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CHANGES OF CROSS-SECTIONAL MORPHOLOGY AND CHANNEL CAPACITY DURING AN EXTREME FLOOD EVENT, LOWER TISZA AND MAROS RIVERS, HUNGARY

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Abstract

When examining the characteristics of individual floods Hungarian researchers primarily investigate hydrological and hydraulic processes, whilst the relation between flood events and morphological changes of the river-bed are widely ignored. The present research quantifies the morphological changes of two cross-sections of the lowland reaches of the River Tisza and its tributary, the River Maros, during a high magnitude flood which occurred in spring 2000. During the flood several key morphological cross-section variables (mean depth, channel bed elevation, maximum depth, cross-sectional area and channel capacity) were monitored. Relationships between these data and daily river stage height series of the flood and specific stream power were determined. Results suggest that the identified morphological changes highly affect the channel capacity of the two cross-sections during the flood event. The channel capacity changes (9-10%) were almost identical for both study sites. However, different morphological processes characterised the two cross-sections. We found that morphological parameters depend not only on the actual stream power, but the available amount of sediment for transport, the rate of stage and stream power change.

Keywords: flood, riverbed morphology, specific stream power, water conducting capacity

INTRODUCTION

As a consequence of continuous stage height and discharge monitoring since the end of the 19th century the hydrology of the major Hungarian rivers is fairly well known. Numerous authors have studied the hydrological characteristics of the floods occurring on the Tisza and Maros Rivers (Bogdánfy Ö. 1906, Károlyi Z. 1960a, Bezdán M. 1998, 1999, Vágás I. 2000, 2001, Illés L. et al. 2003). Vágás I. (1984) observed on the River Tisza that the peak stage heights of floods with similar discharges tend to increase since the beginning of the measurements. In order to explain these changes climatic, hydrological, and land use changes in the catchment were investigated (Nováky B. 2000, Rakonczai J. 2000, Somogyi S. 2000, Bodolainé Jakus E. 2003, Gönczy S. et al. 2004). Other studies put a special emphasis on the role of floodplain aggradation (Nagy I. et al. 2001, Gábris Gy. et al. 2002, Kiss T. et al. 2002, Sándor A. – Kiss T. 2006). However, morphological processes (e.g. bank erosion, incision or aggradation) acting in the river channel during floods have rarely been analysed on Hungarian Rivers, even though these processes also influence flood stages (Starosolszky Ö. 1956, Károlyi Z. 1960ab, Sipos Gy. et al. 2007). At the same time more channel survey and discharge data are available (Szlávik L. – Szekeres J. 2003), which could further help the analysis of morphological development.
It is widely accepted that the increasing bed load transport and intensive dune and bar migration during floods have an effect on cross-sectional area (Bogdánfy Ö. 1906, Németh E. 1954, Károlyi Z. 1960b). Thus, morphological changes may contribute to (i) the characteristic loop-like curve of stage-discharge relationships (Németh E. 1954), and (ii) the differences of mean flow velocity during the rising and falling limbs of floods (Németh E. 1929, Vágás I. 1984).

The present study analyses the channel cross-section evolution during an exceptional, high magnitude flood in 2000 at two gauging stations located on the Tisza and Maros Rivers. The aim of the research is to monitor and to quantify morphological changes at each cross-section, and to compare the two rivers with different hydrological characters. The analysis also can help to understand channel changes (channel capacity) during floods, and provide a further explanation for increasing flood levels at the same discharge.

STUDY SITES

The study sites are located on the lowland, sand-bedded reaches of the rivers Tisza and Maros (*Fig. 1A*). The channel cross-sections are at the Algyő (Tisza River) (*Fig. 1B)* and Makó (Maros River), *(Fig. 1C*) gauge stations. These sites were chosen because they are located on similar, lowland sections of the studied rivers. The need for comparison is also supported by the fact that both rivers were severely regulated, but gave different answers for human intervention (flood hazard has increased on the Tisza, but not on the Maros).

One reason for this can be that the two rivers show very different discharge and sediment regime, as it is shown in *Table 1.* Flood duration is significantly longer on the River Tisza (1.5-3 months) than on the Maros, being much flashier (1-2 weeks) (Török I. 1977, Andó L. 2002). The sediment regime of the two rivers is also different. Based on the total sediment loads, the Tisza transports significantly more suspended sediment. However, the specific suspended sediment load is almost three times more on the Maros than on the Tisza indicating greater sediment concentrations. In terms of bed load transport the difference between the two study sites is even more important, as both the total and the specific bed load are significantly higher on the River Maros.

The Algyő gauge station is located at a bridge on a straight section of the River Tisza between two meanders 191.8 river kilometres (rkm) upstream of the estuary (*Fig. 1B*). The bankfull width at the cross-section is 115 m. Based on the full series of measurements (1929-2000), the mean depth is 12.8 m, maximum depth is 18 m, and the thalweg is usually located in the middle of the cross-section, which is typical of inflectional reaches.

The Makó gauge station is located 24.6 rkm from the Maros estuary at the upstream end of a fairly long, straightened reach of the river (*Fig. 1C*). Bankfull width is 112 m, mean depth is 4.8 m. Averaging all the avai-

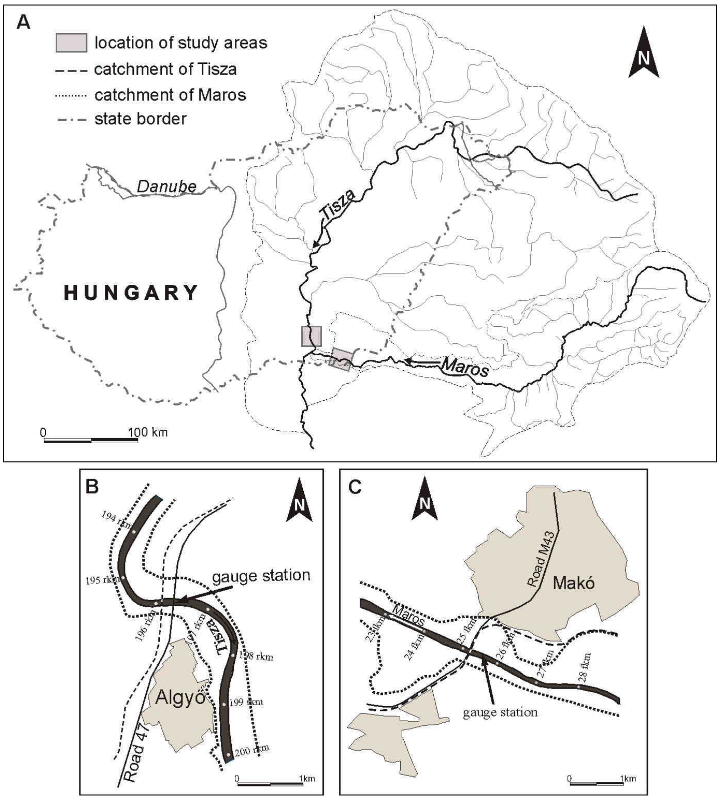

Fig. 1 The location of the studied reaches (A), and the locations of monitored gauge stations near Algyő (B) and Makó (C

Table 1 Characteristic stage, discharge and sediment load values at the Algyő (Tisza) and Makó (Maros) gauge stations. The specific sediment load (t/m^3) is sediment load (t/y) divided by mean discharge (m^3/s). (source of data: http://www.vizadat.hu and Bogárdi 1955, 1971)

		Tisza (Algyő)	Maros (Makó)
Stage height (cm)	maximum (1976-2000)	983	624
	mean (1976-2000)	284	36
	minimum (1976-2000)	-3	-104
	bankfull (2000)	610	310
Discharge (m^3/s)	maximum (1976-2000)	3 820	2 420
	mean (1976-2000)	930	161
	minimum (1976-2000)	63	34
	bankfull (2000)	2 020	850
Sediment load (t/y)	suspended load (1971)	18 700 000	8 300 000
	bed load (1971)	9 000	28 000
Specific sediment load** (t/m^3)	suspended load (1971)	$6{,}3\times10^{11}$	$1{,}6\times10^{12}$
	bed load (1971)	$3{,}1\times10^{8}$	$5{,}5\times10^{9}$

lable cross-sections (1988-2000), the "average" cross-section displays two troughs near the two banks and an elevation in the middle of the channel (*Fig. 7)*. The cross-sections refer to frequent thalweg shifts and thalweg dissection.

METHODS

The stage and discharge data were provided by the ATIKÖVIZIG (Directorate for Environmental Protection and Water Management of the Lower Tisza District). Regular depth measurements, related to discharge monitoring, are similarly made by the ATIKÖVIZIG at the studied gauge stations since 1988. The endpoints of the cross-sections are stable survey-points and their geographic coordinates are determined. In case of the Tisza (Algyő site), water depth is determined from a bridge at 5 m intervals. On the Maros (Makó site) the measurements are made along a steel wire at 2 m intervals. Measurements are carried out on a monthly basis, except during flood events and extreme low water periods when discharge and water depths are monitored daily.

During the selected study period (February 01. 2000 – June 30. 2000) 35 water depth measurements were made on the River Tisza at the Algyő gauge station, and 28 on the River Maros at Makó. In order to follow morphological changes, reference water levels were set at both cross-sections. This reference level was bankfull water stage. It is relatively stable, clearly definable and has a geomorphic importance in terms of signing the stage at which the maximum stream power is exerted on unit area of the riverbed. As a consequence, the comparison of morphological changes became possible in between the two cross-sections as well.

The following morphological channel variables were calculated and monitored: mean depth [d_{mean}]; maximum depth [d_{max}], cross-sectional area [A], all measured from the bankfull level, and morphological roughness [r]. Roughness was defined as the morphological diversity of the riverbed. Its value was calculated as the summed difference between concomitant depth values [d] with the following roughness equation:

$$r = \sum_{i=0}^{n} \left| d_i - d_{i+1} \right|$$

This roughness index is not in relation with those derived from the grain size of riverbed sediments (e.g. Starosolszky Ö. 1970, Fehér F. et al. 1986). It evaluates the channel from the aspect of morphology, and thus it can be identified as form roughness (Nikora V. I. et al. 1998, Millar R. G. 1999).

Based on the dataset of stage variation different phases of the flood could be separated (rising stage, peak flow, falling stage). In order to analyse the different phases of the flood from the point of view of the changes in morphological parameters, the parameters were related to the daily rate of stage variation and specific stream power [ω]. Specific stream power enabled the comparison of the two rivers in terms of energy conditions during different flood phases. Specific stream power was determined according to Graf W. H. – Altinakar M. S. (1998):

$$\omega = Qsg\rho/w$$

where [Q] is discharge (m^3/s), [s] is water surface slope (m/m), [g] is gravitational acceleration (m/s^2), [ρ] is the summed density of liquid and solid phases (m^3/kg), and [w] is water surface width (m). Water surface slope was determined on the basis of stages measured at the studied gauge station and the closest station upstream (6 and 10 km). The floodplain component of width and discharge was disregarded, thus the specific stream power of the channel itself was determined.

CHARACTERISTICS OF STUDY PERIODS

In the spring 2000 a long-lasting flood period was detected in the eastern part of the Carpathian Basin, which could be divided into two main floods. An early spring smaller flood wave was followed by the main flood in May, when simultaneous, long-lasting floods developed on the River Tisza and its tributaries, including the River Maros (*Fig. 2*). The floods of both rivers were divided into differenat phases (*Fig. 3-4*) based on the direction of stage change.

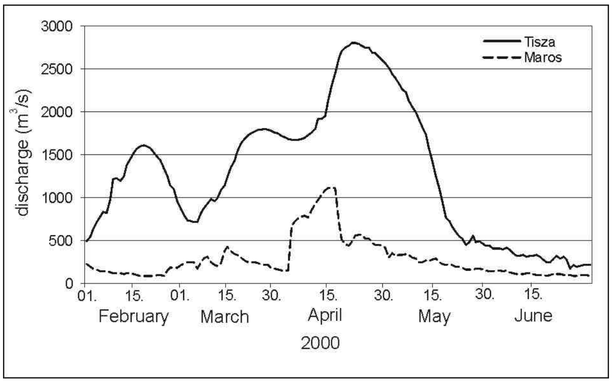

Fig. 2 Discharge curves of the 2000 flood at the Algyő (Tisza River) and the Makó (Maros River) cross-sections (source: Hydrological Year Book, calculated data)

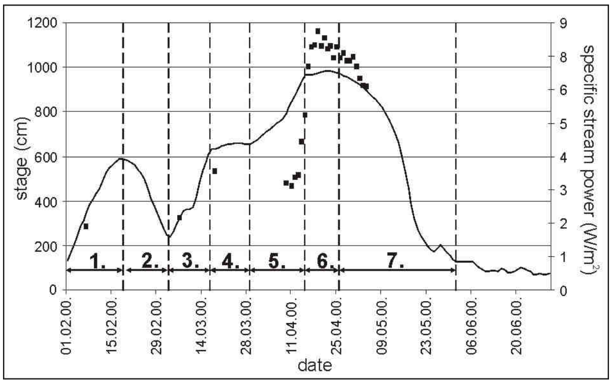

Fig. 3 Hydrograph (solid line) and specific stream power (squares) at the Algyő cross-section (Tisza). Black squares also indicate dates of channel cross-sectional measurements. Phases of floods are indicated as 1-7

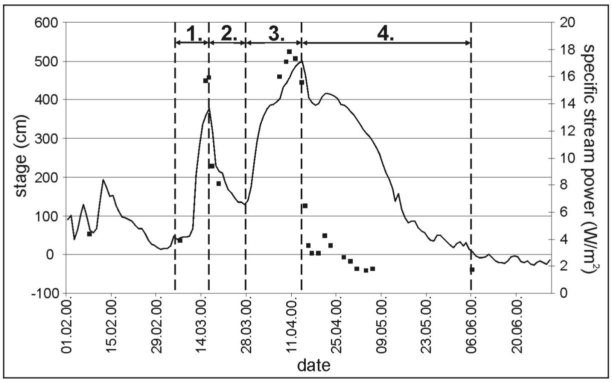

Fig. 4 Hydrograph (solid line) and calculated data of specific stream power (squares) at the Makó cross-section (Maros). Black squares also indicate dates of channel cross-sectional measurements. Phases of floods are indicated as 1-4

The first, early spring flood crest was reached after a very rapid stage rise on both rivers (Tisza: 32 cm/day in average, 39 cm/day maximum; Maros: 55 cm/day in average, 139 cm/day maximum). The flood on the River Tisza reached its crest earlier (phase 1; *Fig. 4*), on February 18 (Algyő: H=587 cm, Q=1610 m^3/s). On the River Maros the highest stage was measured one month later (phase 1-2; *Fig. 3*), on March 16 (Makó: H=378 cm, Q=345 m^3/s) (*Fig. 3-4*). Subsequently, a 17-day and an 11-day long intensive stage fall occurred on both rivers (Tisza: 23 cm/day; Maros: 24 cm/day). Along with the increase of discharge and water surface slope the value of specific stream power at the Makó gauge station (Maros) showed a sudden rise, reaching its maximum during the short peak stage (20 hours) period (ω=15,9 W/m^2). During the first, early spring flood no cross-sectional measurements were performed at Algyő (Tisza), thus no specific stream power could be calculated.

The second flood wave resulted in significantly higher stages on both rivers, at the Algyő gauge station (Tisza) even a new record was observed, since the beginning (1842) of the stage measurements. In the case of the Tisza the major flood, which started in March and terminated in May can be divided into five phases (phase 3-5; *Fig. 3*). First there was a quick stage rise between the 4 and 21 March (in average 24 cm/day, occasionally 66 cm/day), then an eight day long peak period came. Until April 21 another, less intensive rise occurred (in average 14 cm/day, occasionally 32 cm/day). Following the flood crest (H_{max}=983 cm, Q=2810 m^3/s) stage fell back to its pre-flood level in 42 days (in average 20 cm/day stage fall). Values of the specific stream power changed with stage variations. The maximum value (ω=7,3 W/m^2) was reached on April 19, two days before the peak flow arrived (*Fig. 3*). It can be explained by surface slope changes, as the greatest slope is measured before the flood crest.

In case of the Maros flood the rising limb of the second, major wave can be considered continuous (phase 3, *Fig. 4*). The rate of stage rise was similar to that of the Tisza (22 cm/day, occasionally 67 cm/day). The flood crest was reached in 18 days on April 14 (H=499 cm Q=1120 m^3/s), then it was followed by a relatively quick fall (15 cm/day), the continuity of which was disturbed by only a small late wave (*Fig. 4*). The maximum value of the specific stream power was reached four days before the peak flow period at the end of the rising limb (ω=17,8 W/m^2); later it decreased slowly (*Fig. 4*).

Hydrographs of the two rivers (*Fig. 3-4*) are similar in the number of flood crests; however, peak flow durations were much longer in the case of the Tisza than the Maros, and the Maros stage fall was more rapid (20 cm/day versus 15 cm/day). Energy conditions showed greater fluctuations at Makó (Maros) during the flood, and the maximum value of specific stream power was three times higher than in the case of Algyő (Tisza). Reasons were the significantly greater water surface slope and suspended load concentration apparent on the Maros. Another difference between the two rivers was that the maximum value of specific stream power occurred 2 days and 4 days before the peak flow of the main flood wave at Algyő and Makó, respectively (*Fig. 3-4*).

MORPHOLOGICAL CHANGES AT THE ALGYŐ CROSS-SECTION (TISZA)

First rising limb (Phase 1) and second rising limb (Phase 3)

During the first flood (February 1 – March 4) only one rising limb discharge measurement was performed, thus the exact description of morphological changes was not possible. However, the water-depth data obtained on February 7 could be compared to those measured during the rising limb of the main flood wave (*Fig. 6*), since the cross-section was recorded in both cases among similar stage and discharge conditions. Minor differences were experienced in terms of maximum depth (d_{max}=18.2 m, and d_{max}=18.5 m). The roughness index increased slightly (r=28.7 and r=29.2; see *Fig. 6*), as the specific stream power was also greater in phase 3 (February 8: 1.6 W/m^2, March 9: 2.0 W/m^2; see *Fig. 3*). However, in both cases the energy of the system increased suddenly due to intensive stage rise (36 cm/day and 30 cm/day).

Second rising limb (Phase 3) and first peak flow period (Phase 4)

During the first part of the main flood wave (March 4 to March 21) only two cross-sectional surveys were made (*Fig. 3*), one during the intensive rising limb and another during the 8-day long peak flow period.

Rising limb stage increase rate was 30 cm/day in average, with a maximum between March 12 and March 18 (44-66 cm/day). At that time relatively high maximum depth (d_{max}=18.5 m) and roughness index (r=29.2) characterised the channel (*Fig. 6*).

During the peak flow period (March 22-30) both maximum depth (d_{max}=18.0 m) and roughness (r=28.5) dropped, although specific stream power increased in the meantime from ω=2.0 W/m^2 to ω=3.5 W/m^2. Thus, we suggest that the morphological difference between the rising limb and peak flow channel can be independent from changes in the specific stream power.

Third rising limb (Phase 5)

Following a few days of stability water level started to rise again between March 31 and April 19 in the beginning at a rate of 12 cm/day but from April 10 at a rate of 30 cm/day. During this time mean and maximum

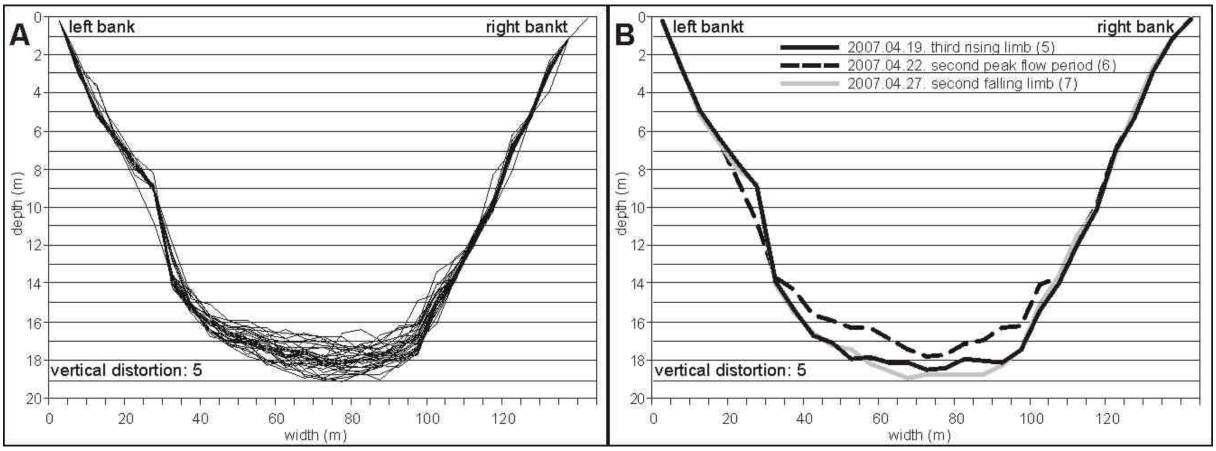

Fig. 5 (A) Monitored cross-channel sections (28) during the 2000 flood (February 8 – May 16) on the Tisza at Algyő. (B) Three characteristic cross-sections taken at different phases of the flood

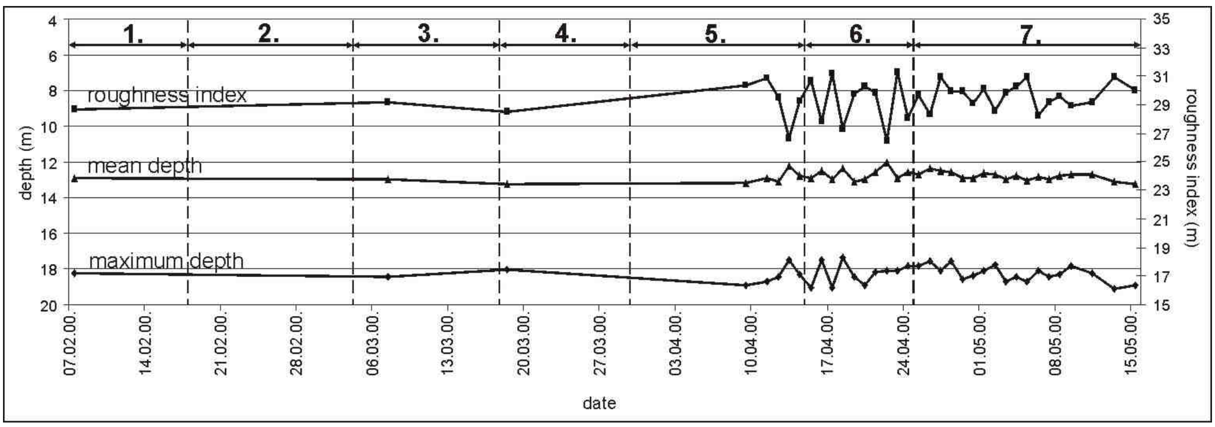

Fig. 6 Variation of morphological parameters during the 2000 flood at Algyő (Tisza). 1-7 indicates the different phases of the studied period

depths were increasing, however in a highly fluctuating manner (*Fig. 6*). The most intensive erosional activity can be related to this period, as the greatest mean and maximum depth values were measured on April 19 (d_{mean}= 13.1 m; d_{max}=19.1 m). Also, at this phase the roughness index of the riverbed reached its maximum (r=29.9 – 31.3) as dunes and dune sequences developed (Fig. 5B). The most probable reason for the river incision and intensive transportation is the greatest value of specific stream power during the flood (on April 19: ω=7.3 W/m^2). Note, that the maximum of ω was experienced two days before the peak stage was reached, its reasons are also in relations with the watersurface slope increase before the flood crest.

Second peak flow period (Phase 6)

During the peak of the main flood wave (H_{max}=983 cm) the mean and maximum depth of the channel (d_{mean}=12.6 m and d_{max}=18.2 m) decreased by 10% (*Fig. 6*). In the background the decrease of stream power (from ω=6.9 W/m^2 to ω=6.5 W/m^2) is the aggradation within the channel (*Fig. 3 and Fig. 5B*). As a result, the area of the cross-section decreased and reached its minimum value (A=1585.4 m^2). In accordance to the aggradation the lowest roughness index was also experienced at this time (r=26.5 on April 22) meaning that r decreased by 10% compared to rising limb maximum values. These changes suggest that the intensity of sediment transport, initiated mainly during the rising limb, decreased significantly in the peak phase (*Fig. 5B*).

Second falling limb (Phase 7)

Subsequent to the 3-day long peak flow period starting on April 21, the water level started to fall at an increasing rate till May 14. In the first period of stage fall (7 cm/day) parallel with the decrease of specific stream power (*Fig. 3*) depth values dropped (d_{mean}=12.6 m; d_{max}= 17.6 m), i.e. the channel aggraded. Nevertheless, when stage fall became more intensive and reached values of 12 cm/day, erosion occurred again (*Fig. 5B and Fig. 6*). The process of channel incision was continuous (d_{mean}=13.0 m; d_{max} =19.1); therefore, cross-section area increased and reached its maximum (A=1742.6 m^2). Roughness also increased (r=30.0), higher values were measured only during the most intensively rising days (*Fig. 6*). At the same time, the value of the specific stream power significantly decreased (from ω=6.4 W/m^2 to ω=5.5 W/m^2).

MORPHOLOGICAL CHANGES AT THE MAKÓ CROSS-SECTION (MAROS)

First rising limb (Phase 1)

In the rising phase of the first flood wave (March 10-16) depth and roughness values increased significantly: mean depth by 11 cm (5%), maximum depth by 84 cm (21%) and the roughness index by nearly 50% (from r=13.4 to r=19.7) (*Fig. 8*). Overall, the channel deepened, while the riverbed was characterised by several half a meter-, meter-high forms, which can be interpreted as dunes developing due to the increase of stream power (*Fig. 7B*). In the meantime, by the disappearing of the right bank trough, no permanent thalweg could be identified in the channel. This phase occurred while a large quantity of bed sediment was entrained and started to move in the channel as a result of sudden specific stream power increase (from ω=3.9 W/m^2 to ω=15.9 W/m^2) (*Fig 7B*).

First falling limb (Phase 2)

Right after the peak of the flood (March 16) as water surface slope and specific stream power decreased the

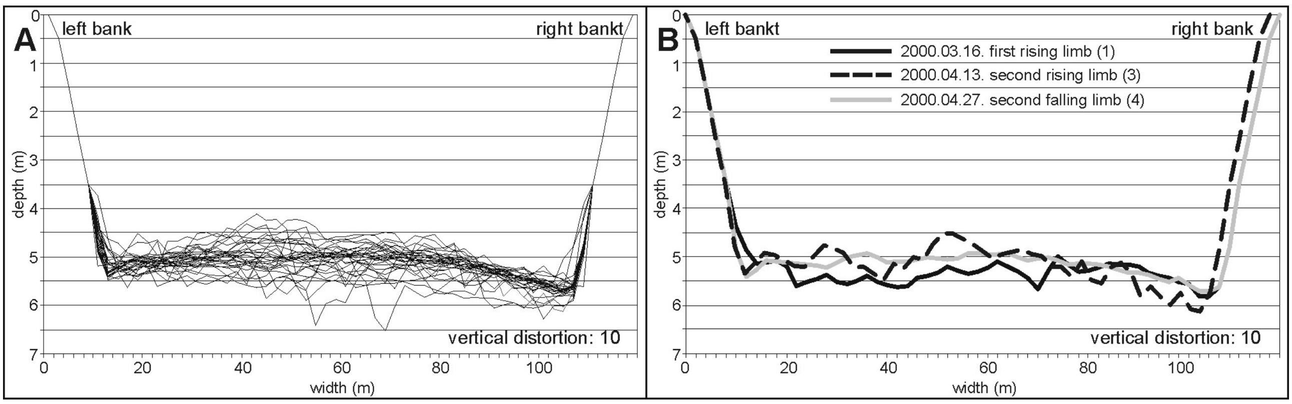

Fig. 7 (A) Monitored cross-channel sections (22) during the 2000 flood (February 8-June 6) on the Maros at Makó. (B) Three characteristic cross-sections taken at different phases of the flood

values of morphological indices dropped back suddenly. In 3 days mean depth and maximum depth decreased by 16 cm (6%) and 82 cm (21%), respectively. Thus, depth practically returned to pre-flood levels, unlike the roughness index, which did not reach its former value, and decreased from r=19.7 to only r=15.3 (*Fig. 8*). The slight decrease of roughness was due to the development of a positive form in the middle of the channel (*Fig 7A*). Based on one cross-section, it is not possible to describe the form; however, it seems as if the profile of a mid channel bar, formed from dunes overrunning each other due to the decrease of stream power (Nikora V. I. et al. 1997), can be observed.

Second rising limb (Phase 3)

During the first part of main flood wave stage rise (March 27-April 7) no measurements were made. The April 7 cross-section shows that the width of the mid channel accumulation increased up to 70-80 m. In the meantime, a small trough appeared at its axis; thus, roughness increased significantly again (r=17.8) (*Fig. 8)*. On the next day (April 8) the erosion of the trough was more expressed; in this way, actually, a third thalweg developed in the channel. In the following days, mean and maximum depth and roughness were fluctuating intensively (*Fig. 7A and Fig. 8*). Consequently, from a morphological aspect this phase of the flood can be considered as the phase of significant sediment relocation in the form of dunes and bars.

In terms of the second flood wave the greatest roughness (r=19.0) mean and maximum depth (d_{mean}=4.58 m, d_{max}=6.12 m) values were measured on April 13, one day before the peak stage (*Fig. 7B and Fig. 8*). Two important observations were made in connection with the above. Firstly, the greatest morphological diversity and the maximum of specific stream power (April 10: r=16.1 m, d_{mean}=4.55 m, d_{max}=5.62 m) did not coincide (compare *Fig. 4 and Fig. 8*), and morphological indices were the highest when the value of ω already started to decrease (from 17.9 W/m^2 to 16.7 W/m^2). Secondly, even at this time depth values and roughness were significantly smaller than those experienced during the first flood wave, although at that time specific stream power was lower. Therefore, it is not at all obvious that the higher the specific stream power is the greater morphological diversity and cross-sectional area can be expected.

Another morphologically important pheno-menon was that during the rising limb of the second flood wave (April 7-April 14) the base level of the riverbed was 20-30, in some cases 50 cm higher than during the first flood. Thus, the second flood wave did not scour the channel bed, but probably it transported the previously relocated sediment in the form of dunes and bars (*Fig. 5B*). We suggest that, the gentler rise of stage during the second wave and the high volume of already entrained sediment from the upper sections explain the shallower riverbed.

Second falling limb (Phase 4)

The very short peak flow period (April 14) was followed by a rapid stage fall, during which mean depth decreased by 9 cm (4%) in 5 days; thus, in accordance with decreasing stream power the bed was filled up. Then due to a slight stage rise within the falling limb depth and roughness values increased a little (*Fig. 8*). However, on the basis of the April 23 and 29 cross-sections, later the bed became almost even, and roughness dropped to 71% of the maximum value. From a

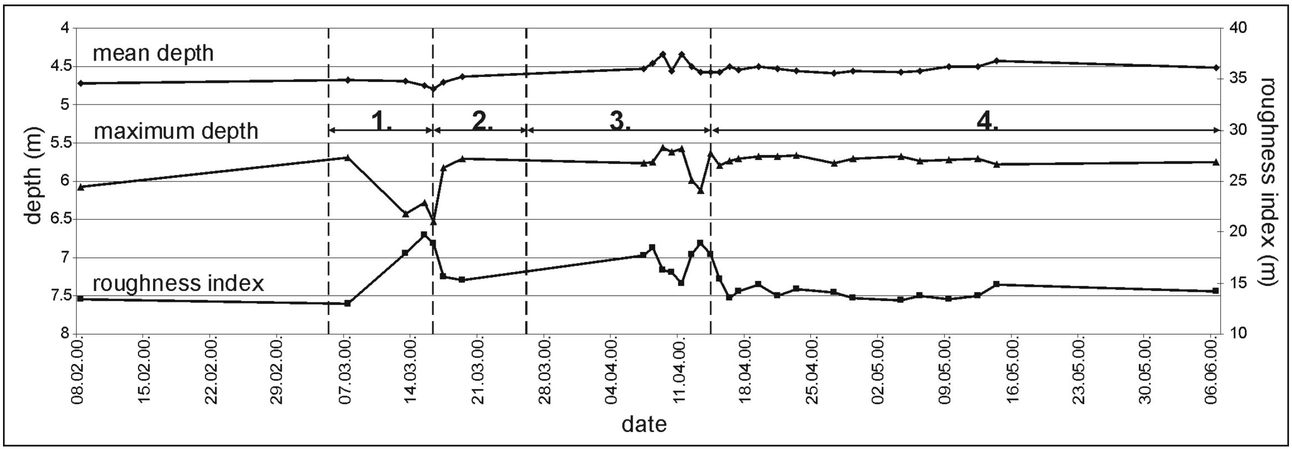

Fig. 8 Variation of morphological parameters during the 2000 flood at Makó (Maros). 1-4 indicate the different phases of the study period

morphological aspect this is in connection with the disappearance of separate thalwegs (*Fig. 5B*). Nevertheless, depth values stayed almost the same during the late part of the falling limb. Finally, by the beginning of May a slight left bank accumulation appeared (side bar) and the thalweg returned to the right bank. If cross-sections taken right before and right after the 2000 spring flood are compared, then mean channel depth decreased by 18 cm (8%), maximum depth hardly changed (6 cm, 2%), and form roughness was very close to its original value (r=13.4 m before and r=14.1 m after).

CHANGES IN CHANNEL CAPACITY

The above-described morphological parameters also define the actual channel capacity of the two studied cross-sections. At the Algyő gauge station (Tisza) bankfull cross-sectional area significantly increased during stage rise (phase 1, 3 and 5; *Fig. 9*). In these phases the cross-section area and stream power increased simultaneously. However, the tendency of the area increase was characterised by significant variations. In some occasions a 6-7 % daily change was detected in cross-sectional area during the main flood wave. These processes indicate intensive morphological changes in the channel.

During the peak flow period depth values and the diversity of the riverbed significantly fell back, resulting the decrease of cross-sectional area and thus water conducting capacity (March 18 rising limb: A=1711 m^2; March 18, peak stage: A=1631 m^2). Minimum conductivity values occurred during maximum stage and discharge (April 21, peak stage: A=1585 m^2), when water surface slope and concomitant stream power decrease were apparent. It was also observed that the same values of stream power resulted in lower channel capacity during the peak flow period then during the rising limb (e.g. April 17, rising limb: ω=6.8 W/m^2, A=1715 m^2; while April 21 peak flow: ω=6.8 W/m^2, A=1585 m^2) (*Fig. 9*).

At the Algyő gauge station of the Tisza during stage fall depth and roughness increase were experienced. This resulted in a larger bankfull cross-sectional area and an increased water conducting capacity (April 25: A=1675 m^2, May 5: A=1714m^2). When stage fall became more intensive a significant fluctuation was observed; however, daily changes did not exceed 3%, representing continuous morpho-logical development, though less intensive than at the rising limb. In the meantime, along with the slow decline of discharge and slope the value of specific stream power also decreased (April 24: ω=6.5 W/m^2; May 4: ω=5.5 W/m^2) (*Fig. 3*). Consequently, a completely different relation was observed between stream power and conducting capacity than during the rising limb or at peak discharges (*Fig. 9*).

In terms of the Makó cross-section (Maros) the 2000 flood resulted in some similar situations. At the rising limb of the first flood wave similarly to the rising limb of the Tisza main flood wave bankfull cross-sectional area increased, however its degree was only 2%. The maximum channel capacity during the entire flood occurred at the peak of the first wave (March 16, short peak period: A=565 m^2) (*Fig. 10*). By the start of bar migration during the next rising limb, in spite of increased discharge and stream power bankfull area was decreasing. When the river reached its maximum specific stream power during the main flood wave (ω=17.8 W/m^2) cross-sectional area was 5% lower than in a similar period of the first wave (12.9 W/m^2). This contradicts the relationships experienced at Algyő, though there the work of the first flood wave could not be assessed precisely.

Following the short peak period of the Maros (20

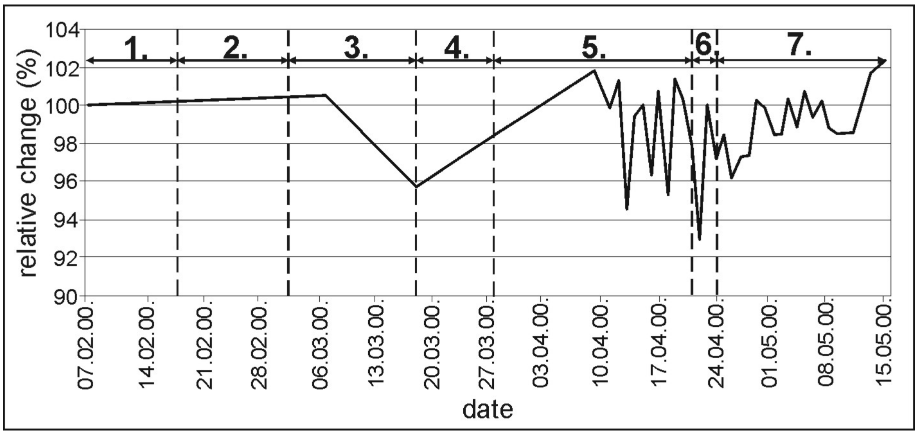

Fig. 9 Relative change of the bankfull cross-sectional area during the 2000 flood at Algyő, Tisza. Value of the first measurement was taken as 100%

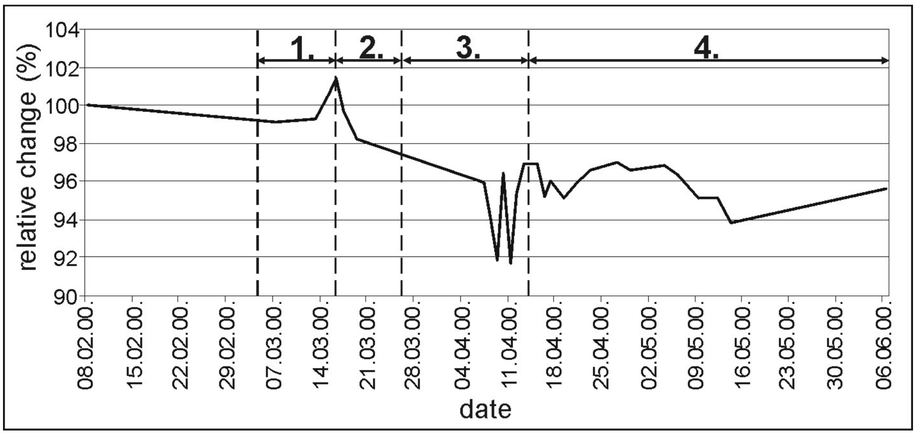

Fig. 10 Relative change of the bankfull cross-sectional area during the 2000 flood at Makó (River Maros). Value of the first measurement was taken as 100%

hours) as stream power and roughness decreased no significant variation was detected in channel capacity (*Fig. 10*). At the end of the falling limb the bankfull area of the cross-section (A=533 m^2) was almost identical to the value observed during peak flow (April 19: A=530 m^2); however, by this time ω dropped to 1.68 W/m^2 which was only one tenth of the peak stage value. Consequently, morphological processes during the falling limb were different than at the Algyő cross-section. The possible reason for this is that the river due to the sudden loss of stream power was not able to transport further the bed load pulse initiated by higher energy periods. According to Sipos Gy. (2007), bedforms created by flood waves remain stable in the channel and for post-flood low waters it takes a relatively long time to restore the original bed state within the sand bedded River Maros.

The difference of the maximum and minimum cross-sectional area measured during the entire spring flood was 9.1% (ΔA=157 m^2) on the Tisza and 9.6% (ΔA=54 m^2) on the Maros. Thus, total variation was very similar (*Figs. 9-10*). In terms of maximum daily change, area difference was greater at Algyő (6.9%) than at Makó (5.1%). Nevertheless, variations during one day are not possible to determine at the present measurement frequency. Still, it seems well supported that relative variations in channel capacity were very similar at the two cross-section during the 2000 flood, despite of the fact that the maximum of specific stream power was 2.6 times greater in case of the Maros, and the standard deviation of these data was 6.2 at Makó, while it was only 1.8 at Algyő. The suggested reason why higher and more diverse stream power conditions did not cause greater morphological changes on the Maros is the remarkable volume of bed load (*Table 1*), which may buffer the energy variations of the river. However, the precise role of bed load in this respect is not possible to assess in detail because of the few number of sediment discharge measurements.

CONCLUSIONS

At both the Algyő cross-section of the Tisza and the Makó cross-section of the Maros significant morphological changes were observed during the 2000 flood. These changes greatly influence the channel capacity of the channel. Morphological development was compared to variations in specific stream power and the rate of stage rise or fall.

The way and degree of changes were different at the two sites. On the River Tisza at Algyő significant variations were experienced in depth and roughness during the rising limb, depending on the value of specific stream power and the intensity of stage rise. The overall process at this phase was the lowering of the bed level, thus the increase of channel capacity. During the days of the peak flow period, along with the sharp decrease of stream power the cross-sectional area decreased. This can be explained by the reduction of bed load transport and subsequent in channel aggradation. Nevertheless, at the falling limb of the flood in spite of the definite decrease of stream power depth increased again, and the area of the bankfull cross-section grew. In order to explain this controversy, further investigations are necessary.

On the River Maros, at Makó erosional activity was dominant only in the rising limb of the first flood wave. The greatest channel capacity was detected at this phase. Contrary to the processes at Algyő, during the main flood wave a continuous bed level rise was detected at Makó, even in case of periods with the highest energy levels. During the abrupt falling limb of the hydrograph the morphology of the channel settled, though depth values and bankfull cross-sectional area changed insignificantly.

Both the total and the daily variation of conducting capacity was similar at the two gauge stations, meaning a 9-10% difference between the maximum and the minimum cross-sectional area and a maximum 5-7% daily change. Similarity is striking considering that variation of specific stream power were much significant in the case of the Maros than on the Tisza (Makó $\omega_{max}/\omega_{min}$=10.6; Algyő $\omega_{max}/\omega_{min}$=4.6).

The paper proved the intensive cross-sectional changes during a flood, the processes outlined above show obviously a natural fluctuation. Therefore, based on only one flood it would not be sensible to generalise their role in the long term increase of flood levels. However, based on our present research, it is obvious that both in terms of the Tisza and the Maros the maximum of channel capacity usually will not coincide with maximum discharge and stage or maximum stream power. Therefore, morphological processes related to bed load transport can have a significant influence on peak stages and flood levels. Though earlier studies proved that the increasing bed load transport and intensive dune and bar migration during floods have an effect on cross-sectional area (Bogdánfy Ö. 1906, Németh E. 1954, Károlyi Z. 1960b), but could not calculate changes in detail. Our study proved that before the flood crest the specific stream power reaches its maximum, causing intensive scouring and bedload transport. However, at the period of flood crest the specific stream power is already decreased, therefore despite of former beliefs aggradation can truly overwhelm erosion at this phase, resulting significant channel capacity decrease. Earlier studies also over generalized the role of falling stages, supposing intensive aggradation; however, we proved that slow scouring can also occur in this period.

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