord-lendth (H) values of the meandering paleo-channel zones and the number of the analysed meanders

V., where the original discharge was ca. 508 m^3/s, while the discharge of the misfit channel was only 27 m^3/s. In these cases the earlier discharge of the paleo-channel zones is similar to the present-day bankfull discharge of the Maros (680 m^3/s, Sipos, 2006) and lower than the mean discharge (600 m^3/s) of the Tisza (Sándor, 2011). The bankfull discharge values of the misfit channels are close to the minimum discharge (31 m^3/s) of the present day Maros (Sipos, 2006).

Slope conditions on the alluvial fan

The height difference between the highest (103 m asl) and lowest (77 m asl) points of the alluvial fan is almost 30 m. The greatest slope was found in the central part of the fan (mean slope: 31.0 cm km^{-1}), whilst slightly lower values were experienced in relation with its axial (23.8 cm km^{-1}) and distal parts (24.9 cm km^{-1}, *Fig. 5)*. These parameters reflect the normal radial profile of an alluvial fan (Rachocki, 1981) referring to coarse sediment deposition in the central zone of the alluvial fan (Lecce, 1990).

Our aim was to find relationship between slope and channel pattern. The mean channel slope of meandering zones is 12.3 cm km^{-1} and of the braided channels is slightly higher, 17.6 cm km^{-1}. Therefore, in the central part of the alluvial fan, which has the greatest surface slope, more braided channels or braided channel sections were formed than in the distal zone, which is characterised by mostly meandering channels.

Table 3 The β-values (L/H) refereeing to the development phase of bends and the calculated mean bankfull discharges (Q_{bf}). Discharge calculations were based on the radius of curvature (R_c), half-wavelength (L), chord-length (H)

Zone	β	Bankfull discharge (m^3/s)			
		R_c	L	H	Q_{bf} mean
I.	1.68	649	423	405	493
	1.46	225	70	61	119
IV.	1.80	1154	765	770	896
V.	2.35	673	570	281	508
	1.55	58	13	10	27
VI.	1.73	2199	2087	2376	2220
VIII.	1.40	1919	1076	1899	1631
IX.	1.80	2497	2462	3006	2655
XI.	1.58	1327	908	998	1078
XII.	1.30	1084	524	774	794
XIII.	1.29	2853	1474	2955	2427

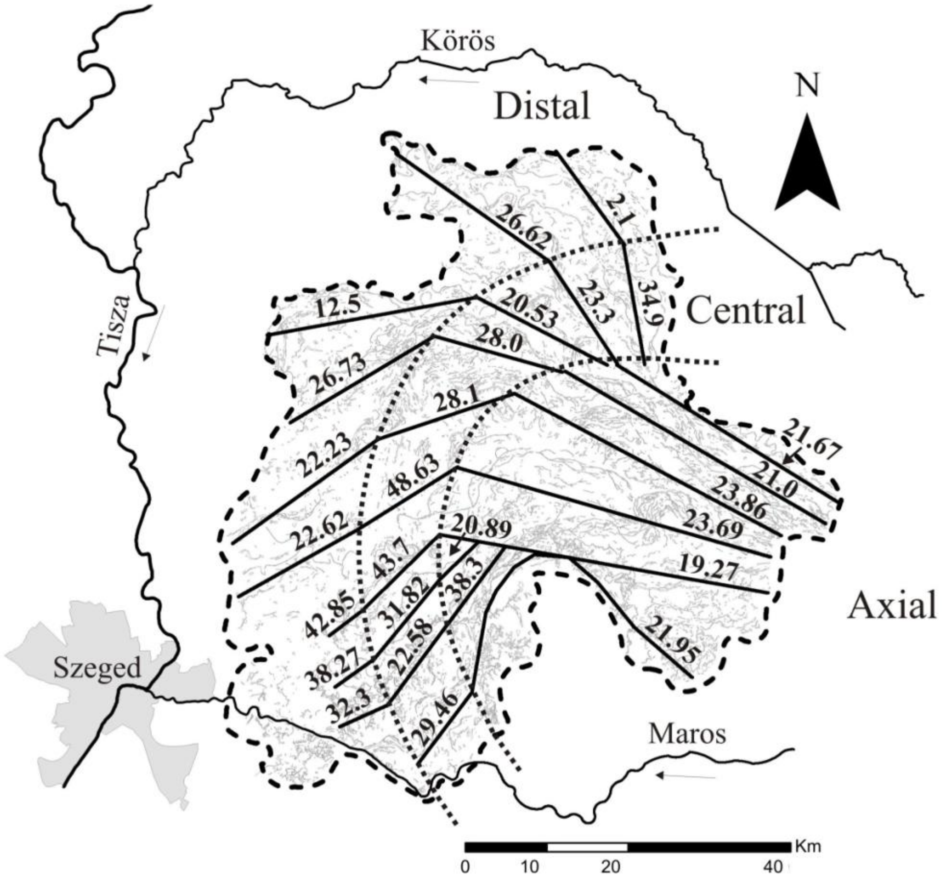

Fig. 5 Slope calculations were made along radial lines following the paleo-channel zones in the axial, central and distal parts of the alluvial fan (cm km^{-1})

The entrenchment ratio of braided paleo-channels is between 1.0 and 1.4, while meandering paleo-channels are more incised (entrenchment ratio: 1.5-2.0), and in case of misfit paleo-channels the ratio is above 2.0. Comparing the longitudinal slope profiles it becomes clear that in case of the braided paleo-channels longitudinal profiles of the floodplain and of the channel are almost parallel. In contrarily, the profiles of the meandering and misfit channels are convergent towards downstream. This can be explained by the tectonic uplift of the apex part of the alluvial fan or by an intensive accretion on the distal parts.

The relationship between channel slope and the channel pattern changes is the most conspicuous in zone No IX. The channel pattern is braided in the axial part of the alluvial fan, meandering in the central part and in the distal part is braided again. These changes are reflected in channel slope as well. The channel slope is 22.4 cm km^{-1} in the eastern part, 19.2 cm km^{-1} in the meandering zone and 25.6 cm km^{-1} where the pattern changes and braided pattern appears again. The pattern change shows similar characteristics in other zones as well, thus the slope of braided channels is usually higher than that of the meandering ones.

CONCLUSIONS

The surface of the Hungarian part of the Maros River alluvial fan was divided into 13 paleo-channel zones based on the channel pattern and morphometric parameters of the identified paleochannels. These zones showed braided, meandering, misfit and anastomosing patterns, though in some zones have a mixed character.

Braided paleo-channels are exceptionally large, their mean width varies between 1.4 and 3.7 km. They are bordered by 1-1.5 m high natural levees, and their channel is dissected by bars. The sinuosity of the braided channels is between 1.0 and 1.2, being under the threshold (1.5) of Leopold and Wolman (1957). The longitudinal profile of the floodplain and the braided paleo-channels are almost parallel (entrenchment ratio: 1.0 and 1.4). These channels mostly appear in the central zone of the alluvial fan, where the surface slope is the highest (its mean value is 31.0 cm km^{-1} and the maximum slope is 49.0 cm km^{-1}), thus these channels could play important role in the sediment transportation and aggradation of the alluvial fan. Similar braided pattern can not be found nowadays in the Carpathian Basin, but they were more abundant in former geological times. Some braided paleo-channels were found on the Romanian part of the Maros's alluvial fan with very similar channel parameters. Braided paleo-channel generations were also identified in the Middle Tisza Region (Gábris et al., 2001) dating back to the Late Glacial Maximum and to the Younger Dryas periods. However, on the alluvial fan of the Hernád and Sajó Rivers braiding channel networks were not identified on the surface despite of the frequent channel changes (Nagy and Félegyházi, 2001; Nagy, 2002).

Meandering channels on the alluvial fan have a highly variable size. Values horizontal morphometric parameters were the lowest in the case of misfit channels (Rc=67-106 m, L=228-340 m, H=147-229 m), thus they had the smallest bankfull discharge (27 and 119 m^3/s). Nevertheless, much larger meanders do also exist on the alluvial fan (Rc=202-656 m, H=845-2394 and L=435-1402 m) with bankfull discharges between 490-2650 m^3/s. The meandering paleo-channels are mostly located in the central and distal parts of the alluvial fan. Their channel slope varies around 12 cm km^{-1}. The entrenchment ratio of meandering channels is between 1.5 and 2.0, referring to slight incision. Floodplain and channel slopes are convergent downstream referring to tectonic uplift at the axial part of the alluvial fan or intensive downstream accumulation.

According to the calculations of Gábris (1986), the mean discharge of the Száraz Brook (in paleo-channel zone I) varied on the alluvial fan between 34 m^3/s and 307 m^3/s. In the present study the paleo-channel of the Száraz Brook was classified as a misfit channel. In zone No. I its mean bankfull discharge was 119 m^3/s, while the older meandering paleo-channel, in which it was developed, had a ca. 500 m^3/s mean bankfull discharge.

Comparing the calculated bankfull discharge to the present values of the Tisza and Maros we found that the largest meandering paleo-channels had bankfull discharges (2427-2655 m^3/s) similar to the present-day peak discharge of the Maros (1600-2500 m^3/s, Fiala et al., 2006) and the flood discharge of the Tisza (2400-3200 m^3/s, Sándor, 2011). The discharges of medium sized meandering paleo-channels (493-794 m^3/s) are around the present day bankfull discharge of the Maros (680 m^3/s, Sipos, 2004) and the mean discharge of the Tisza (800 m^3/s, Tímár, 2003). However, the smaller, misfit paleo-channels transported only 27-119 m^3/s water, comparable to the minimum discharge of the Maros (31 m^3/s, Sipos, 2006).

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