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GENERATIONS OF MEANDERS IN SERBIAN PART OF TISA VALLEY

Abstract: This study discusses the evolution of the Serbian part of Tisa (Tisza/Theiss) valley in the context of phase meandering process during the Late Pleniglacial and Holocene. This study is focused on the subsiding central part of the Pannonian (Carpathian) Basin in the Vojvodina province. Palaeomeanders are reconstructed by using digital elevation models. Large number of old river beds are eroded and filled with deposits, and only a few remainings of them can be found on modern maps. The identification of these channels were achieved by studying historical maps of the region, and by creation of a digital elevation model. Spatial disposal and altitude correlation allowed identification of several palaeomeander generations in the Tisa valley. The formation of different generations are the result of concurrence influences of neo-tectonic processes of subduction in the western part of the Great Hungarian Plain and climate variability during the Late Pleistocene and Holocene. Studying hydro-geomorphologic characteristics of meanders is based on determination and analysis of their characteristic parameters: wavelength, arc length and radius of curvature.

Key words: hydro-geomorphology, meanders, Tisa

Introduction

This study discusses lateral movement of the lower part of the Tisa valley that is a key region to understand the evolution and hydro-geomorphologic characteristics of meanders in the lowland of the Pannonian Basin during the last 25 ka. This part of the river has a very small descent of the river bed and is highly susceptible for typical meandering process. Between Szeged and Titel the descent of the bed was 1.86 cm/km before the regulation in XIX century. Now it has increased to 1.94 cm/km - still inconsiderable (www.terra.hu). Numerous meanders are consequence of intensive lateral erosion. The present course of the Tisa River is the cause of drastic regulation which was made between 1846 and 1910. The river length was shortened by 60 %. On the Lower Tisa during the

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hydro-technical works 12 windings have been cut through. This project established fast transportation of high water as well as flooding protection. The meander zone has been narrowed by building the levees with a relative height of 5 m. This way free flooding was restricted causing disturbance of natural conditions of the meandering process.

By the end of the Early Miocene, the Pannonian Basin started its formation by systematic subsidence. Link between the Pannonian and the Valachian-Pontian Sea had disappeared by the increasing of the Carpathian arch. Many of Carpathian streams slowly filled the Pannonian Basin during the Pliocene. The level of the Pannonian Lake successively decreased. By the end of the Pliocene the drainage basin had been slowly established. Streams from increasing margin zones were introduced toward subsiding depressions. Changing of the subsiding amount in space and time caused evolution of a complex runoff throughout the entire Pleistocene. By the end of Pliocene local subsiding among faults created dramatic reorganization of the runoff of the Pannonian Basin (Gabris, 1998).

Several scientists tried to get geochronological of these changes (Borzi, 1989; Gabris, 1998). Mike (1975) interpreted the changes of the Tisa river course as a result of neotectonic activity in the area. During the Early and Middle Pleistocene the course of the Tisa flowed much more towards the east then the present course through the eastern part of present Hungary. As a result of subsiding margin depressions the runoff has been crucially changed by the end of the Pleistocene. The Danube gradually shifted its course westward and took its present position during the Late Pleniglacial. Absence of older traces from the Late Pleistocene in recent valley has confirmed this statement (Pecsi, 1959). Anomalies in thickness of the Late Pleistocene and Holocene sediments in the recent Danube valley were detected by geological studies. This proves the theory about westward shifting. Formation of younger depressions has caused striking changes of the Tisa river system and its tributaries. Schumm et al, (2000) suggested that a westward shift can be explained in terms of reactivation of the Mid-Hungarian Line in the Late Pleistocene. Accordingly, the Tisa river flows through an area that has very strong neotectonic activity. Rapid migration of the river channel from its previous course is defined as *avulsion*. Avulsion is a widely investigated phenomenon, including studies of the deltaic floodplain of the Rhine-Meuse system (Stouthamer, 2001). Timar et al. (2005) concluded that the age of the main Tisa avulsion is older then it was previously thought. Instead of 10-11 ka, the avulsion date can be estimated as 16-18 ka, after the Last Glacial Maximum (LGM). The river course has been shifted westward by about 80 km. Leaving the Bodrogkoz depression (Northeastern Hungary) the Tisa river established a new valley. Westward shifting of the Danube caused movement of the Tisa river in the same direction (Fig. 1).

During the LGM, intensive aeolian processes occurred (Marković et al., 2008). Abandoned channels were partially filled in with loess like material. Accordingly, almost every meander with significant amount of water preserved its fossil morphology on the Upper Pleistocene Terrace (UPT) as oxbow ponds. Meander shape depressions on the UPT are the remnants of the pre-loess fluvial relief. Large palaeomenders in the valleys of the Zlatica and Galacka Rivers, Veliki and Mali Bikač, Paktovo and Rondetler (Map 1) could not been incised by these small streams, but powerful courses of the palaeo Tisa River.

The lower part of the Tisa River valley is represented by typical plain morphology: Bačka and Titel Loess Plateau, the Upper Pleistocene Terrace (UPT), and the alluvial plain. Plateaus are relicts of loess-palaeosol sequences which are not eroded by fluvial erosion. Titel plateau is consisted of more than 50 m thick loess-paleosol sequences which are formed during the last five glacial-interglacial cycles (Marković et al, 2005).

The UPT is located along the alluvial plain of the Tisa River. In Serbian geologic and geomorphologic studies many synonymous terms are used to determine these units - such as: Loess Terrace, Town Terrace, or Diluvial Terrace. Nevertheless, these terms do not represent the true nature of the UPT. Structure of terrace sediments is rather heterogenic. The lower part is consisted of clastic sediments with different grain size, while the upper section contains various grain sizes. The terrace above the alluvial plain is 6 to 8 m higher. Since the polygenetic character of this morphological unit, it would be the most accurate to define it according to the time of its formation. The surface of the UPT is intersected by abandoned channels which are reduced significantly. Erosion processes can be traced on slopes above palaeo-meanders, i.e. near Lok, where the relative height slope above the Danube alluvial plain exceed 3 m. Previous results (Timar et al., 2005) indicate the westward shift of the Tisa River course. Accordingly, the left side of the valley is full with old river beds, abandoned meanders, point bars, depressions and river branches.

The alluvial plain is the lowermost geomorphologic element. It extends more then 130 km along the both river banks. The width of the plain varies and reaches 27 km. Morphology of the alluvial plain is consisted of: abandoned channels, oxbow lakes, flooding depressions, point bars, sand bars, hills, and islands. Bar height is equal with the mean bankfull discharge, i.e. 1.5 m above mean water level. Prior to the regulation of the Tisa River valley, the extensive alluvial plain has been flooded constantly. Nowadays, flooding is strictly limited on the narrow section among the levees.

Methods

This study is focussed on the lower Tisa river valley extending from the Horgoš cut meander at the Serbian/Hungarian border to the confluence of Tisa and Danube. Based on the 1:25000 scale topographic maps a high resolution digital elevation model (DEM) has been compiled for the study area. The vertical contour interval on these maps is 2 m. The exact projection (Gauss–Krüger) and geodetic data parameters are utilized for the purpose of georeference software tool Microstation (Bentley) that was used for obtaining and for data analyzing. By establishing digital data base usage of CAD tools were provided. The following elements were transited in vertex mode:

- Hydrographic elements (the Tisa river banks, tributaries, canals, abandoned channels, oxbow lakes, small lakes and Danube river banks)
- Morphologic elements (elevation contour lines between 72.5 – 90 m, and point bars).

The dimensions of abandoned channels provide indirect data about the discharge of the palaeo river stream (Dury, 1976; Gabris, 1986). According to the work of Dury (1976) meander wavelength is an important parameter. The relationship between meander wavelength and mean discharge, valid for the rivers of the Great Hungarian Plain, was defined by Gabris (Timar et al., 2008) as follows:

$$L/2 = 80{,}3\ (Q\ cp.)^{0{,}36} \qquad (1)$$

where Qmean is the mean discharge in m^3/s, L is the meander wavelength in meters. According to e.g. Williams (1983), this formula cannot be simply inverted to estimate the discharges from the wavelength. Instead of the inversion, a new formula was derived from the original data of Gabris (Timar et al.,2008) as the following:

$$Q\ cp. = 0{,}0009\ (L/2)^{1{,}8} \qquad (2)$$

Results

Several generations of meanders have been identified in the eastern part of the Tisa valley by using DEM. These generations have been formed as a result of tectonic movements and climatic changes during the Late Pleistocene and the Early Holocene (Tab. 1, Map 2-3). Depths of fossil river beds imply their genesis time. In analyses of abandoned channels it is important to determine their position, either on higher section of the UPT or on lowland of the alluvial plain (Fig. 1).

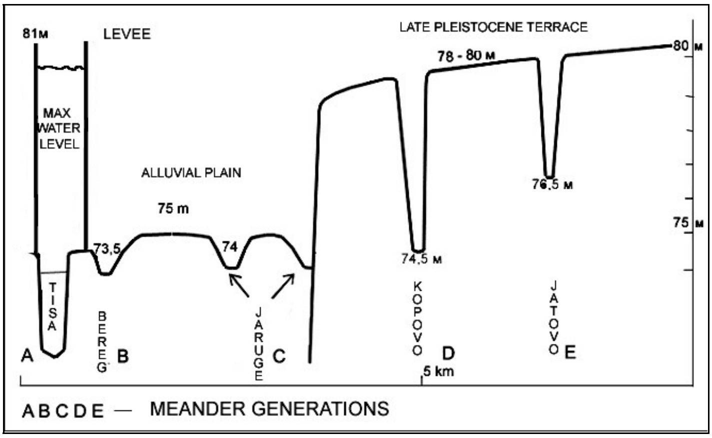


Fig. 1. Cross section of the Tisa valley near Novi Bečej

Morphometric dimensions of meanders are gained precisely enough by DEM. Four parameters were analyzed linear length (L), wavelength (Ml), amplitude (A), and radius of curvature (Rc). Results are presented in table 2.

Table 1. Palaeogeographic evolution of Tisa's fluvial activity during the last 25 ka according to Gabrıs et al. (2008) and relation with definited generations of the meanders

ka Yrs.	Geochrono.Scale	Climate Phases	Fluvial Activity	Characteristics
	Holocene		**A** Generation	Pre-regulation channel
			B Generation	Dry climate, low discharges
17.5	Pleniglacial	Interstadial	**C** Generation	Glacial melting
21		Last Glacial Maximum		Aeolian accumulation
23		Interstadial	**D, E** Generations	Warm and humid climate

Table 2. Morphometric parameters of different generations of the lower part of the Tisa valley

A Generation	**Name**	**R Curvature** (km)	**Wavelength** (km)
	Martonoš	1,1	7,0
	Kanjiža	1,6	12,5
	Sanad“8”	1,4	9,4
	Batka	1,7	10,0
	Medenjača	3,3	13,5
	Ljutovo	2,5	14,0
	Čurug	2,8	17,0
	Mean value	2,0	11,9
B Generation	**Name**	**R Curvature** (km)	**Wavelength** (km)
	N.Kneževac	1,3	13,0
	Bereg	2,2	12,0
	Siget	1,1	8.2
	Zaribnik	0,7	6,0
	Labudica	0.9	7,0
	Mean value	1,2	9,2
C Generation	**Name**	**R Curvature** (km)	**Wavelength** (km)
	Djala	6,1	26,5
	Senta	3,3	26,0
	Čoka	5,8	19,0
	Rokunda	2,6	18,0
	Jaruge	4,7	25,0
	Nadjoš	4,0	18,0
	Ror bara	3,5	19,0
	Mean value	4,3	21,6
D Generation	**Name**	**R Curvature** (km)	**Wavelength** (km)
	Paktovo	1,2	15,6
	Kopovo	3,1	20,2
	Kornjačara	2,8	15,0
	Okanj	2,5	17,5
	Mean value	2,4	17,0
E Generation	**Name**	**R Curvature** (km)	**Wavelength** (km)
	Rondetler	4.8	24,0
	Ludoš	2,8	17,0
	Mali Bikač	2,7	16,5
	Ostrovo	3,1	18,0
	Rusanda	1,3	21,0
	Mean value	2,9	19,3

The easternmost meanders are incised on the UPT (Fig 2). These palaeomeanders are clustered as the “E generation” Petra near Perlez, Koć near Aradac, Rusanda, Bečko Brdo and Ostrovo, Jatovo, and Mali Bikač near Bašaid, Ludoš and Rondetler near Idjoš, and abandoned channels near Banatsko Arandjelovo. The approximate value of their radius of curvature (2.900 m) and wavelengths (19.300 m) are directly proportional to the extreme high mean discharges of the palaeo Tisa River during humid interglacials of the Late Pleistocene Position of the “E generation” meanders on the UPT and their dimensions indicate their formation time and cutting before the LGM. Bottoms of abandoned channels rise 1.5 – 2.5 m above the present alluvial plain. The channels altitudes distinguish them from younger generation meanders.

The large palaeochannel of the Tisa river (Fig. 2) formed a highly curved meander Mali Bikač-Jatovo with the wavelength of 4.800 m and the length along the channel is 11.425 m. The mean shape coefficient is 2.3. Such an omega – like meander shape, with the shape coefficient considerably exceeding the optimum value for a meandering channel (which is 1.6 after Makkaveev, 1955), could have resulted either from low flooding levels or from high stability of the floodplain. This meander was incised by the palaeo Tisa during the interstadial phase of the last glacial maximum.

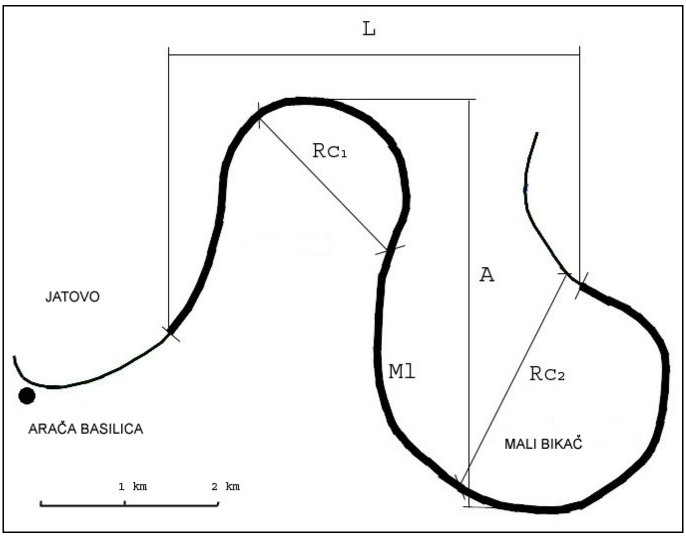


Fig. 2. Palaeomeander Mali Bikač-Jatovo

Beneath the slope of the UPT another "D generation" has been incised. This cluster includes Donja Devenj near Djurdjevo, Aradačko Kopovo, Okanj, palaeomeander near Kumane, Slano Kopovo and Lasino Kopovo, Paktovo and Delečir near Novo Miloševo, Rit near Bočar, Celeruša Bara, and palaeomeander near Krstur. Among all palaeomeanders on the Upper Pleistocene Terrace this fossil channels are positioned the lowest toward the alluvial plain, 0.5 – 2 m above it.

Slano Kopovo, a relict of the Late Pleniglacial fluvial erosion, is situated near Novi Bečej on the UPT. Meander dimensions correspond with dimensions of other palaeomeanders of the "D generation". The loop radius of curvature is between 1.200 m – sharp meander Paktovo, and 2.500 m – Okanj. Mean bankfull width – 450 m exceed dimension of the present Tisa River channel. This meander ratio between the width and the loop radius of curvature means it has been incised by more powerful discharges than present ones, i.e. active meander Ljutovo has ratio 200 : 2.300. By activation of the fault zone on the margin of the Great Pannonian Plain the Tisa river has shifted westward. This way palaeomeander has become fossilized. However, its hydrological functions remained as Slano Kopovo oxbow lake.

At least 3 generations of palaeomeanders can be identified between the UPT and the Tisa river (Map 3). The crucial morphologies on the alluvial plain are large cut off meanders open to the river. This clearly implies on gradual westward shifting of the river. Similar forms traced in the other parts of the valley are dated (Vandenberghe, 2003).

By the end of the Pleistocene global warming process occurred. When large amounts of water trapped in glaciers were released mean discharge increased, discharge amplitudes decreased, and frequency of bankfull discharge intensified. Bankfull discharges have the biggest importance on meandering processes. Below UPT incised the "C generation" clusters of abandoned channels Peglajz near Zrenjanin, Siget near Aradac, Ror Bara near Elemir, Nadjoš near Taraš, Jaruge and Mali Begej near Novi Bečej, Donji Rit near Bačko Gradište, Rokunda near Novo Miloševo, Lap near Padej, Kerina Bara near Ostojićevo, the Čoka meander, Veliki Rit near Senta, Veliki Rit near Kanjiža, and abandoned channels near Martonoš and Djala. All the largest palaeomeanders belong to the "C generation". Mean radius of curvature – 9.200 m and mean wavelength – 21.200 m are proportional to extreme mean high discharge that has created them. These enormous meanders could have been established during the postglacial phase and global warming of the Early Holocene. Among the "C generation" meanders the most remarkable ones are the Djala meander (Rc – 6.100 m; Ml –

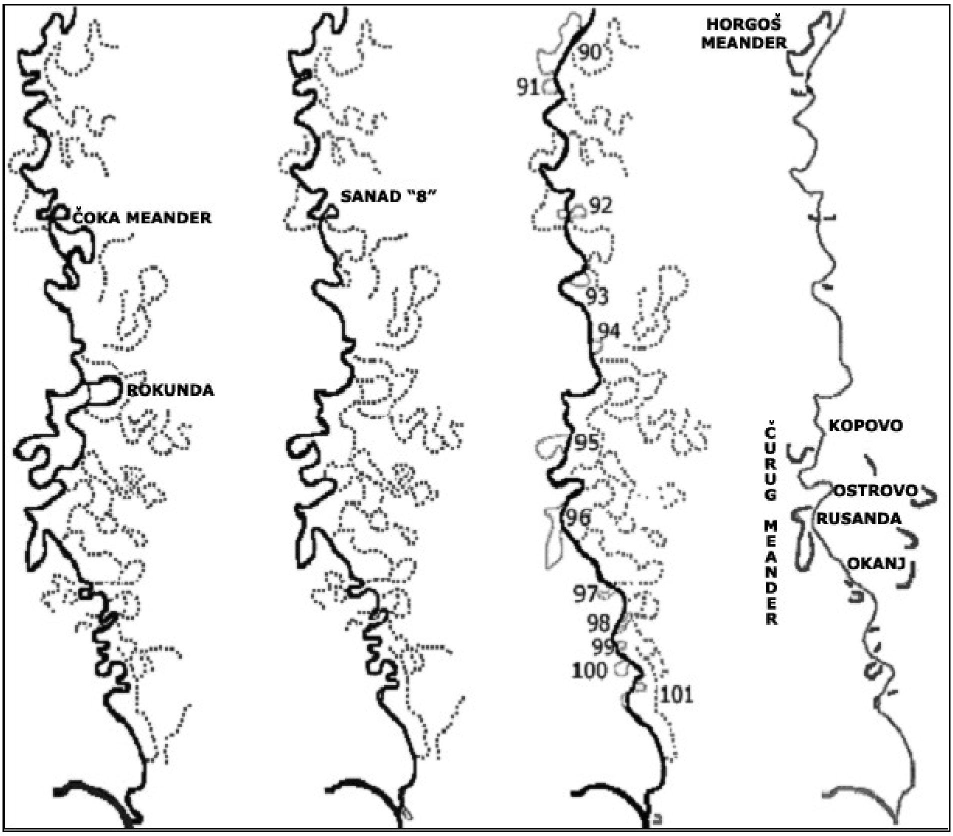
26.500 m), the Čoka meander (Rc – 5. 800 m; Ml – 19.200 m), and Jaruge downstream of Novi Bečej (Rc – 4.700 m; Ml – 25.000 m).

For the meandering process bankfull discharge has pivotal influence. This occurs when a river bed is filled with water just before flooding. With global warming after the LGM total discharges of the temperate latitude European rivers expand. The "C generation" meanders are created in conditions of dramatic increased frequency of bankfull discharges compared with mean discharges.

Closer to the Tisa river it is possible to identify another younger generation of meanders – the "B generation". This cluster includes smaller meanders: Labudica and Zaribnik near Mužlja, Gospodarev Siget near Aradac, Alah Bara near Žabalj, Bereg and Borjaš near Taraš, and abandoned channel near Novi Kneževac. Mean radius of curvature – 1.200 m, and mean wavelength – 9.200 m imply an smaller bankfull discharge which incised them. The "B generation" could have been created during a dry period of the Holocene.

The "A generation" is the last pre-regulation channel of the river and includes Šuljmoš Ada, Komonj, Vrbica, Ajlaš, Jegmeč, Mrtvač, Vrbak, the Čurug meander, Medenjača, Molska Šuma, Batka, Sanad "8"- like meander, the Martonoš meander, and the Horgoš meander. Together with cut offs a protective line of high levees was carried out. Levees follow the channel throughout the entire valley causing the limitation and slowing down of meandering process. Prior to the regulation in 19th century the Tisa River has flooded its valley refilling abandoned channels. Levees construction has incited decrease of the water table and caused the drainage of shallow sections of palaeomeander basins. This can be traced on the maps of the Torontal County of 1910 and the Bacs-Bodrog County of 1905 where all oxbow lakes were significantly bigger than present ones. Nevertheless, the Tisa River has not lost its meandering character. The slope of the river channel is still insignificant and sediment transport capacity is not large, which is a good preposition of meandering processes.

Based on analyses of the Torontal County maps between end of 16th century and beginning of 20th century a reconstruction of the Tisa River valley can be made (Fig. 3). Prior to 18th century east of the present river several active channels can be traced. By continual aggradations these channels were abandoned as shown on the 18th century map of Torontal County. Abandoned meandering channels were common on waste areas both on the alluvial plain and UPT. On the bank of relict meander Jatovo, near Slano Kopovo, remnants of a 11th century church are found. Aracs basilica was built in 13th century on the same location implying a protective strategic role of an anterior hydrologic active channel.



end of 16th ct end of 17th ct early 20th ct early 21st ct

Fig. 3. Reconstructions of the Tisa flow from 16th century to present based on geographical maps.
(Torontal varmegye, veg. XVI, XVII, XVIII, 1896, Budapest)

It is easy to point out the differences if we observe parameters of the fossilized "E generation" meanders of the Tisa River and meanders of the Zlatica River near Idjoš (Fig. 4, Tab. 3). Linear length of the Rondetler channel – 9.000 m is twelve times bigger than mean value of the same parameter of Zlatica meanders. The same results are found among other parameters. Ratios between parameters are showing the similar results on two rivers with different discharges. Dimensions of meanders are directly related to discharges and bankfull discharges, while different ratio between parameters appoints to stadium of evolution.

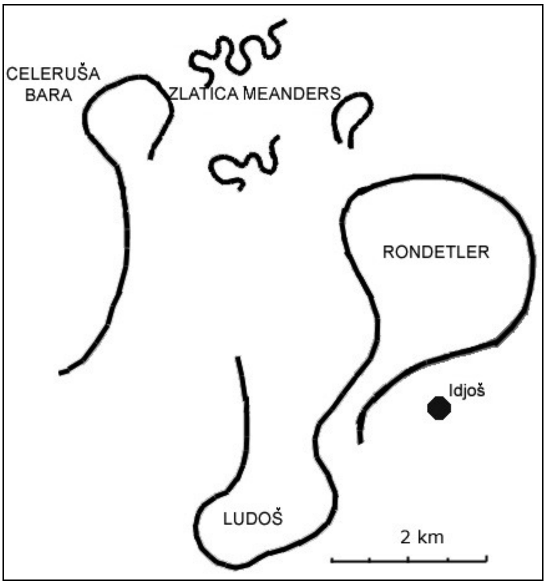


Fig. 4. Fossil meanders of the Tisa and Zlatica rivers

Two courses with different discharges and with the same tectonic conditions and evolutionary stadium will have almost the same characteristic ratio between parameters no matter of course size.

Table 3. Morphometric parameters of the paleomeanders of the Tisa and Zlatica rivers

Parameters and parameter ratios - Zlatica River						
L (m)	**Ml** (m)	**A** (m)	**Rc** (m)	**Ml/L**	**Rc/A**	**A/L**
850	1.751	700	400	2.1	0.5	0.8
750	1.625	500	375	2.2	0.8	0.6
650	1.751	775	375	2.6	0.5	1
Parameters and parameter ratios - E meander generation of the Tisa River (Rondetler)						
L (m)	**Ml** (m)	**A** (m)	**Rc** (m)	**Ml/L**	**Rc/A**	**A/L**
9600	24,000	9,000	4,875	2.5	0.5	0.9

3.1. Evaluation of mean annual discharges of the Tisa River during the Late Pleniglacial and the Holocene

Largest meanders have been incised before 10 ka, during the time of global warming after the late Pleistocene. The average water discharges of the palaeo Tisa during the warmer and humid interstadials of the Late Pleistocene were dramatically larger then present ones. Dimensions of the "E generation" and the "D generation" abandoned meanders indicate this. Average linear length – 7.000 m i.e. 6.800 m are basis for calculation of the average discharges during this period. Using Eq. (2), following rates were obtained: "E generation" mean discharge was 2.155 m^3/s, while the "D generation" has mean discharge of 2.000 m^3/s. A release of an enormous quantity of water after the LGM has increased the average discharges over 2.500 m^3/s. During the Holocene smaller climatic changes occurred effecting the creation of the "B generation". Average discharges dropped to just over 500 m^3/s, significantly below the contemporary values of 800 m^3/s.

Summary

The area between the mouth of the Maros river and the confluence of the Tisa river with the Danube has pivotal importance for hydro-geomorphologic investigations. Abandoned free meandering channels of the palaeo Tisa can be identified on a high resolution digital elevation model (DEM). This study has focused on morphogenetic evolution of meanders. Morphological characters and presence of water in oxbow lakes are proofing the long existence of flowing water and fluvial erosion on the investigated area. Recent and fossil channels and their hydro-morphologic parameters were analyzed. Based on the analyses phase evolution has been determined during the Late Pleistocene and the Early Holocene. Several generations of meanders were identified. The easternmost channels were incised on the UPT, while younger meanders were formed on the alluvial plain. Formation of several generations of meanders was caused by the combined influence of tectonic movements of subsiding and climatic changes during the Pleistocene and the Holocene. Average discharge varied from extremely large to extremely small. Largest meanders have been formed during the humid climate of Interglacials (E and D generations), i.e. during global warming after the Last Glaciation (C generation). Parameters radius of curvature (Rc) and length (L) are proportional to bankfull discharges which has pivotal significance in meandering process.

Regulation of the Tisa River valley and creation of protective levees along channel has dramatically changed the evolution of palaeomeanders. Abandoned channels suddenly were left without connection with the trunk river, the Tisa itself. Partial hydrological function kept only the largest cut off meanders

situated on the UPT as oxbow lakes: Kopovo, Ostrovo, Rusanda and Okanj. Evolution of these lakes remains open to discussion.

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