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DOWNSTREAM MORPHOLOGIC CHARACTERISTICS OF THE ALLUVIAL SECTION OF LOWER RIVER OGUN, NIGERIA

Olutoyin A. Fashae, Adetoye Faniran

Department of Geography, University of Ibadan, 200284 Ibadan, Nigeria
*Corresponding author, e-mail: toyinafashae@yahoo.com

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Abstract

Rivers constitute an important focus of attention in surface water studies because of their dynamic nature. Therefore, natural rivers develop a wide range of channel forms whose characteristics vary as a function of the position within the fluvial systems. This study examined the river channel morphologic parameters along the alluvial section of River Ogun in South western Nigeria. Data on the channel morphologic variables were collected through field measurement of the bankfull cross sectional characteristics of the river from where the longitudinal characteristics were defined. 48 cross sections were randomly established at bankfull stage along the river channel stretch of 90 km. Bankfull depth and width at each of the cross sections were determined using sonar (electronic sounding machine) that was mounted to a boat. Velocity was measured with the aid of a current meter, while other morphological parameters were estimated from the field data. Analysis of variance revealed that downstream morphological characteristics of the river varies distinctively at each cross section with bedslope as the most significantly varied among all other morphologic parameters (F=91.18; P=0.00). Pearson product moment correlation technique revealed that bankfull width had a correlation of 0.8 and 0.9 with wetted perimeter and cross sectional area respectively while bankfull depth (maximum) had correlations of 0.9, 0.8 and 0.78 with hydraulic radius, wetted perimeter and cross sectional area respectively. The research also revealed that gradient affects the discharge with a positive correlation of 0.9. The study ascertains the extent of variability in the morphologic characteristic of River Ogun which provides scientific basis for river maintenance and management.

Keywords: bankfull depth, bankfull width, alluvial section morphologic characteristics, river channel, Lower River Ogun

INTRODUCTION

The assessment of river condition relative to some ideal state is a concept receiving increasing attention in fluvial geomorphology. The morphology of any river shows a great variability and dynamic behaviour. Therefore, the river channel as a subsystem and an important component of the river basin system deserves studying in some details to enhance river-basin management which provides scientific grounding for river maintenance and management. Monitoring of channel morphology extends understanding of types and rates of responses to environmental changes. A proper understanding of this is essential for mined-land reclamation, channel modification for flood control and navigation, identification of areas of active tectonics and the litigation of boundaries etc. (Elliot, 1984). River channel morphology provide information on river characteristics and behaviour, infact, river morphology has been a subject of great challenge to scientists and engineers who recognized that any effort with regard to river engineering must be based on a proper understanding of the morphological features involved and the responses to the imposed changes (Chang, 2008). Examining river network behaviour enhances understanding of the way in which geomorphic processes behave across networks.

Several river condition assessment methods have been designed for countries worldwide; AusRivAS (Parsons et al., 2002), the Index of Stream Condition (Ladson and White, 1999; Ladson et al., 1999), the River Habitat Audit (Anderson, 1993) and River Styles (Brierley and Fryirs, 2005). River Styles for instance, provides a framework for assessing river condition using geomorphic criteria and achieves this largely by comparing the geomorphic character of reference reaches to test reaches of similar river types (Brierley and Fryirs, 2005). The investigation of river channel morphology and the attendant features is an interesting aspect of geomorphology which is of immense importance in understanding the processes affecting landforms. Therefore, geomorphic river condition assessments are valuable mechanisms for determining the present and future health of river systems (Maddock, 1999).

River morphology depicts the form of a river along its length and across its width and consequently its shape. River morphology is explained by channel patterns and channel forms, and is influenced by such factors as discharge, water surface slope, water velocity, depth and width of the channel, amount and size of the transported material, river bed materials, etc. These factors are not independent but inter-related to each other. Several studies had been carried out on the form and shape of river channels for instance, Soar et al., (2001 suggests that stream system adjusts in order to maintain a steady state, or dynamic equilibrium between the driving mechanisms of flow and sediment flow and the resisting forces of bed and bank stability and resistance to flow. Ward and D'Ambrosio (2008) in their study on stream classification identified factors that can influence channel morphology and concluded that channels with bedrock, have limited sediment supply whereas cobble and gravel bed channels are high energy channel with high sediment supply. Therefore, erosion instability, mass wasting and debris flow are more dominant processes as the bed material become finer and these affect channel morphology. They also emphasize slope as a major factor in channel morphology, as slope changes from upstream to downstream, an in relation the channel morphology also changes. Moreover, Montgomery and Buffington, (1997) emphasized that spatial variation is sediment supply may govern channel morphology in different segment of rivers. Channel response to increase sediment supply depends on the ratio of transport capacity to sediment supply. They linked the variables of channel morphology such as width, depth, bed slope grain size, bed forms and patterns to function of sediment supply, transport capacity and vegetation. Transport capacity in terms of frequency, magnitude, and duration of discharge and slope. Riparian vegetation also influences channel morphology in different ways. Vegetation protects banks from erosion and increases flow resistance by increasing roughness and reducing flow velocities so that channels with dense riparian forests tend to be narrower (Brookes et al., 2000). Moreover, vegetation on river banks and woody debris within the channel may act as sediment traps that create different channel morphologies and modify the channel type (Schumm, 2005). All these factors affect river channel morphology.

Over the last several decades, stream morphology researches has been undertaken by scientists in a wide variety of disciplines, yet our understanding of channel morphology, features and the factors influencing them is still incomplete. Most geomorphological investigations involving channel morphometry are concerned with the definition, measurement and analysis of quantitative indices describing the cross section, the bedform and long profile as well as the plan geometry of rivers (Goudie et al., 1990). According to Goudie (1990), morphology and particularly the cross section and plan-form properties of the channel has increasingly been linked to river flow characteristics which are also related to properties, quantities of bed materials and transported sediments.

Every river channel has its own characteristics that is unique in its own way and the dynamism involved in downstream river morphologic variables suggests the need for quantitative understanding of the behavior of river morphologic variables and this remains an important but yet elusive goal in fluvial geomorphology. Alluvial rivers are dynamic landforms subject to rapid change in channel shape and flow pattern. Examining alluvial river network behaviour enhances understanding of the way in which geomorphic processes behave across the channel. The variation in river channel morphology is a result of great range of hydrological conditions, sediment characteristics and geologic histories of the river. The nature of the materials through which a river flows initiates the three types of stream channels: bedrock, semi controlled and alluvial. Alluvial channel is composed of sediments transported by the river and it is susceptible to major morphologic change and to significant shifts in channel position as the alluvium is eroded, transported and deposited, and as the sediment load and water discharge changes. Since the alluvial section of any river is dynamic in nature in terms of its morphology, there is the need for a quantitative understanding of alluvial channel form and response to changes in governing conditions remains an important yet elusive goal in fluvial geomorphology (Fashae, 2011).

Analysis of river channel morphology appears to have been largely studied as many of the research efforts on river channels have focused almost exclusively on channel pattern (Ebisimiju, 1994; Holz and Baker, 1981; Beschta and Platts, 1986; Thorne, 1997; Friedman et al., 1996). Since, river channels show some common characteristics in areas of similar landform. The river channel as a subsystem and an important component of the river basin system deserves studying in some details to enhance river-basin management. This is the reason for examining some aspects of river channel morphology along the alluvial segment of River Ogun before empting into the Atlantic Ocean at the Lagos lagoon by analyzing the channel morphologic characteristics, interrelationship among the morphologic variables and the downstream variation for channel morphologic variables.

STUDY AREA

The Ogun River basin is located between latitudes $6^{o}33'$N and $8^{o}58'$N and longitudes $2^{o}40'$E and $4^{o}10'$E (Fig. 1). The catchment area is about 23,000km^{2}.

River Ogun takes its source from the Iganran hills at an elevation of about 530m above mean sea level and flows southwards over a distance about 480km, before it discharges into the Lagos lagoon. The lower River Ogun is defined for this study as the stretch from Mokoloki town to Isheri town downstream, especially areas underlain by sedimentary Abeokuta formation which consists mostly of sandstone of medium to coarse grain, poorly sorted and micaceous (Oyawoye, 1972). There are clay and mudstone intercalations; cross bedding is common and the rock is soft and friable, except where cemented locally by ferruginous materials. The main sedimentary rocks are the alluvial deposits, coastal plain sands both of Quaternary age. The choice of this portion of the Ogun River as the study site for this research work is based on the fact that most of the principal factors that control river geomorphology, namely: climate, geology, hydrogeology and relief, are relatively constant along the study segment of River Ogun coupled with the fact that the river is perennial in its flow.

The climate of the study area is controlled by the Inter Tropical Discontinuity (ITD). The ITD is an atmospheric zone between the maritime South West monsoon wind and the dry North East trade winds. This zone in West Africa moves with the location of the Sun in such a way that during the Southern summer, the ITD moves close to the coast and during the Northern summer, the ITD moves northwards to about latitude 14-15^{o}N. As a result, the rainy and dry seasons are well marked. The rainy season begins earlier in the south where it lasts from March until the end of October or early November, giving at least seven months of rainfall. North of Oyo and Iseyin, the onset of the rains is delayed and generally begins late in April or early May and ends in mid-October (Ogun River Basin Development Authority, 1981). In late July and early August, dry days are prevalent and sufficiently regular to constitute what has been termed the "little dry season", with mean monthly figures below 100mm. The mean wet seasonal rainfall is about 1,015mm to 1,525mm in the Lower Ogun river and about 510mm to 1,525mm in the Upper (Ogun River Basin Development Authority, 1981). The actual number of rainy days ranges from 250-280 days. The mean annual rainfall of the study area ranges from 900mm to about 2000 mm (Ogun River Basin Development Authority, 1981). Temperatures are fairly uniform throughout the year with a mean annual of 26^{o}C -27^{o}C with an annual range of 5^{o}C to 8^{o}C while the relative humidity ranges between 60% and 80% (Ogun River Basin Development Authority, 1981). Annual evaporation rates are also high throughout the year, with monthly amounts varying from about 90mm in July to over

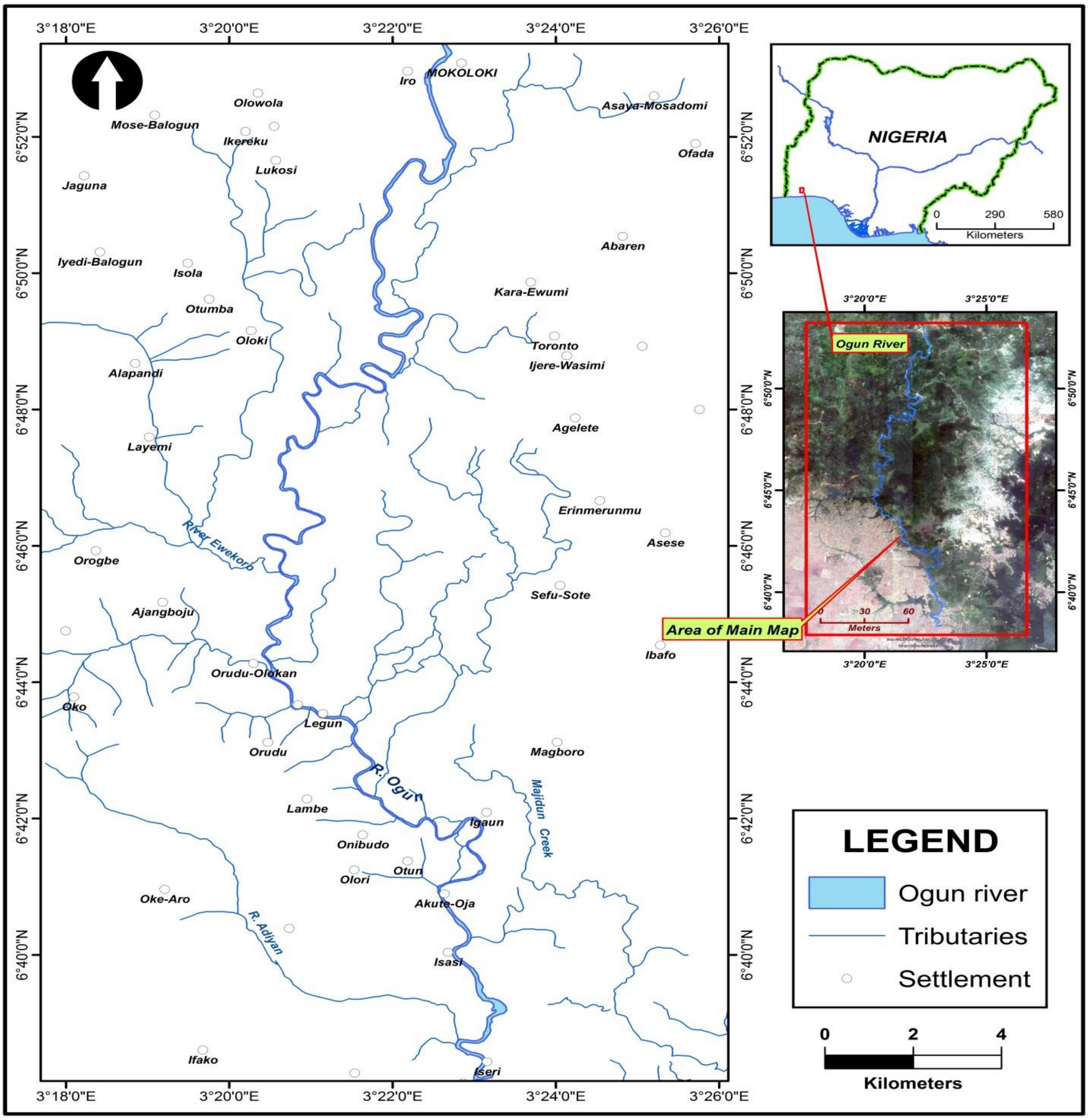

Fig. 1 Map of River Ogun showing the Alluvial River study Segment

130mm in January. The mean annual water surplus of the study area ranges from 254mm in the North to 508mm in the coastal belt. The total annual potential evapotranspiration is estimated at between 1600mm and 1900mm.

The Lower River Ogun is characterized by low slope angle and extensive floodplains with marshes and swamps. The total catchment of the lower Ogun is approximately 12,630km^2 while the length of the study stretch is approximately 90 km. The Lower Ogun Basin, where the study stretch lies has a mean slope of about than 3% and the landform consists of plains with straight and gently undulating topography. The general topography is characterized by a low, flat plain along the river, subject to frequent seasonal flooding and influenced by groundwater. For instance, at Mokoloki, the river bed sediments are coarser, making this section of the river channel relatively shallower and narrower, water being contained in less than 20% of the channel width while at the much lower section around Isheri, the channel is characterized with an average bankfull width of about 115.6m. Much as result of the downstream increase in the discharge and it subsequent production of alluvium that are mined for construction purposes. River Ogun basin comprises of two major rivers; Oyan and Ofiki at the upstream section, while other tributaries such as the Rivers Ewekoro and Adiyan are located at the lower extent of this study section (Fig. 1). Some of these tributaries are areic with no definite course. There is a lot of human influence on the river for instance, a number of portable water projects were mounted on the river for the provision of water to the rural populace. These include the mini water works at Akute (Fig. 2).

The drainage pattern of the river is dendritic in nature. Many of the subsequent and obsequent rivers and stream often dry up completely during the dry seasons while the consequent river (Ogun) often have reduced water level and discharge thereby leaving extensive floodplains and migratory bars at the sides. The lower River Ogun is characterized by a minimum discharge value of about 2.3m^3/s and a maximum values of 40 m^3/s at Akute . An increase in downstream discharge is indicative of the sudden change in the channel gradient due to the impoundment of water by barrage at Akute (Fig. 2). In addition, within downstream locations, further adjustments of the channel efficiency were achieved by the changing channel pattern of meanders and braids. This is evidenced with the occurrences of some fluvial forms such as ripples and pools sequences and formation of sand bars by the alluvium

MATERIAL AND METHODS

The morphological variables were evaluated for both the longitudinal and cross sectional profiles of the river to provide useful information on the state of the river channel at the time the study was carried out. The morphologic variables were collected through field survey where a total of forty-eight bankfull cross sections was unevenly surveyed at bankfull stage along the river channel stretch of 90 km. This is as a result of the occurrence of straight, meandering and braided channels along the river channel. The bankfull width and depth were also measured using automated SDE-28 ECHO depth sounder (sonar) whose visual interface was mounted in

Fig. 2 Barrage at Akute along River Ogun with the insert showing the width

the boat and the traducers was attached to the base of a moving boat, then suspended into the water to receive sound signal that translates into the depth values. The sonar machine has the capability of measuring the width perpendicular to the direction of the sounding from bank to bank. The depth values were collected at the centerline of the river. Bedload material was collected using the grab sampler technique by scooping the river bed to trap materials for its particle size at equidistant locations along the cross section. These materials were mixed together to obtain a composite representation of the cross section before taken to the laboratory for analysis using the hydrometer method. The coordinates of each cross section were recorded with the aid of an attached Garmin Global positing system (GPS). Beschta (1986) suggested that any attempt at characterizing channel morphology must recognize its three-dimensional aspects, therefore all the other channel morphologic variables, such as wetted perimeter, hydraulic radius and cross sectional area were calculated. Current meter was used to obtain measurements of the flow velocity from which the discharge of the river at each cross sectional point was estimated. Analysis of variance (ANOVA) that states that there is no significant variation in the downstream morphologic variables at 0.05 significant (α-) level was used to test for the variation of the downstream morphologic variables.

RESULTS

The longitudinal profile of Lower River Ogun

The alluvial section of the Lower River Ogun channel at bankfull stage suggests a concave-upward shape along its downstream gradient (Fig. 3), with an elevation of 29.7m above the mean sea level at Mokoloki located at a distance of about 10km downstream the studied segment of River Ogun while the elevation at Isheri is 8.1m above the mean sea level which is about 90 km downstream of Mokoloki, thus the river drops 21.6m along the studied reach. Hence, longitudinal zonation of channel forms may be recognized from the headwaters downstream to the river mouth.

It could be observed that there is a progressively lower gradient and an increase in the bankfull discharge as reflected the continuous addition of tributaries and increasing drainage area downstream. The profile is punctuated at knick points where the river cuts through valley floors as indicated at about 58km distance which is sharply defined due to human interference of the location of a barrage and sand mining activity respectively. The linear relationships that typically exists between gradient and downstream distance along the longitudinal profile of River Ogun reveals $R^2 = 0.49$, a value significant at 0.05 α-level with gradient accounting for 49% in the variation. The significance of the gradual lowering in the channel gradient provides explanation for the erosive and deposition work along the meanders and braided sections of the river and the plausible reason for the increase in fluvial landforms along the study stretch. Features such as ripples and pools sequence are evidenced at the concave and convex sections of these meanders which are interspersed by braids between the 10km to 40km downstream distance. These features are created by pattern scour and deposition at bankfull discharge where the riffles tend to occur at the inflection points and pools at bends. Also, oxbow lake, a lake with curved plan occupying cut-off channel reach that has been abandoned were encountered along the stretch while point bar deposits which are sediments laid down on the inside of meander bend largely by accretion are more pronounced.

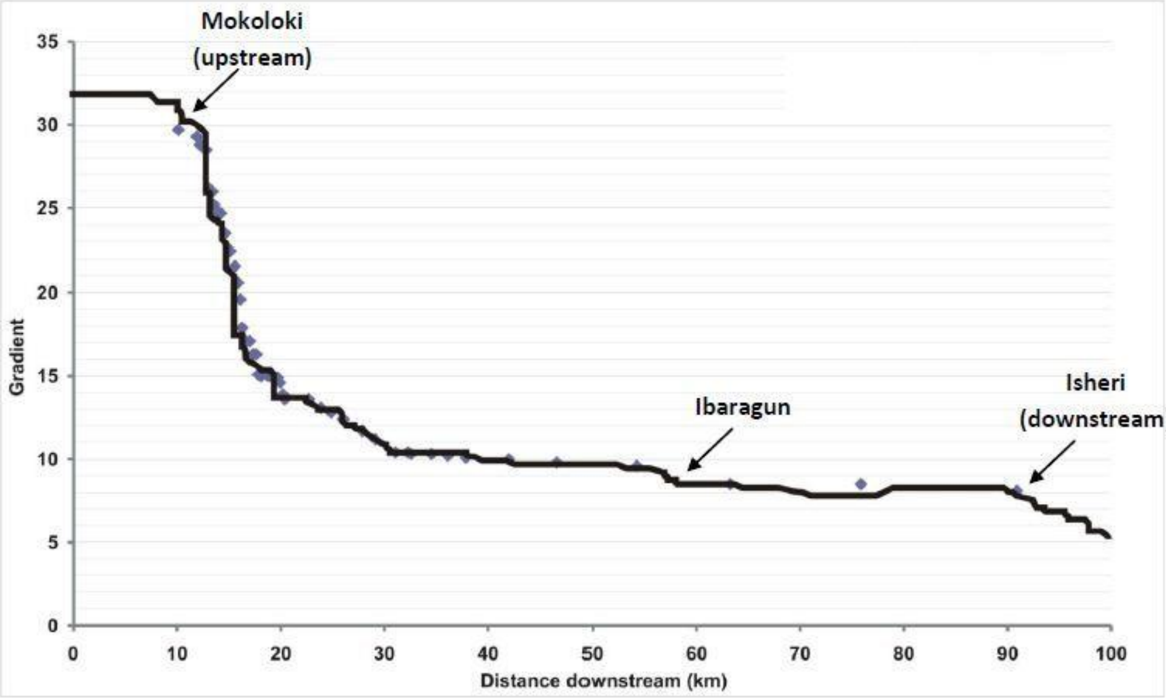

Fig. 3 Longitudinal Profile of Lower River Ogun

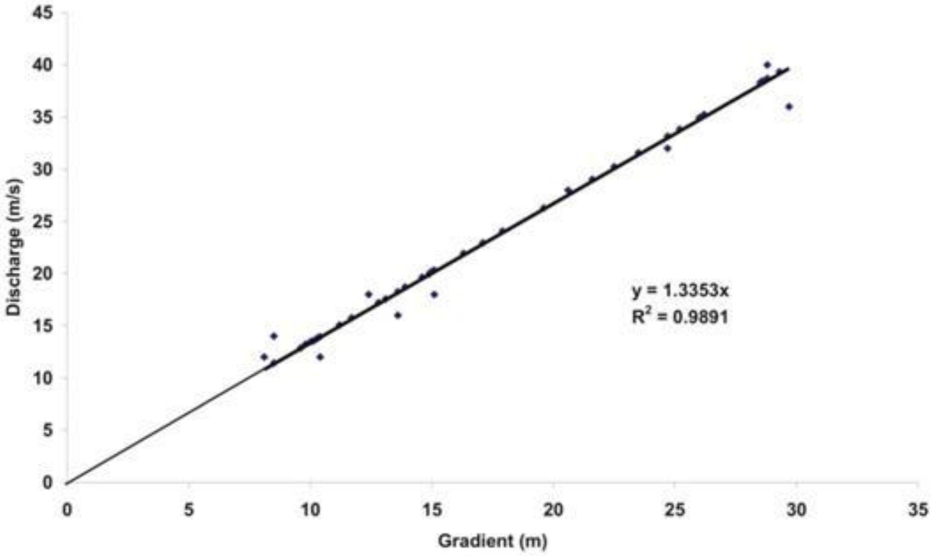

Fig. 4 Relationship between bankfull discharge and gradient along the Lower Ogun River Channel

number of factors are responsible for the concavity of river longitudinal profiles, notably the energy profiles best represented by the discharge pattern. This is evident from the linear relationships that typically exists between gradient and discharge along the longitudinal profile of rivers, which in this study reveals $R^2 = 0.98$, a value significant at 0.05 α-level (Fig. 4).

Variation of River Ogun Channel Morphologic Variables with Downstream Distance

River channel morphology of an alluvial channel reflects the movement of water and the particle size of the load flowing in it. The volume of water flowing within the channel together with the sediment load (dissolved and bedload) helps in shapening the channel morphology. A statistical description of each morphological variable along the channel is important as it provides a general summary illustration of the tendencies peculiar to the study (Table 1).

Depth and width are important variables of a river channel that suggests the morphology of any river. The maximum bankfull depth, which is indicative of the thalweg, or a line drawn to join the lowest points along the entire length of a riverbed shows that 4.3 m was the minimum point while the maximum was 9.6 m. The range of 5.3 m in the maximum bankfull depth indicated a wide gap between the deepest and the shallowest points along the thalweg from the centre line of the channel. However, the mean bankfull depths varied from a maximum of 7.4m to a minimum of 3.7 m. Figure 3 revealed that as the river tends towards reaching its mouth and with increasing distance downstream, there is an

Table 1 Morphological characteristics of the Lower River Ogun with the downstream analysis of variance (n =48)

Downstream variables	**Range (Min-Max)**	**Mean (standard deviation)**	**Downstream F-ratio**	**Variation (Significance value)**
Downstream distance from Mokoloki (km)	80.8 (10.1-90.9)	25.1(16.8)	-	-
Maximum depth (m)	5.3 (4.3-9.6)	7.7(1.2)	0.42	0.66
Mean depth (m)	3.7 (3.7-7.4)	6.0(0.8)	1.19	0.30
Bankfull width (m)	84.4(31.1-115.6)	59.8(15.3)	0.40	0.68
Width-depth ratio (-)	14.2(5.1-19.4)	10.2(3.2)	1.21	0.31
Crossectional area (m^2)	800.6(253.8-1054.4)	458.0(142.0)	0.08	0.93
Wetted perimeter (m)	86.3(47.6-133.9)	75.1(15.2)	0.30	0.74
Hydraulic radius	4.0(3.9-7.9)	6.0(0.8)	0.24	0.79
Discharge (m^3/s)	29.0(10.9-39.9)	2.3(9.1)	0.67	0.8
Particle size ratio	54.0(39.2-93.2)	71.3(14.4)	0.34	0.72
Bedslope (frictional slope)	0.4(-0.1-0.3)	-0.005(0.09)	91.18	0.0
Valley gradient	21.6(8.1-29.7)	17.0(6.7)	0.69	0.51
Velocity (m/s^1)	1.0(0.2-1.2)	0.5(0.2)	0.68	0.80

increase in depth which might be as result of the corresponding increase in downstream discharge except for the knick points that experience a huge increase in depth (Fig. 5). The knick points along the studied river section are indicative of accumulation of bedload at the barrage at Akute with an increase in gradient. Even though depth increases downstream, distance alone might not account for variation pattern observed (Fig. 6).

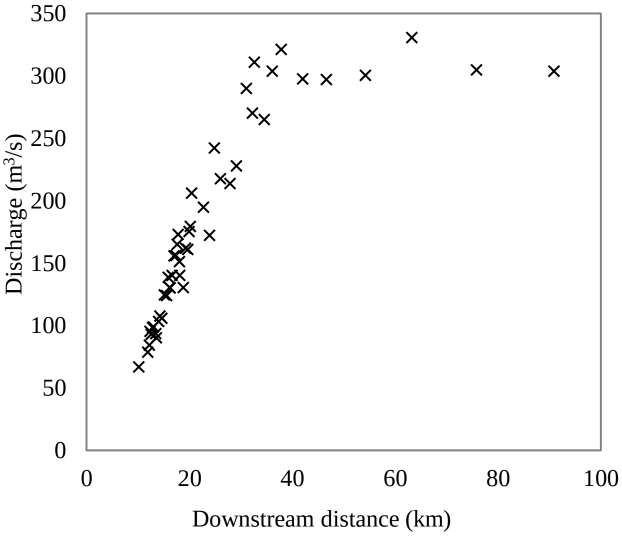

Fig.5 Relationship between discharge and downstream distance

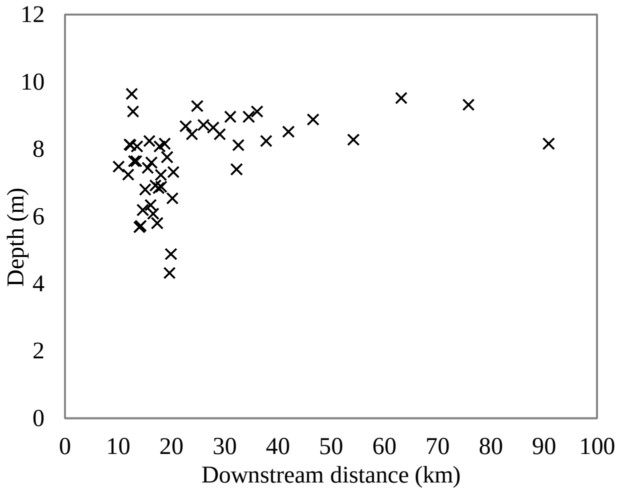

Fig. 6 Relationship between downstream distance and depth

The increase in depth suggests that there is a downstream increase in suspended sediment concentration which would invariably dampen turbulence (Merritt and Wohl, 2003). It was observed that there is a relationship between the particle size of the bed materials (mean=71.3) and the channel form with a decrease in size downstream. This accounts for wide, shallow and fine/smoother banks.

Theoretically, the bankfull width of a river is a function of its occurrence, magnitude of flow, type of transported sediment and composition of the bed and bank materials of the channel. The Lower River Ogun channel is characterized by a minimum bankfull width of 31.1 m, maximum bankfull width of 115.6 m and a mean of 59.76 m along the study stretch. Although river channel widths may generally increase downstream, a channel can still have a stable width even though the river is migrating laterally at a constant annual rate. As Clifton (1989) suggested, overall width, depth, and cross section area do not increase systematically downstream, while the spatial variability results from prevailing vegetation conditions. The width of a river can therefore remain relatively constant where erosion on one bank is compensated for by corresponding sediment deposition along the opposite bank. This is evident in some sections of the river where there are widths changes due to their response to the fluctuation in the rainfall amount and intensity that encourages the formation of migratory sand bars along this alluvial river (Fig. 7)

However, the downstream increase in width may be attributed to the composition of the bed and bank materials of the river channel. This could be linked to removal of the riparian vegetation for active farming activities (Fashae, 2011).

In summary, the morphologic characteristics of the river channel vary at different points along the river segment. This variation is indicated in the differences in values of the variables observed from the cross sections of the river. In order to provide an understanding of the variability of the channel morphologic factors in the study area, investigation of the spatial variations of the channel form variables along the downstream was carried out. The results revealed that variations occurred in virtually all the parameters downstream as reported in Table 2 where the analysis of variance for all the channel form variables indicated that there are variations. The F ratio which implies the extent of variation showed that the bed slope (F ratio 91.18 was the most variable downstream among the morphologic parameters considered followed by width depth ratio (1.21), while the cross-sectional area is the least variable with an F ratio of 0.08. The bed slope with F ratio as high as 91.18 is the most widely varied downstream, less variations occur in particle size ratio downstream with F ratio of 0.34. However, only the variation in bed slope reflected a statistical significant difference at 0.05 α-level while all other parameters varying downstream albeit with no statistical variations. This can be attributed to the fact that the study was carried out within a definable reach that is, along the alluvial segment (5th order) of River Ogun. The significant variation in bed slope was however attributed to the rapid changes in the work of the river downstream, since the discharge increases systematically downstream, it is not unreasonable to expect the down cutting of the river channel bed changing as the flow, erosion and deposition actions changes, even within the same reach of the river. Furthermore, the finding that the bed slope and width depth ratio were the most variable morphological parameters along the 5th order section of the River

Fig. 7 Migratory sand bars along the Lower River Ogun channel

Ogun channel was instructive because the two are about the best variables conceptually considered to describe the changes in channel shape. The increment in width depth ratio as the river flows towards its mouth is represented in Fig. 8.

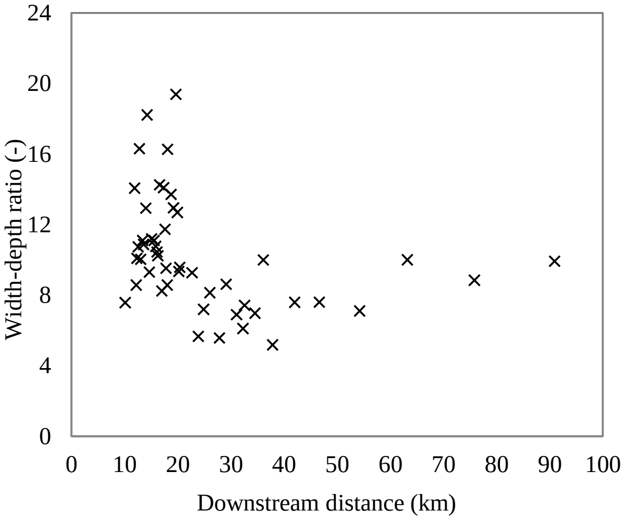

Fig. 8 Relationship between width depth ratio and downstream distance

Interrelationship among River Ogun channel morphologic variables

The interrelationship among channel morphologic variables along the alluvial section of the River Ogun was investigated using correlation analysis, to test the relationship occurring among the channel form variables. This technique deals with associations between two or more variables providing measures of the strength of association and statistical tests of its significance. The Pearson's product moment correlation method which considers parametric relationships was employed because the morphologic variables were measured at random intervals. This relationship was particularly considered with reference to the distance downstream, the result of which is reported in Table 2.

The width depth ratio at any point along the River Ogun channel was expectedly most influenced by the bankfull width with a correlation of 0.9 significant at 0.05 α-level while the wetted perimeter had a correlation of 0.8. The cross sectional area had a correlation of 0.9; the hydraulic radius dependent on the bankfull depth (maximum and mean) and the cross sectional area had correlations of 0.9 and 0.8 and 0.78 respectively.

In addition, as the river channel tends to near its mouth, the discharge, gradient and the flow velocity all reduces in magnitude. The width depth ratio, the bankfull width, wetted perimeter and the hydraulic radius also changes significantly as revealed from the multivariate graph in Figure 9. As the width depth ratio and the bankfull width increases towards the mouth of the river, the hydraulic radius decreases.

These were detected along the section investigated in this study to reveal negative correlation of -0.36 and -0.34 between downstream distance and bankfull width as well as width depth ratio respectively, significant at 0.05 α-level occurs, while a similarly positive correlation of 0.23 occurs between downstream distance and the hydraulic radius. This implies that the portion of the river distinctively describes the width, depth and hydraulic characteristics of River Ogun channel.

Downstream of River Ogun suggests that there is a reduction in the channel boundary resistance due to alluvium along the banks, while the channel-bed materials become slightly fine grained. The channel bed is composed of fine sand particles and the banks are mainly non-cohesive (Miller, 1956). The substantial changes observed in the correlation matrix has been reported in other studies including pattern changes

Table 2 Correlation matrix of downstream channel morphologic parameters

	Distance downstream	Maximum bankfull depth	Mean bankfull depth	Bankfull width	Width-depth ratio	Cross sectional area	Wetted perimeter	Hydraulic radius
Distance downstream	1							
Maximum bankfull depth	0.41	1						
Mean bankfull depth	0.08	0.82	1					
Bankfull width	-0.36*	-0.12	0.00	1				
Width depth ratio	-0.34*	-0.56	-0.55	0.90*	1			
Cross sectional area	-0.10	0.46	0.48	0.82*	0.39	1		
Wetted perimeter	-0.30	0.04	0.13	0.80*	0.73*	0.90*	1	
Hydraulic radius	0.23	0.90*	0.80*	0.30	-0.22	0.78*	0.45	1

*Correlation significant at 0.05 α-level

(Graf, 1988a), substantial widening (Burkham, 1972; Osterkamp and Costa, 1987; Kresan, 1988) and lateral migration (Graf, 1983b), entrenchment (Graf, 1983a) and floodplain erosion and deposition (Wells, 1990; Zawada and Smith, 1991).

DISCUSSION AND CONCLUSION

Rivers from source to mouth show a great variation in morphological characteristics such that the size and shape of the channel readily describes the section of the river. From the study, it can be inferred that among the eight morphological variables studied. The bankfull width and the depth of the channel indicate the most significant attribute of the channel form. The width depth ratio and bed slope were found to be the most variable morphological parameters along the studied channel. This is instructive because the two are the best variables conceptually considered to describe the changes in channel shape. The ratio of stream channel length to down-valley distance, which was measured on the long profile of the River Ogun, indicated the stream type (alluvial) and how the stream channel slope was adjusted to that of the valley slope. The interrelationship among channel morphologic variables along the alluvial section of River Ogun revealed that both the width depth ratio and the cross-sectional area at any point in the channel

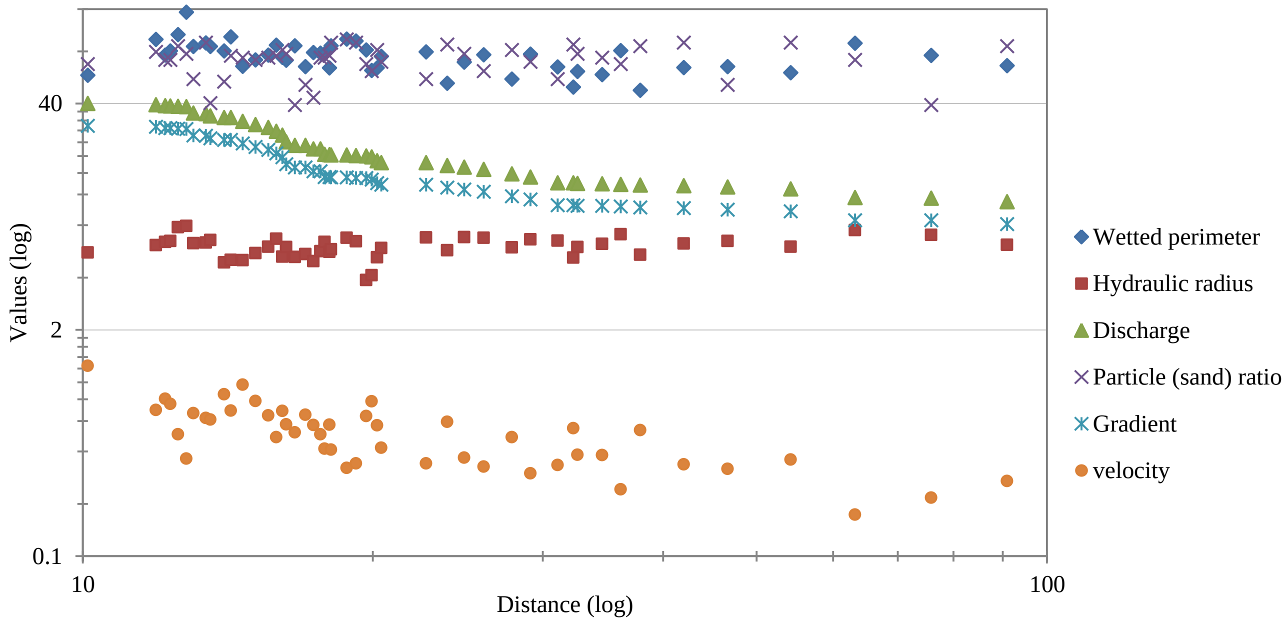

Fig. 9 Downstream pattern of the morphologic variables along the Lower River Ogun

were most influenced by the bankfull width with a correlation 0.82 significant at 0.05 α-level. Also, the wetted perimeter was equally related to the bankfull width with a correlation of 0.8 and the cross sectional area with a correlation of 0.8, the hydraulic radius was found to be dependent on the bankfull depth (maximum and mean) and the cross sectional area from a correlation of (0.9 and 0.8) and 0.78 respectively. The gradient of the channel most perfectly affects the discharge with a positive correlation of 0.9 significant at 0.05 α-level. The downstream increase in channel width might be due to the loose bank materials which reflect on the bank cohesion and roughness of the channel. The river discharge which is closely related to the flow velocity and the channel cross sectional area summarizes the processes occurring within the alluvial section of the River Ogun channel and resultant fluvial features, such as braids, incised meanders, point bars, riffles and pools.

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DROUGHTS, DRY SPELLS AND LOW WATER LEVELS IN MEDIEVAL HUNGARY (AND CROATIA) I: THE GREAT DROUGHTS OF 1362, 1474, 1479, 1494 AND 1507

Andrea Kiss[1*], **Zrinka Nikolić**[2]

[1]Institute for Hydraulic Engineering and Water Resources Management, Vienna University of Technology, Karsplatz 13, 1040 Vienna, Austria
[2]Department of History, University of Zagreb, Ivana Lučića 3, HR-10000 Zagreb, Croatia
*Corresponding author, e-mail: kiss@hydro.tuwien.ac.at

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Abstract

In the present paper five significant late medieval drought events, occurred in Hungary (4 cases) and Croatia (1 Dalmatian case), are discussed based on contemporary documentary evidence. Information on long-term lack of precipitation, severe annual (or multiannual) water shortage, extreme low water levels of major rivers or bad harvest and severe food shortage in 1362, 1474, 1479, 1494 and 1507, often accompanied or followed by locust invasions, were documented both in narratives, account books, charters and letters. Apart from causing food shortage or difficulties in transportation (e.g. of salt), these greatest known documented drought events of medieval Hungary were blamed for weakening the country's military defence (e.g. low water levels) and providing good opportunities for Ottoman-Turkish attacks. These great drought events sometimes occurred one year later than those of the neighbouring areas in Central Europe – a fact that can be probably explained by the bi- or multi-annual nature of dry spells (e.g. in and around 1474, 1479, 1507) that does not necessarily fit the frame of a calendar year.

Keywords: droughts, dry spells, low water levels, food shortage, medieval Hungary and Croatia

INTRODUCTION

Drought is one of the most significant natural hazards in Hungary as well as in most of the Carpathian Basin (e.g. Pálfai, 2004), and this is especially true for historical times (see e.g. Pálfai, 2009; Kiss, 2009; Vermes and Pálfai, 2007). In medieval Hungary direct information on drought events is available only in a few cases. These few cases, however, may provide precious examples on how severe droughts effected late medieval socio-economic conditions, and also on the society's reaction (e.g. weak harvest, tax reductions, special actions/permissions of authorities, effects on military operations). They become even more apparent when comparing to other countries, for example, in the Central European region. Another interesting point is that most of the known medieval drought events appeared in combination with other reported natural hazards (e.g. heat and devastating hails: 1507, locust invasion: 1474–1479).

In the recent decade regional overviews, including the Middle Ages were published concerning the Czech Lands (Brázdil et al., 2013), Germany (included in: e.g. Glaser, 2008), for the Eastern Alpine region (included in: Rohr, 2007 – medieval extremes). For the last 500 years, for example, in the discussion of low water levels of the Upper-Rhine by Pfister et al. (2006) in Switzerland, or about the droughts occurred in Spain (e.g. Domínguez-Castro et al., 2008). In the context of a famous historical drought, recently the most well-known early modern case, the 1540 drought event – which otherwise was also combined with great heat – was discussed on a European scale (Wetter et al., 2014).

The term 'drought,' with clearly indicating serious water deficit for a longer period of time, can sometimes have slightly different meanings: meteorological drought, hydrological drought, agricultural and socio-economic drought have their own definitions in the different disciplines (e.g. Heim, 2002; Pálfai, 2004; Brázdil et al., 2013). In historical documentary evidence one can often find descriptions referring to drought either in its agricultural drought (i.e. affecting harvest and food production), or in its hydrological drought (i.e. referring to conditions of water bodies, e.g. groundwater level in wells, water levels of lakes/water flows) meanings. Due to its importance in food supply, agricultural drought usually plays an important role in historical documentation (e.g. 1362, 1507 in our present cases), but hydrological drought – with problems in using (or not being able to use) major water flows (1494) or in military operations (e.g. 1474, 1479, 1494) as well as shortage of water supply (1362, 1507) – can also rather often appear in historical documentation. Socio-economic consequences of great droughts can be followed practically in all of our five studied cases.

Henceforth, despite relatively scarce documentation on the topic, we can clearly identify some extraordinary great drought events in the countries of the Hungarian crown; such cases were, for example, documented in 1362, 1474, 1479, 1494 and 1507. The inclusion of the later date (1507) in discussion is due to the Hungarian termination of the end of the Middle Ages (1526). These occurrences are also interesting because reports about the five great drought events remained at least in four different sources types: while the 1362 and 1494 cases are preserved in charters, the 1474, 1479 and 1494 examples remained in a contemporary chronicle, the 1507 great drought event (and some of its consequences) was reported as contemporary inscriptions in an Almanach (notes of a Buda citizen), and an extensive set of information was also included in an economic-administrative source, the account books of the bishop of Eger (his administrator's accounts). Thus here, as a first paper on the topic, examples are provided when clearly great drought events were reported in contemporary medieval documentation.

LATE MEDIEVAL DROUGHTS AND DRY SPELLS IN CENTRAL EUROPE AND BEYOND

For the better understanding of the studied cases, it is worth to have an overview on the medieval–late medieval dry spells and droughts known from the surrounding areas. Due to the fact that some studies and published evidence in this topic are already available for the Eastern Alpine region, the Czech Lands and for Poland, it is also possible to discuss some parallels between the Carpathian Basin and its immediate neighbourhood.

In the Eastern Alpine region, based mainly on contemporary narratives and partly also on other (e.g. charter) evidence, some of the years with droughts or longer dry spells and water deficit (often combined with mentioning heat), documented in 13th–early 15th-century reports, were included in the book of Christian Rohr (2007) 1244, 1255, 1262, 1276, 1277, 1307, 1311, 1312, 1313, 1360, 1394, (1401, 1356, 1425 – suggested by Glaser, 2008), 1426, 1427, (1473 – suggested by Brázdil and Kotyza, 1995) 1503, 1513, 1514. In case of Austria, drought in reports is often combined with an extensive loss of domestic animals, for example in 1277, 1360, 1394, 1426, 1427, while sometimes drought is followed (or accompanied) by reports on food shortage or hunger (e.g. in 1255 in Austria, or in 1312, 1313 in the Czech Lands, Austria and Bavaria (e.g. Brázdil and Kotyza, 1995; Rohr, 2007) as well as urban fires (e.g. 1244 in Austria: Rohr, 2007). It is interesting to conclude that, concerning our discussed late medieval drought events, currently we find almost no parallels in known medieval Austrian documentation (only 1473: on year earlier than reported for Hungary).

In the Czech Lands, based on various types of contemporary source evidence, shorter or longer periods of dry weather and/or drought events were identified in the following years: 1091, 1121, 1128, 1177, 1194, 1252, 1260, 1262, 1266, 1283, 1307, 1312, 1315, 1326, 1328, 1333, 1334, 1337, 1348, 1352, 1368, 1369, 1371, 1393, 1423, 1425, 1432, 1441, 1442, 1461, 1469, 1471, 1473, 1476, 1480, 1482, 1501, 1503, 1504, 1506, 1509, 1512, 1513, 1516, 1517, 1518, 1520, 1525 (see Brázdil and Kotyza, 1995; Brázdil et al., 2013: Table 1 and Fig. 3). In the Czech Lands, with regards to our study period, especially the 1500s and 1510s stand out with 5-5 years of considerable dry periods reported in a single decade, while the 1260s, 1330s and the 1470s with 3-3 cases per decade are also rather significant. This list, containing any dry-weather information found by the authors concerning the Middle Ages, provides further information concerning our examples: in connection with the listed drought years in Hungary and Croatia, it seems that 1473 and 1506 (thus, one-one year before our great drought events), and 1480 (one year after our great drought case) were reported as years with dry spell or drought in the Czech Lands.

According to the weather event data collection for Poland (containing references up to 1500: Malewicz, 1980) based on narrative evidence dry spells, droughts or low water levels were documented concerning the years 1322, 1332, 1361, 1379, 1442, 1448?, 1451, 1452?, 1455, 1459, 1461, 1463, 1467, 1468, 1469, 1473, 1474, 1475. However, from a contemporary report (by Marcin Biem) it is also clear that 1494 was an important drought year, too (Limanówka, 2001). Thus, based on the currently available medieval Polish evidence the 1450s, 1460s and 1470s have the most importance; and the year of 1361, and both 1474 and 1473, 1475 (i.e. the years before and after) are also mentioned as years with significant droughts. Both from the viewpoint of Dalmatia, Croatia and Hungary, documentation related to the Central and East-Mediterranean areas of Europe (or the region east to us) would have great further importance. However, no studies have been carried out so far on the Italian) droughts, and we find no parallels of the discussed events in the Greek medieval weather-related investigations either (e.g. Telelis, 2008).

As we can see, the years with shorter or longer dry periods, discussed in the present study, sometimes have parallels in the neighbouring areas, but in most cases currently there are no direct parallels known from the areas closest to the Carpathian Basin. Nevertheless, this is also true when comparing the available documentary evidence of the neighbouring areas to each other. On the one hand, this is clearly due to the differences in climatic conditions and the great territorial variability of precipitation; on the other hand, it also depends on the quantity (and type) of the related available documentary evidence. Consequently, while even less significant dry spells might have been reported in some years well covered by sources, sometimes even a great drought event may have remained forgotten due to lack of sufficient documentation. Based on our present knowledge, this is also true for the Carpathian Basin where both the great territorial variability of precipitation (also of precipitation extremes) and the uneven spatial and temporal coverage of documentary evidence may prevent the detection of most dry spells and droughts occurred in the Middle Ages.

Looking around in the broader neighbourhood, multiannual drought periods were documented in the East European Plain both in the early 1360s and the early 1470s (e.g. Klimenko and Solomina, 2010).

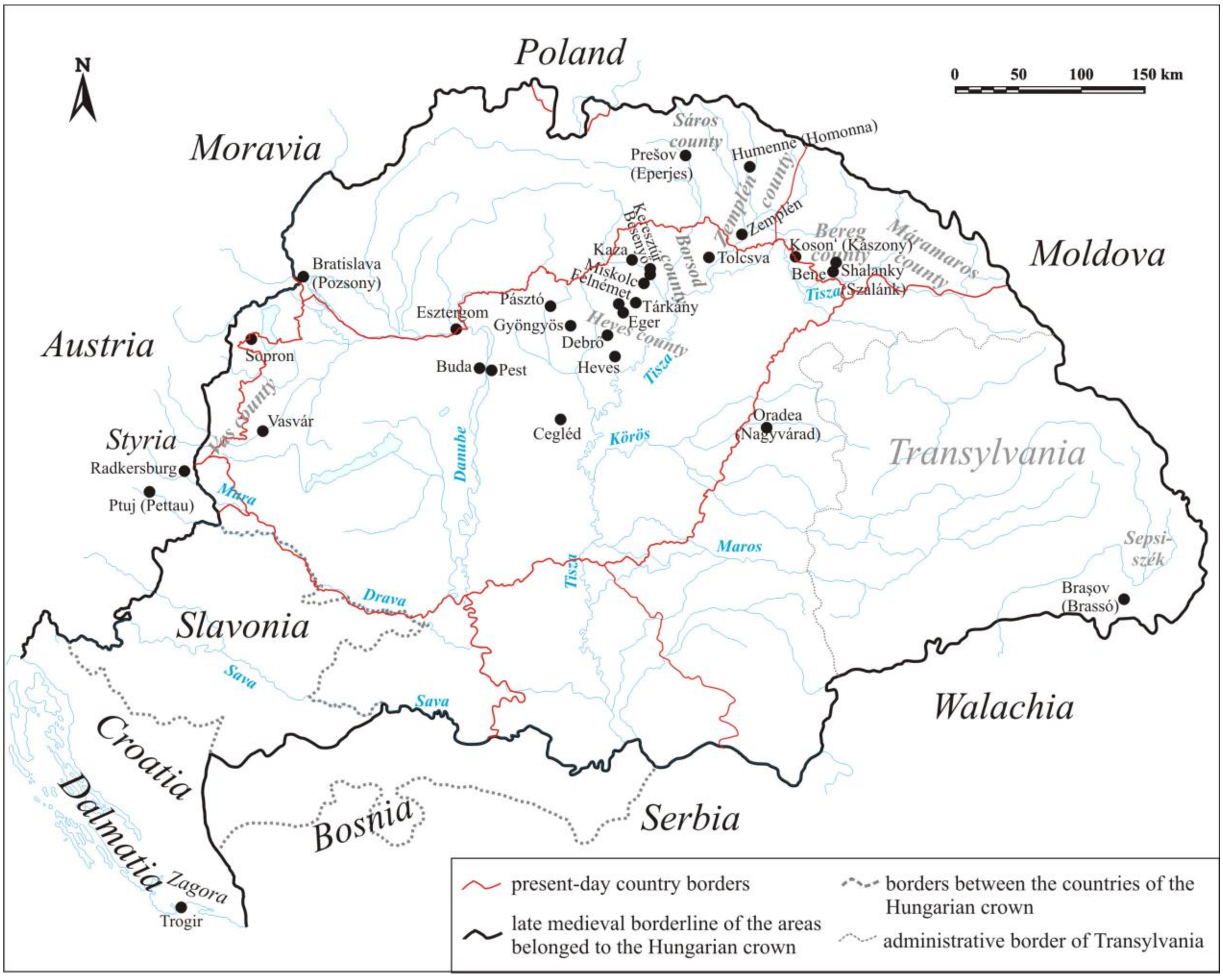

Fig. 1 Locations in late medieval Hungary, Croatian kingdoms and Austria, mentioned in the present study (historical settlement names in brackets)

Concerning the German areas (esp. the southern and central parts), in parallel to our discussed case studies, Glaser (2008) suggests that summer drought occurred in the years 1473 (also in 1471, 1472), 1479 (and the year before) as well as in 1506. As for spring droughts both 1479 and 1507 are listed among the drier years; additionally, the autumn was also suggested as dry in 1507.

As we can see, our case studies have some parallels in Central Europe with special emphasis on the areas west, north and northeast to the Carpathian Basin. Unfortunately, at present little is known in the topic concerning the areas south and east to the Carpathian Basin, except for the early 1362 drought evidence referring to Trogir at the Dalmatian coast (for locations, hereafter see *Fig. 1*). However, since at that time Trogir – with large part of Dalmatia – also belonged to the Hungarian crown, this case is included in the present paper in more detail, and is discussed in the next chapter.

SPRING 1362 IN DALMATIA: DROUGHT AND DUKE'S GRAZING PERMISSION

The first drought evidence, discussed in the present paper, is not from Hungary or the Carpathian Basin, but from Trogir (Trau) at the Dalmatian coastline. On 25 March (2 April in Gregorian Calendar – hereafter GC) in 1362, the duke of Dalmatia and Croatia (*banus*) gave permission to a pastoral community called *gens Morlachi* (the so-called 'Black Vlachs') to stay with their animals within the boundaries of the town of Trogir until the day of Saint George (24 April; GC: 2 May), because of the great drought (ed.: Smičiklas et al., 1915; Fejér, 1834). This special (and rather exceptional) permission was issued by the duke (ban) of Dalmatia in the name of the Hungarian king especially because of the great drought. The permission was given in order to avoid the mass extinction of their animals which formed their predominant property (and incomes); as suggested in the charter, particularly the young lambs were in danger of death ("..., *tamen quia emporis nimia siccitas et onerosa nunc ad presens in tantum imminebat, ac etiam agnellorum teneritas a loco ipsius habitationis remoti fuissent in maximum damni periculum incidi potuissent,...*"). Thus, in the Dalmatian Zagora area, due to the drought, there was not enough water and grass to feed the animals (even on basic level).

This fact indirectly also indicates that the situation at that time was not so severe along the seashore as in the hinterlands, in the surrounding (limestone) mountain area (Zagora): Morlachs temporarily could stay in a piece of land in the Trogir area where fresh water was also available for their animals. The dating of the charter (25 March in Julian Calendar – hereafter JC) as well as the duke's permission suggest that at least the usual winter–early spring precipitation was missing in (late) 1361–1362. For us the most important information is that, according to the contemporary eye witnesses, at that time great drought prevailed, and it had already lasted long enough to have clear threatening signs that forced Morlachs to leave their territory and go into a clear conflict by entering (using, and causing damages in) the lands of Trogir. Additionally, the wording "in those times" may allow thinking in a broader time frame of months concerning the severe water deficit in the area. As the Morlach sheperds were allowed to stay with their animals only up to 24 April (GC: 3 May), this fact may indicate the protection of belongings before the taxation date (day of St. George); but also that they hoped for some April–May precipitation.

As we can see, beyond mentioning great drought in early–mid spring time, the case has some further interesting social consequences: the pastoral community had to leave and go beyond its usual grazing territory, and entered the (prohibited) territory of the town of Trogir. This caused controversies with the citizens of Trogir that a decision and an exceptional solution (and guarantee), with reference to the special environmental conditions, were needed from the highest legal-political authority (duke and the king). Thus, not only the terminology but also the following special legal solutions suggest the extraordinary nature of the drought event.

A probable further interesting (although some later) contemporary information from Hungary is that, according to the protesting charter of the canon and bishop of Veszprém against the parish priest of Pest (today E-Budapest) town, the grape harvest of a particular vineyard in the Pest area started in this year rather early, as the tithe was already taken by 22 September (JC; charter edition: Fejér, 1834; regesta: Bártfai Szabó, 1938).

For 1362, no drought or dry spell evidence for this year are available in the Czech or German databases. However, in Austria 1360 was a drought year (Rohr, 2007), and information is available on the great drought of 1361 in the Polish evidence (Malewicz, 1980). Additionally, the years of the early 1360s were also an important multiannual drought period (including 1362) in the East European Plain (e.g. Klimenko and Solomina, 2010). From a multiannual perspective it is also interesting to mention that in the years 1363-1366 locust invasion were reported in Italy (taken by the NE winds, the "vento schiavo temperato" - from the direction of the S-Carpathian Basin; see: Camuffo and Enzi, 1991), in 1364 in Tyrol/Austria and Germany (see Rohr, 2007; Glaser, 2008). Furthermore, central governmental acts organising the distribution of crops were initiated in 1362 in Bohemia (Brázdil and Kotyza, 1995) and in 1364 in Hungary (for charter edition: Fejér, 1834).

Apart from the 1362 charter, problems with Morlachs were further mentioned in other years in the late medieval period, although without referring to any natural hazards as a cause. As discussed by Klaić (1880; 2010) the Morlachs caused problems with occupying areas for grazing or were mentioned in connection with a settling process in charters dated to 1344 (ed: Ljubić, 1870), 14 December 1357 (ed.: Smičiklas, 1914), 5 November 1383 (ed.: Stipišić and Šamšalović, 1916), 2 November 1387 (ed.: Gunjača and Stipišić, 1981), 17 June in 1402 (ed.: Hrabak, 2010) and in 1465 (ed.: Kukuljević Sakcinski, 1863). Although without possessing any direct (or even indirect) evidence we cannot draw any further conclusions, it is interesting to add that in some of these years longer dry spells were mentioned, for example, for the German areas (Glaser, 2008) in 1344 (summer), 1383 (summer and autumn), and in 1402 (spring). Furthermore, dry periods were reported one year earlier, in 1464 (spring and summer; and also in the preceding years), and in another case one year later: in 1388 (autumn).

THE GREAT DROUGHT OF (1473-)1474 AND SOME POTENTIAL CONSEQUENCES

An extraordinary (multi-)annual drought?

Concerning the year of 1473, extreme dry and hot weather was reported for the Czech Lands. Other sources reporting on the same weather conditions in the entire Poland and many parts of the German areas (for overviews, see e.g. Malewicz, 1980; Brázdil and Kotyza, 1995; Glaser, 2008). Moreover, the contemporary Polish history writer, Jan Długos, himself also mentioned that the unprecedented heat and lack of rain also prevailed in whole Europe (Dlugos 1877–1878). It is, therefore, somewhat surprising that the similarly contemporary Antonio Bonfini in his very detailed work about Hungarian history did not mention this fact at all, only the drought of the next year. 1473 was the year when King Matthias led military campaigns to Silesia against the Polish king, and the only detail Bonfini noted (apart from the very detailed descriptions of military and political/diplomatic operations) that there was food shortage in Poland and the Polish troops struggled with shortage of food supply, a problem which was clearly not present in the Hungarian camp (ed.: Kulcsár, 1976).

From our point of view, Bonfini's descriptions in Hungary starts to be interesting from late winter, 1474: on 7 February Ottoman troops suddenly crossed the Danube and the Maros rivers, destroyed many settlements, but especially the rich merchant town, (Nagy)Várad (today Oradea in Romania; see also: Florianus, 1884). The quick crossing and appearance of a significant (even if not big) Turkish army in Várad, very far from the Turkish-Hungarian borderline, may suggest cold and dry conditions (i.e. little or no snow) already in late January–early February in the south-east parts of medieval Hungary (see *Fig. 1*).

However, descriptions on the real drought came later: for this year, Bonfini reported on the great shortage of water ("*Insolita hoc anno aquarum penuria fuit*") and year(s)-long drought – in which springs dried up ("*siccitas perennes quoque fontes exhausit*") – (ed.: Kulcsár, 1976). Due to this drought, main rivers of the country had very low water levels, and the Ottoman Turkish troops could (again) enter Hungary by crossing the main rivers ("*Turci superato Savo Pannoniam incursarunt.*"). Bonfini's dating is clear and correct: the year of these Turkish attacks undoubtedly took place in 1474. Nevertheless, while describing the drought, Bonfini in his text applies the word "(*siccitas*) *perennes*" which has the meaning of the 'entire year', but it may also mean a period longer than a year. The lack of mentioning 1473 drought in Bonfini's case can also be explained as the author, whose primary interest was on politics and speak in favour of the Hungarian king, simply did not find 'important enough' to mention in more detail the circumstances that weakened the Polish army against Hungarians in the Silesian 'affair', while in 1474 it was rather important to mention the environmental circumstances that clearly helped the Ottoman-Turkish troops in their rather successful military campaigns.

Furthermore, it is interesting to add that 1473, as the year of a great heat and drought in Hungary, is more widespread in the literary tradition of non-contemporary evidence than the 1474 drought itself: for example, in the domestic early 17th-century *Chronica Leibitzeriana* (in the Spiš area), similar to the 17th-century chronicle of Caspar Hain from the same region (Bal, 1910–1913), great heat and drought are dated for the year 1473 (Schmauk, 1889: "*MCDLXXIII. Jam magnus calor & siccitas fuit incipiendo a Pentecoste* (JC: 5 June, GC: 14 June) *usque ad festum omnium Sanctorum* (JC: 1 Nov., GC: 10 Nov.), *ut silvae a Sole acccensae sint, & radices etiam in terra exaruerint.*"). However, there is no mention of the 1474 drought at either places. Also referred by Antal Réthly in his compilation on weather events (1962), the mid-16th century Swiss polyhistor, Conrad Lycosthenes (1557) similarly reports on the great drought that caused forest fires and rivers drying up in Hungary, and also that even the Danube would have been crossable in 1473, in the year when the king of Cyprus, Jacob (II) died ("*Aestate ob siccitatem & aestum nimium syluae incensae, flumina siccata, ita ut Danubius in Hungaria meabilis fieret. Iacobus Cypri rex obiit, ...*"). Still, there is always a possibility that the two 17th-century chronicles took the year (and the information) from the same local German 16th-century source (in general, see e.g. Szabó, 2014), and this is as well probable in case of the mid-16th century German author, Lycosthenes. Therefore, even if it is possible that already 1473 was dry in Hungary, these non-contemporary sources alone cannot be applied to support the idea.

A potential consequence? The great locust invasion in (1473–)1474–1479

A probable consequence of the great drought, affecting large parts of Europe, was the severe locust invasion started in the same years (in Moldova and further) and lasted until the end of the decade. In the Austrian *Continuatio Mellicensis* (ed.: Pertz, 1851), the beginning of a 3-year long locust invasion is dated to 1473: coming from Moldavia, locusts spread over in Transylvania, Hungary, and reached as far as Bohemia and Linz in Austria ("*1473. .... eodem anno et sequentibus tribus locustarum grex magnus et innumerabilis ex Moldavia emersus, per totam Transsilvaniam, Ungariam, usque Bohemiam, et in Austria usque Lincz multa debachatus est.*"). Locust invasions are usually associated with dry periods; their long-distance travel is strongly connected to specific changes in wind circulation. Locust invasion of Hungary was as well mentioned referring to 1474 in the (Styrian) *Chronicon Anonymi Leobiensis*; in this later case the chronicler specifically mentioned them to be seen at Esztergom (see *Fig. 1*) located in Central Hungary (as a later, additional note to the early 14th-century part of the chronicle: "*Anno 1474 in Hungaria apud Strigonium idem genus locustarum modo quo hic est expressum apparuit.*"). Both Polish and Czech chronicles mention 1474 as the starting year of locust invasion (Brázdil and Kotyza, 1995). In this case dating of Czech sources is especially interesting because, as the *Continuatio Mellicensis* suggested, the (usual) route of locust invasions led through Hungary, then continued to the Czech Lands, most probably via the Vienna area, and further in the Danube valley, towards Linz.

Similarly, according to the contemporary domestic *Chronicon Dubniciense* (ed.: Florianus, 1884), this locust invasion happened in the same year as the Turkish attack of (Nagy)Várad (today Oradea, Romania), in 1474. Moreover, the same source clearly dates the great amount of locusts to July and August which appeared in such quantity that, except for the leaves of vine stocks and trees, they consumed all green vegetation ("*Nec hoc tacendum esse putaui, quod in estate anni predicti signanter in Julio et Augusto mensibus, innumerabiles et incredibilis multitudinis locuste, catheruatim quasi magni montes, per climata et partes dicti regni Hungarie hinc inde volitantes vise sunt; que omnia virencia pro usu earum preter folia arborum et vinearum vendicarunt,....*". See also: Csukovits, 2008).

Thus, the locust invasion most probably started in the areas east to the Carpathian Basin in 1473, and the outbreak in Hungary occurred in the next year, in 1474. Concerning duration of the locust invasion the information is more diverse: the *Continuatio Mellicensis* suggested 3 years (presumably for Austria), Czech narratives referred to 2 years, whereas for Hungary the *Chronicon Dubniciense* claimed that this locust invasion lasted almost/around 5 years. However, taking 1474 as the starting year of the invasion and 1479 as the last year, this invasion lasted for 6 years in Hungary. As we will see, similar to the starting year(s), the last year(s) of this great locust invasion was also famous of its extensive drought.

DROUGHT, LOW WATER LEVELS, TURKISH ATTACK AND LOCUSTS: 1479(-1480)

As described by the contemporary author, Antonio Bonfini (ed.: Kulcsár, 1976), again for the luck of the Ottomans, great drought occurred in early 1479: up to the 7 Kalenda of April (JC: 26 March; GC: 4 April) there was no rain at all ("*Fortuna Turci audaciam sequitur fovetque, nam tanta siccitate is annus exaruerat, ut ad VII. Kalendas usque Aprilis nunquam tantum pluerit, quantum sitibundum terre dorsum parumper aspergere potuisset.*"). Bonfini blamed this winter and early-spring drought for the extraordinary low water levels of the Sava and Drava rivers. The two rivers had so little water that, rather unusually, in many places they were passable. The Drava, that has always been a navigable river, became passable on foot ("*Utraque Pannonia Savo hinc et Dravo illinc circumventa Istro munitur et Turcorum* *incursum amnes inhibent, pre insolenti vero siccitate Savus in plerisque locis vado transiri poterat. Dravus semper ac ubique navigabilis eo anno pedibus traiici passus est; in causa fuit insolentissima siccitas, cum fluvii tres ubique navigentur.*"). The possibility of an easy crossing provided (again) a great opportunity for some Ottoman Turkish troops to attack Slavonia, West-Hungary up to Vasvár (Castrum Ferreum) and Styria up to Radkersburg in summer, where they caused immense damages ("*Turcus vadi exploratorem invenit ad Dravum, quem multa mercede conduxerat. Transmisso iam Savo triginta Turcorum milia in Dravi repente ripa consedere ac ii tutum vadum edocti superato amne Pannonias invadunt, in pagos, in homines ac pecora iuxta deseviunt, ferro ignique isquequaque debacchantur, ad Castrum usque Ferreum et ad Styriam Rachospurgumque decursant.*").

According to Bonfini, the Ottoman attack occurred in August, when the king and his people were occupied by the country meeting in Olomouc. It is interesting that, even if the Turkish attack occurred in (mid–late) summer, Bonfini blamed the winter–spring drought for the low water levels of the Sava and Drava rivers. Nonetheless, due to the very low water levels, the rest of the spring and summer had to be also dry. In the further understanding of extreme low water level conditions we also have to take into consideration that in the German scientific literature both 1478 and 1479 were mentioned for their dry summers: in 1479 also spring was notably dry in the German areas (Glaser, 2008). In the Czech Lands no such problem is mentioned for 1478, but the summer and early autumn of 1479 were hot and dry. Heat and drought were even more significant, in 1480 (Brázdil and Kotyza, 1995).

About the Turkish attack to Carinthia through Bosnia in August 1478 (JC: ca. 10 August; GC: 20 August) only the many (3000) casualties due the broken Drava bridge (but no drought) were mentioned by the Polish chronicle writer (Długos, 1877–1878). However, Bonfini (as we could see before) explicitly mentioned at the year 1479 that the great drought made crossing and invasion clearly easier for the Ottomans. In the same time, according to the *Chronicon Dubniciense*, in Hungary locusts made the greatest damage in the last years of their stay (since 1474), namely in 1478 and 1479 (ed.: Florianus, 1884: "*... et iam admodum multiplicate continuis annis in regno durauerunt, fere quinque annis integris, dampna indicibilia, signanter hoc anno, scilicet millesimo quadringentesimo septuagesimo octauo inferentes, et similiter in anno millesimo quadringentesimo septuagesimo nono.*").

Either as a separate case or as a continuation of the 1479 drought, great aridity is also reported by a contemporary source (Gyöngyösi's *Vitae fratrum eremitarum*) in spring 1480, when – fulfilling the king's request – the Paulines of the Budaszentlőrinc monastery carried out a religious procession asking for rain. The rain did arrive during the procession, and refreshed the vegetation (source ed.: Hervay, 1988; see also: Fedeles, 2007).

As a conclusion, similar to the previous 1474 case the very low water levels of major rivers, together with the consequent Ottoman Turkish attack, were reported to be caused by a prolonged drought. Due to the severity of water deficit, this drought lasted most probably longer than a three-month winter-early spring period, suggested by the contemporary chronicler, and the drought might have continued (maybe in a lesser extent) in spring and most of the summer, too. Furthermore, based on some German parallels we cannot exclude the possibility that the previous year might have been also drier than usual, and (again similar to the case of 1473-1474) the fact that Bonfini did not mention drought for the previous year does not exclude its potential occurrence. Although Antal Réthly, referring to Bonfini, also mentions a drought in 1478, in the works of Bonfini drought is mentioned only under the year 1479 (and not in 1478).

DROUGHT, LOW WATER LEVEL, FOOD SHORTAGE, TURKISH ATTACK IN 1494

The large-scale, half-year drought

A more direct and detailed report of a clearly severe and extensive drought is available 15 years later: as reported again by Antonio Bonfini (ed.: Kulcsár, 1976) in his extensive works, in the year of 1494 there was continuous drought for six months in Hungary ("*Quin etiam tempus maxime idoneum nacti, quod et rex in Transylvanie finibus aberat et perpetua sex mensium siccitas omnes prope amnes, qui Ungarie propugnacula sunt, ita exhauserat,...*"). Rivers, that protected Hungary (as well as Croatia and Austria) against Ottoman Turkish attacks, had so low water levels again that it was easy to cross them and thus, in the entire October Turkish troops continued destroying lands in South Hungary and Slavonia, and they also attacked and devastated South-Styria up to Pettau (today Ptuj in NE-Slovenia) ("*... ut multis in locis facile traiici vado possent, per totum Octobrem mensem populationes atque indencia usque ad Petoviam perduxerunt.*"). Moreover, since these events were followed by a hard winter in which all rivers were firmly covered by ice, the Turkish troops could return to the Sava river, killing those who were unable to proceed ("*Inde Dravo ad Petoviam traiecto et magnis detrimentis illatis hominum ad septem milia abduxerunt. Post autem metu, ne intumescentibus sub imminentem hiemem omnibus aquis intercluderentur, ad Savum regressi, quicunque aut etatis aut corporis imbecillitate languoreque sequi non potuerunt, eis capita in ripa fluminis detruncarunt ....*"). It is an interesting fact that while they easily crossed the Sava, they continued mainly to the northwest, and crossed the Drava only at Pettau (i.e. did not attack the Transdanubia to the north by crossing the Drava at its lower sections, but rather Styria, and crossed the Drava at its upper sections, much before its confluence with the Mura river).

In an important letter sent by Queen Beatrix (King Matthias's widow) in March 1496 (MNL, DL 98454), the queen asked the count of the Máramaros (today Maramureş, North-Romania) chamber about a large transport of salt that has not arrived since 1494

("*Quoniam et computa tue administrationis salim camere nostre Maramarosiensis anni 1494. noviter elapsi ex relacione venerabilis Philippi de Brixia rationalis nostri intelleximus te in dicto tempore fecisse incidere tumenos salium ...*"). It seems that a rather large amount of salt had not been transported in 1494, and (maybe) remained in the chambers at the Tisza, as – due to lack of waters – they could not deliver the salt ("*de qua quantitate apparet remansisse in cameris prope Ticiam, qui non potuerunt onerari propter defectum aquarum* /*tumenos*?/ *20728,*"). Thus, the Tisza river (where the salt transport was carried out in those times) had so low water levels at least for several months (or the entire year) in 1494 that the transportation of large quantity goods, usually carried in large vessels, was not possible. The letter is silent about the character of the period concerning the next year: we cannot be certain whether the water level of the Tisza was still low in 1495 or it was due to other reasons why the chamber administrators did not send the salt afterwards.

Based on all information, and also King Vladislas' Transylvanian itinerary (see e.g. Neumann, 2014), the half-year dry period most probably started at least in mid- or late spring and continued throughout the summer months. Apart from the long-lasting drought, we especially have to emphasise the reported great spatial extent of the events: the low water levels of major rivers can be detected in contemporary documentation not only in the south, south-western parts of the Carpathian Basin, but dry conditions also prevailed in the (north-)eastern parts, and resulted very low water levels of water flows, including the (Upper-)Tisza river. As mentioned by Bonfini, the drought period was followed by hard winter when the Danube was firmly frozen which repeatedly helped Ottoman Turkish military operations in the south.

Apart from Bonfini's general description on the drought that prevailed in Hungary, we do not know how much the drought affected the more northern, north-western areas. Nevertheless, (maybe showing some similarities to the 1507 case), as mentioned in the contemporary town accounts of the royal town of Sopron, torrential rain or cloudburst caused great damages in the vineyards of Sopron in late June (text ed.: Házi, 1936).

A possible consequence? Food shortage in SE-Transylvania

Regarding the same year, a rather thought-provoking information on food shortage is also available concerning the East-Transylvanian Secler Sepsiszék area (today in Central-Romania): according to an early September royal charter (ed.: Szabó, 1872), the king allowed the Sepsi Secler delegates to go home earlier from the Diet, and also to send much less armed men (only 1/16) to the royal army, due to the great need and shortage of crops and beverages that prevailed in their homeland in that year ("*Annone et victualium caristia, qua nunc ista vestra patria laborat*"). Knowing that the 1494 drought primarily affected the upper (mountain) catchment area of the Tisza river in (North-)Transylvania, it seems probable that the same drought (combined or not with other natural hazards) could be also responsible for the very bad harvests and food shortage of some Secler basins, located in the south-eastern part of Transylvania).

It is rather interesting that up to now, apart from the contemporary reference of Marcin Biem (Limanówka, 2001) concerning South-Poland (Cracow area), in the scientific literature no analogous events (or even a dry spell or low water levels) are known (see Malewicz, 1980; Brázdil and Kotyza, 1995; Rohr, 2007; Glaser, 2008) for this year in the neighbouring areas. As for the Czech Lands and Upper-Austria, in fact rather the opposite weather conditions are described: an early May flood was followed by a very unfavourable, wet summer and then by bad harvest; similar information is available for the Salzburg area where both the summer and autumn were very wet (Brázdil and Kotyza, 1995).

1507: GREAT DROUGHT, HAIL, BAD HARVEST AND POVERTY

A contemporary Buda citizen, János Kakas, mentioned in his Almanach that almost in the entire year, and especially in the summer of 1507 there was very great drought in Hungary (source ed.: Kubinyi, 1971), resulting a significant shortage of crops, wine and hay ("*1507. Hoc fere anno et maxime in estate ingens siccitas viguit per Hungariam ubique, ex qua non mediocris penuria frugum, vini et feni provenit.*"). And this is not the only record about the great drought event: a rather extensive set of evidence about this drought, other natural hazards and their consequences were described in the accounts of the bishop of Eger, Ippolito d'Este (source ed.: E. Kovács, 1992).

It is an especially interesting fact that the great drought reportedly affected even such high elevation areas as Eperjes (today Prešov in NE-Slovakia; see *Fig. 1*) in former Sáros county where leasing and purchase of the tithe was collected after crops: the leasing (*arenda*) and purchase of the tithe were partly paid (on 15 July JC) and partly postponed (to 6 Dec. JC) due to the fact that the great drought in this year destroyed the crops ("*quia siccitas magna isto anno destruxit fruges*"). This last sentence is very important, because here the tax collector gave the great drought ("*siccitas magna*") as 'the' reason for the destruction of cereals. Additionally, the very great drought ("*maxima siccitas*") was also mentioned later, in relation with the Saint Demetrius market in the town of Eger (JC: 26 Oct.; the day when sheeps were traditionally driven back from the open pasture): at that time the cabbages were bought (to be salted), and as there was very great drought, they were (placed) in the meat market (166v. "*.... Item in foro Sancti Demetri (október 26.) caules ad salsandum emit pro castro fl. quadraginta uno et d. octuoginta quattuor et hoc fuit propter maximam siccitatem, ideo fuerunt in caro foro.*").

A summer information in the account books is that some time after 4 July a horse, bought in Transylvania, died in the way between Eger and Esztergom due to the heat ("*.... et recesserunt 19 iunii ab Agria et quarta iulii expedivi ipsos a Strigonio, cui Aloisio etiam assignavi unum equum ex equatibus Sancti Ioannis, loco quorum* *dimisit unum et veniendo ab Agria ad Strigonium et erat de illis sex emptis in Transilvania mortuus est in via propter calores*").

Further interesting information is that in this year there were no fishes in the fisheries (belonging to Eger), and therefore the poor serfs received reduction of the tax (or leasing) ("*Agrie 22 septembris. ... Item ivi extra ad videndum piscaturas, in quibus anno isto non sunt pisces,.. quia pauperes iobagiones non debent agravari in omnibus expensis*"). Moreover, in many cases all over the areas of the bishopric it is also mentioned that there were no bees ("*apes vero non fuerunt*").

In the Heves district in Heves county (and also in Borsod) the harvested crops were bad ("*male fruges sunt omnes*"), and the administrator of the bishopric mentioned that the (bad) price of crops was due to the very bad quality ("*quia male fruges et pessime fuerunt*"). In the same county, in the Debrő (see *Fig. 1*) district the tax officer similarly reported that although there was some harvested grain, it was worthless ("*quas fruges dederunt capetie ducente tritulate, quia nulius valoris fuerunt*"), and as he also mentioned in detail, market (selling) prices fit the very bad quality of crops ("*et videtur, quod sit vendite octingente et quinquaginta tres cum media et dederunt pretium ut supra et capetias novem et plus modicum pro uno fl. et hoc est, quia pessime fuerunt fruge*"). Similar problems were reported from Borsod county Kaza district ("*quia anno isto hic male fruges fuerunt et vernalia multa intus etc*"), and also in Miskolc district (in the same county) where the bishops' administrator added that he saw the bad selling prices, and grain (harvest) was generally bad there ("*videtur dedisse capetias duodecim pro uno fl. et nota, quod hic generaliter non bene venduntur et fruges etiam male fuerunt*").

In Zemplén county, in the Zemplén district tax was only collected in 1508, and in the Homonna district (today Homonné in E-Slovakia), due to the hail, they could not collect any harvests ("*quia anno isto habuerunt grandines in istis duobus districtibus et non potuerunt collocare in acervis*"). Regarding the tithe of cereals (*frugum*) of the Pásztó district in Heves county (see *Fig. 1*) almost similar problems were described: the tax officers noted that the cereals were bad in general (i.e. in growth, in quantity/quality), and were destroyed by rains ("*quia fruges male generaliter huc sunt et per pluvias destructe fuerunt*"). Thus, in these cases not the drought, but hail and rains (convective events?) were blamed for the loss of harvest.

In Bereg county the tithe incomes of Szalánk (Shalanky, today in Ukraine) and Bene (see. *Fig. 1*) were rather small and the wine was "light" ("*que vasa sunt valde minora ceteris et vina sunt levia*"), and – as later mentioned – the sold wine was rather bad ("*quia vina sunt villissima*"). Similarly a small quantity was reported in the Razon (Kazon/Kaszony? – today Koson' in Ukraine) district ("*exegit vasa media, que sunt valde minora*") in the same county. The low quantity of wine both in 1507 and 1508 were noted in the bishop's estate in Gyöngyöspüspöki (today part of Gyöngyös town). Concerning the payment of the wine tithe of Pásztó in Heves county (collected on 6 Dec. JC) the inhabitants asked (and received) a reduction of 10 fl. (they should have paid 75, but paid 65) because the hails destroyed vines and caused lots of other damages ("*quia grandines ibi anno isto destruxerunt vineas et passi sunt multa damna /et ut moris est insimilibus/ relaxavi ipsis fl. decem*"). Similarly, amongst others, the great damages caused by hail was a main reason of tax reduction (on 14 March) in Tolcsva (Zemplén county; in the Tokaj-Hegyalja wine region) from the wine tithes ("….. *Et nota, quod maxima damna passi sunt per grandines anno isto ....*").

As was also indicated in the further parts of the accounts (talking about the travel to Eger and return to Esztergom), the officer mentioned that "great dearth of things" prevailed ("112v. *Item predicto eundo, stando et inquirendo equos et veniendo domum cum famulis eorum et stabulariis et cum equis exposuerunt a recessu suo ab Agria usque ad adventum ver reversionem eorum fl. quinquaginta novem et certe consideratis omnibus et maxime caristia magna rerum, in via non multum exposuerunt.*"). Possibly the combined effects of natural hazards, followed by bad harvest in basic beverages, resulted the great need.

In Felnémet (see Fig. 1) people received tax reduction in this year due to their great amount of works on the St. John church that had burnt down ("*Residium relaxatum est, quia multum servierunt ecclesie Sancti Iohannis isto anno propter combustionem*"). Described in other parts of the text in more detail, the church of St. John (in Eger) was struck by lightning and burnt down in 1506.

In Tárkány and Cegléd people did not have to pay the tax of St. Michael (JC: 29 Sep.) because of their poverty ("*propter paupertatem*"). This question once more appears later when, apart from poverty, their serving works were also mentioned ("*servitia et paupertatem*"). Great poverty (e.g. in Tárkány: „43v. *Census Sancti Michaelis* (JC: 29 Sep.). …. *Tharkan debuisset dare fl. quattuor, sed propter nimiam pauperitatem sunt eis relaxati.*") continued also in the next year and provided reasons for further tax reductions in 1508, too. The account also mentions that disease prevailed (p. 319: " *pestilentia*") in the same year. In these cases the reason for tax reduction was mainly the great poverty of people.

An interesting further information was reported in the same account books (4 October, 1507): the wines collected in Besenyő and Keresztúr (today Szirmabesenyő and Sajókeresztúr, located near the Sajó river; see *Fig. 1*), were partly destroyed, and the remaining part had to be moved to the castle, due to the fact that cellars were filled with water. These circumstances suggest either a (late September–early October) flood (maybe flash flood, torrential rain?) or maybe very high ground water conditions in the area.

As for conclusion, on the one hand a Buda citizen emphasised the great drought that prevailed in Hungary in general, and caused a bad harvest of crops, vine and hay in 1507. On the other hand, from the accounts of the Eger bishopric a broader picture can be obtained: apart from generally low incomes in this year, the great and very great drought was emphasised to be primarily responsible for bad harvests in two cases. Rather interestingly, drought severely affected the higher elevation areas in the north-northeast (Prešov area, E-Slovakia). Further cases suggest that, apart from the great drought, hail and rainfall caused great damages in the crop harvest as well as in the vine stocks in a number of cases in Central and North-East Hungary. Moreover, in summer the drought was combined with heat (at least) in the central parts of the Carpathian Basin. As a result, an extraordinary bad harvest of crops, hay and sometimes also wine was generally reported not only in the central, north-eastern, low elevation areas of the country, but also in the hilly areas. The low amount and bad quality of crops and wine may suggest that, beyond the significant impact of other natural hazards, (similar to the German areas) already the spring was characterised by a serious water deficit that probably continued (combined with heat and maybe convective precipitation events) in summer and (at least partly) in autumn.

Among other, further consequences a casualty (caused by heat), combustion and, apart from bad harvests of cultivated vegetation, in some areas the lack of fish and in many cases that of bees were reported. As a further cumulative effect (of combined hazards – on an annual or multi-annual level), shortage/lack of beverages and especially poverty prevailed (as well as disease mentioned) in extensive areas, and formed the basis/reasons of tax reduction. There might have been a change in weather around the end of September and/or beginning of October towards a more rainy character that induced flood (and/or high ground water table).

Referred in the Réthly compilation (1962), in his work the contemporary author, Antal Verancsics (1504-1573; source ed.: Bessenyei, 1981) gives the information on the extremely great prices due to the shortage of bread, under the year 1508 ("*mondhatatlan nagy drágaság támada egész Magyarországban, kinérnek szík vóta miatt.*"). Very great need in 1508 was also mentioned in the account books of the Eger bishopric, while referring to the expenses of a travel from Eger ("*et certe consideratis omnibus et maxima caristia magna rerum, in via non multum exposuerunt*"). Later in this year a lack of bee-products namely honey and wax (in late March in Eger: "*quia anno non fuit mel neque cera*") was described, and also poverty and pestilence were recorded in the accounts. Apart from this indirect evidence and the potential consequences of the extreme Danube flood in summer 1508 mentioned in Austria (see e.g. Rohr, 2007) that most probably also affected the Danube valley in Hungary, we have at present no more information concerning the character of 1508, and therefore we cannot say in what extent the hazards of the previous year(s) and/or those of 1508 are responsible for the critical conditions prevailed also in 1508 in large parts of Hungary.

As suggested before, in the Czech Lands the summer months of 1506, with special emphasis on June, were mentioned as significantly dry (Brázdil et al., 2013), while in the German areas (according to Glaser, 2008) not only summer 1506, but also spring and autumn of 1507 were notably dry. As for other areas in Europe, apart from the dry spell in Spain (e.g. Dominguez-Castro et al., 2008), in 1506 a significant drought preceded the Lisbon Massacre in Portugal (see e.g. de Gois, 1749). A thought-provoking further information from outside of Europe is that 1506 was the last year of a severe multi-annual drought, for example, in Central Mexico (Therrell et al., 2004). At present, our only available weather-related information concerning the year of 1506 in Hungary is the above-mentioned lightning and fire of the St. John church in Eger, and a flood – most probably influenced by ice – at the end of the year at Buda that suggest a rather cold (late autumn-)early winter in this year (recorded by the afore-mentioned Buda citizen, János Kakas; see in: Kubinyi, 1971).

DISCUSSION

Drought severity - towards a numerical classification

The magnitude of drought events is usually discussed with using numerical values. In historical climate/hydrology research usually a 3-scaled index classification is applied. This classification is in fact the 'dry part' of the 7-scaled precipitation (monthly) index classification, commonly applied in historical climatology (Brázdil et al., 2013; see also Glaser, 2008; Pfister, 1999 etc.). While in more modern times usually an adequate amount of source evidence is available to classify the intensity of a drought event, the situation is often rather different in the Middle Ages when only one or two short contemporary notes are available on the individual events, and the severity of individual months often cannot be defined.

In our present cases terminology (*siccitas*; *ingens*/*magna siccitas*; *maxima siccitas*), information on the approximate length of the drought as well as severity of consequences (extraordinary low water levels of major rivers for a longer duration, bad harvest due to drought etc.) provide further help in estimating the severity of the individual drought events.

Due to mentioning durations, the picture is relatively clear in case of the 1474, 1479, 1494 and 1507 events: the drought of 1474 is described as annual (or even longer) in duration, the 1507 drought was mentioned as a 'whole year, but especially summer' event, while in case of 1479 a 3-4-month (at least), and for 1494 a 6-month drought was mentioned by the (same) contemporary author. Concerning 1474, 1479 and 1494 extreme low water levels of major rivers and the related historical events (i.e. intensified Turkish attacks – utilising extraordinary low water levels) directly and indirectly also supported the description. As for territorial extension, in 1474, 1479, 1494 and 1507 the authors mentioned "Hungary" and thus, probably in these four cases large parts of the Carpathian Basin had to be affected by long dry periods. Additional information on low water levels of the Drava, Sava and the Tisza rivers, and the large-scale socio-economic consequences also suggest that extensive areas (including the alpine catchments) had to be affected by the long-term water deficit.

Less is known about the 1362 Dalmatian case: although great drought (and need for water) is mentioned, some important socio-economic consequences are known that suggest a significant long-term winter-early spring water deficit, no explicit information in the contemporary documentation is available about the length of the drought event. This later information, however, would be probably the most clear indicator of a severe drought (see e.g. Pfister et al., 1999). Nevertheless, the rather exceptional nature of socio-economic consequences and legal/administrative decision (as well as some potential Central European parallels) may suggest that this drought event was also extraordinary in magnitude.

Social, political, economic, military and environmental consequences

When talking about the socio-economic effects of droughts, we may group the consequences as follows:

1) Military operations and devastation of extensive areas (including mass loss of lives) supported by hydrological drought (1474, 1479, 1494): the southern defence line of the Hungarian kingdom (and also of Slavonia) against the Ottoman Empire – due to the unfavourable, flat lowland conditions of the borderline areas – was largely dependent on the hydrological defence line formed by major rivers, such as the Drava, Sava and the Danube and their extensive wetland areas. Apart from the winter cases when firm ice cover of major rivers and the lack of notable snow provided good conditions for a rapid 'raid' of Ottoman Turkish troops (e.g. winter of 1474), prolonged low water levels of major rivers (and dry roads) in the summer half year provided equally favourable conditions for intensive military attacks. These military attacks in the last decades of the 15th century affected not only the countries of the Hungarian crown, namely Hungary, Slavonia (and Bosnia), but also the south-eastern parts of Austria (especially Styria). Thus, repeated (and prolonged) great drought events provided more possibilities for military attacks, reported during the dry 1470s and in 1494.

2) Transportation problems during hydrological drought, due to extraordinary low water levels (1494): while low water levels ease the possibilities for crossing, it may cause great problems in river transportation when lacking the sufficient depth of water has the result that deficiencies occur in the supply of even basic beverages such as salt. Thus, although other environmental circumstances, such as great flood (or damages caused by great flood) or shortage of labour could obstruct salt transport along major rivers (e.g. along the Maros river in 1496; see HNA, DL 65441), in the Middle Ages (even if at the moment in only one known case), drought (long-lasting low water levels) could be also a reason for major transportation problems.

3) Drought caused problems for pastoral communities, and – due to lack of sufficient quantity of fodder and drinking water – threatened with a mass instinct of domestic animals: in the drought case of 1362 domestic animals were mentioned to be threatened by prolonged drought. In this case the usual grazing practices and territory of the pastoral community had to be changed temporarily: Morlachs had to leave their territories and (shortly) occupy those of a highly privileged town, to avoid significant loss of animals.

4) Agricultural, socio-economic drought: can be mentioned in relation with the (very) bad harvests, high prices, food shortage and poverty in 1507 (with food shortage and poverty also in 1508). Although drought is a prevailing factor and may be the main reason for significant socio-economic problems, the drought was combined with other (related) hazards such as heat and convective events (hail, destructive rainfall). Bad harvests, high prices and related uncertainties (even probable casualties) might have been a result of these combined effects (affecting extensive areas). 1507 is the only case when more information is available for a combination of hazards and their consequences. Need and high prices in this year (1507) may be the result of the current bad harvest; however, also with using other Central European parallels, it is that the rather wide-spread poverty was due to the fact that (apart from other social, political circumstances such as generally growing uncertainties due to Turkish attacks in other parts of the country, high taxes etc.) unfavourable conditions prevailed not only in 1507, but also in 1506 (as, for example, in the German and Czech areas), and 1507 would have been already the second year (at least?) with bad harvest results.

5) A further interesting, potential (biological) consequence, also resulting great loss in the cultivated vegetation, might be that around the same time when drought prevailed locusts also arrived (even if the exact consequences on social processes are not reported) and were present (most probably in the 1360s and) in the 1470s. While this invasion caused clearly further socio-economic problems, locusts were 'only' directly reported in Hungary during the drought events of the 1470s (and in the countries where usually locusts arrive from Hungary or Slavonia in the 1360s), while no information is available for their mass appearance in the drought years of 1494 or 1506. However, the outbreak of locust invasions in the 1360s and 1470s clearly coincides with, for example, the prolonged multiannual drought periods occurred in the East European Plain in the early 1360s and 1470s.

One-year shift (or not) with Central-European droughts – any comparison possible?

Although relatively few information is available concerning great medieval droughts, it is interesting that most of the great drought mentions are available concerning the last decades of the 15th century and for 1507. However, due to the low sample size, at present it is yet difficult to draw any conclusion whether or not, compared to other periods, the number of great drought events increased around the turn of the 15th-16th century. The present 'distribution' of known drought evidence is strongly dependent on source availability: as we could see before, most direct mentions of great droughts come from narrative sources, charters and from economic-administrative (institutional) evidence. Prior to the mid-15th century, narratives and accounts (if available) very exceptionally contained weather-related information, and in the charter (and letter) documentation, significant in quantity especially from the early 14th century, any drought-related information appears only in very exceptional cases.

Even if source availability strongly affects our knowledge about medieval droughts, it is still an interesting question why in Hungary (or in Dalmatia) the known great drought years detected are often one year late in the studied cases compared to the reports of other Central European areas. First of all, we have only a few cases and on this basis no general tendencies can be drawn. It is, however, true that in most of the studied cases, namely in 1362, 1474, 1479 and 1507 important drought events were reported in neighbouring areas for 1361, 1473, 1478 (and/or 1480) and 1506.

It is most probably not the 'fault' of the sources: the referred sources are all domestic, contemporary, clearly dated and although the work of Bonfini has vital importance in 1474, 1479 and 1494, the early 1362 drought was described in a legal document (charter), while the 1494 and 1507 drought cases were mentioned in two-two individual contemporary sources (and also in different source types). We rather suggest that – similar to some of the Czech, Polish and German examples – in some years water deficit might have occurred not only in one, but two (or more) consecutive years, and the drought itself got recorded only concerning the year when the major effects and consequences (i.e. socio-economic) became apparent. This is also possible because, as we could already see in the individual case studies, based on the textual context as well as the severity of consequences, it is possible that dry conditions might have already prevailed in the preceding year(s).

CONCLUSIONS AND OUTLOOK

Although relatively few contemporary sources are yet known that directly refer to droughts occurred in medieval Hungary and Croatia, some of the important events are quite well-discussed in the contemporary written sources. Out of these cases, in the present paper the great droughts reported for 1362 in Dalmatia, and for 1474, 1479, 1494 and 1507 in Hungary and partly Croatia (but also affecting the Eastern Alpine area) are discussed in more detail. It is also an advantage of the available contemporary evidence that the discussed drought events were recorded in various source types, including narratives, economic accounts, private notes, charters and letters – all written by contemporary authors.

It is a common characteristics of these drought cases that they were all rather extraordinary in magnitude, but still were mainly mentioned due to their socio-economic (and political-military) consequences. The long-lasting severe shortage or lack of precipitation resulted extreme low water levels of major rivers accompanied by transportation and border security problems on the one hand, and – combined with other natural hazards – harvest failures, severe food shortage and danger of mass extinction of domestic animals on the other hand. Two (or maybe three) of the mentioned great drought cases were accompanied or /followed by significant locust invasions.

Comparing the discussed drought cases with the drought-related evidence available for Central Europe (Czech Lands, Poland, Austria – and also the German areas), in four cases (i.e. 1362, 1474, 1479, 1507) parallels can be found for the preceding year, than for the year actually mentioned in the Hungarian-Croatian evidence. Due to the fact that droughts are usually known when consequences were reported, in most cases it is probable that not only the actually mentioned year, but already the previous year was dry.

In the present paper the reported, most extraordinary medieval drought events were discussed in more detail. However, either in the form of direct or indirect reference, more evidence is available on other dry spells, shorter or longer dry periods that will be discussed in a further publication on the subject.

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CHARACTERISTICS OF POINT-BAR DEVELOPMENT UNDER THE INFLUENCE OF A DAM: CASE STUDY ON THE DRÁVA RIVER AT SIGETEC, CROATIA

Tímea Kiss*, Márton Balogh

Department of Physical Geography and Geoinformatics, University of Szeged, Egyetem u. 2-6, H-6722 Szeged, Hungary
*Corresponding author, e-mail: kisstimi@gmail.com

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Abstract

Before the extensive engineering works the Dráva River had braided pattern. However in the 19-20th centuries river regulation works became widespread, thus meanders were cut off, side-channels were blocked and hydroelectric power plants were completed. These human impacts significantly changed the hydro-morphology of the river. The aim of the present research is to analyse meander development and the formation of a point-bar from the point of view of indirect human impact. Series of maps and ortho-photos representing the period of 1870-2011 were used to quantify the long-term meander development, rate of bank erosion and point-bar aggradation. Besides, at-a-site erosion measurements and grain-size analysis were also carried out. As the result of reservoir constructions during the last 145 years floods almost totally disappeared, as their return period increased to 5-15 years and their duration decreased to 1-2 days. The channel pattern had changed from braided to sinuous and to meandering, thus the rate of bank erosion increased from 3.7 m/y to 32 m/y. On the upstream part of the point-bar the maximum grain size is 49.7–83.4 mm and the mean particle size is 7.6 mm, whilst on the downstream part the maximum grain size was only 39.7–39.9 mm and mean sediment size decreased to 6.1 mm. Due to the coarse sediment supply and the decreasing stream energy the point-bars develop quickly upstream and laterally too.

Keywords: point-bar, meander development, gravel-bar, grain-size distribution, effects of dams

INTRODUCTION

The number of hydroelectric power plants and their reservoirs built on rivers is increasing worldwide due to their sustainable power production, however no one should ignore their environmental effects (Bonacci and Oskorus, 2008). The major effect of hydroelectric power plants and reservoirs is the interruption of the continuity of sediment transport processes, thus the river system will be disconnected (Ristić et al., 2013). The disconnection is manifests in the form of flow regime alteration, changing in slope and velocity, which result in altered stream power conditions (Kiss and Andrási, 2011). Behind the dam, in the reservoir the power of the flowing water significantly decreases, thus most of the sediment (33-99%) retained, thus the reservoir is slowly filled up (Peter, 1997; Petts and Gurnell, 2005; Woodward et al., 2007). Usually on the downstream section the hydrology becomes more even, as the height and frequency of floods decreases, whilst the height and duration of low stages increases (Williams and Wolman, 1984; Petts and Gurnell, 2005; Lajolie et al., 2007). Downstream of the reservoirs the process of "clean water erosion" is significant (Knighton, 1998), therefore accelerated lateral or vertical channel erosion takes place (Williams and Wolman, 1984; Petts and Gurnell, 2005). As the result of the accelerated erosion and the controlled (usually decreased peak) discharge the river mobilizes the smaller particles from the riverbed, thus the bed-material gets coarser, therefore bed armour develops (Dietrich et al., 1989). These processes alter the morphology of the rivers, therefore very often downstream of the reservoirs the channel pattern changes (Gregory and Park, 1974; Williams and Wolman, 1984; Xu, 1996; Brandt, 2000; Magilligan et al., 2008), or the rate of the processes (e.g. meander development) alters (Shields et al., 2010; Blanka, 2009). Some of the hydroelectric power plants are peak-operated, thus during the main hours of energy consumption mini-floods are generated resulting in the mobilisation of the bed-load and modification of the bed-forms (Merritt and Cooper, 2000; Kiss and Andrási, 2011). The spatiality and temporality of the bed processes could be evaluated by analysing the grain size of the bed-load (Belal, 2015). The gravel-bars in rivers are sensitive indicators of the altering fluvial morphology caused by dams, as they could be destroyed by floods or stabilised by vegetation (Fergus, 1997; Xu, 1997).

The main reason of the formation of fluvial bars is the local decrease in flow energy (Sipos, 2004). During the bar development the first step is the deposition of coarse bed-load sediment in the space between the high-energy transportation routes, later in the low-energy zones finer sediments also trapped behind the large gravels (Leopold and Wolman, 1957). Around the evolved form the flow splits, which results in increased bank erosion. Due to the lateral erosion the river widens locally, thus it loses energy (Ferguson and Werrity, 1983). Ashmore (1991) made laboratory experiments and measurements to understand the dynamics of the bar formation.

There are two main types of river bars (Balogh, 1991). The first group is located in the middle of the river, and the mid-channel bar, the crescent-shaped bar, the longitudinal bar and the transverse bar belong to this group. The second group is located along the banks and this group consists of the point-bar and the side-bar. The diagonal bar is a transitional form between these two groups (Knighton, 1998), though by time all these bar types can transform into each other, which makes their identification difficult. According to Dykaar and Wigington (2000) the spatial and temporal variations of the river bars causing braiding are determined by the speed of accumulational and erosional processes, and variations of discharge.

Human activities have been altering the hydrology and the morphology of the Dráva River since the 19th century. First the large meanders were cut-off resulting in metamorphosis, as the meandering pattern became braided (Kiss and Andrási, 2014). In the 20th century the regulation was completed by revetment and groynes constructions, side-channels blockages, and construction of reservoirs and hydroelectric power plants. These engineering works altered the water and sediment regime of the river, leading to morphological alterations. The aim of our research is to study the formation of a meander in detail, and to evaluate the role of indirect human impact in meander development.

STUDY AREA

The Dráva River springs in the Tyrolean Alps and runs to east, so after 749 km it flows into the Danube. Its catchment area (40,489 km^2) extends to five countries. The area studied in detail is downstream of the confluence of the Dráva and Mura Rivers (Fig. 1), near to the Croatian village Sigetec (at 220–222 fluvial km). The selected meander is just 26 km downstream of the Donja Dubrava Hydroelectric Power Plant, thus its indirect effects could be studied in detail, whilst no other direct or indirect human impact affected the evolution of the bend.

The slope of the studied section of the Dráva River upstream of Őrtilos gauging station is 80–130 cm/km, whilst along the studied section it decreases to 45–55 cm/km (Kiss et al., 2011). The mean discharge of the river is 510 m^3/s and the rate of sediment transport (280,862 t/y) is recently only the 28% of the amount it used to be before the construction of nearby hydroelectric power plants (Bonacci and Oskorus, 2008). The grain size of the bedload decreases downstream: cobbles with a diameter of 6-8 cm are frequent, though only coarse sand appears near Barcs, and at the confluence of the Danube and Dráva Rivers the dominant fraction is sand (Kiss and Andrási, 2012).

The hydro-morphologic properties of the Dráva have been greatly altered during the last one and half centuries (Kiss and Andrási, 2012). Between 1784 and 1904 altogether 65 meanders were cut off shortening the original length of the river by 185 km, the last cut-off was made in the 1990's (Remenyik, 2005). Several bank-sections were stabilized, and groynes were built to block side channels and to support shipping, especially downstream of Barcs. Since 1910's numerous (22) hydroelectric power plants have been constructed on the Austrian, Slovenian and Croatian section of the Dráva River. The Croatian hydroelectric power plants were built between 1975 and 1989, significantly changing the flow and sediment regime of the river (Bonacci and Oskorus, 2008). As a result of these regulation works the frequency of the floods decreased (Kiss and Andrási 2011). In the study area the lowest, Donja Dubrava Hydroelectric Power Plant generates 1.5–1.7 m high "mini flood-waves" twice a day due to its peak-hours operation.

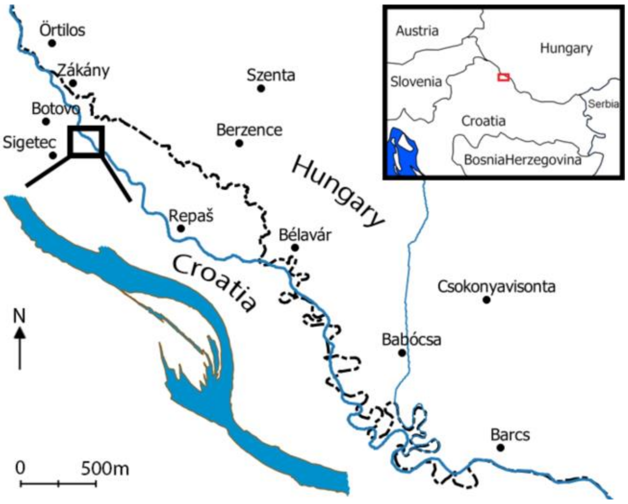

Fig. 1 The studied meander is located east of Sigetec, on the Croatian section of the Dráva River

METHODS

The hydrological changes of the Dráva were evaluated based on daily stage data measured at the Barcs gauging station since 1900. The frequency curves of the stages were made for each decade to evaluate the hydrological changes. As floods are very important forces in the fluvial system, the number of flood-days (over 420 cm) and their return period were also calculated.

The long-term development of the selected meander (section) was studied based on a map series containing the Third Military Survey (1870), the maps of the Hydrological Atlas of the Dráva (1966), topographical maps (made in 1944 and 2001) and an ortho-photo (2011). These maps were geo-corrected using ERDAS Imagine 9.1 and Quantum GIS 2.8., as they were made using different scale and projection systems. The average channel width of the Dráva was defined as the ratio between the area of the polygon between the bank-lines and the centreline. The lateral erosion was calculated based on the area of the polygon between bank-lines surveyed at two different times. The arch-length was measured between two inflection points along the centreline, whilst the chord length was measured directly between the two inflection points. The amplitude refers to the size of the meander, as it is the greatest perpendicular distance between the chord and the centreline. The radius of curvature is the radius of the greatest circle fitted into the meander's centreline. The development stage (β) of the meander was determined after Laczay, as the ratio between the centreline and the chord length.

The short-term bank erosion was measured annually between October of 2013 and January of 2015. Field measurements were made using the Real Time Kinematic network and the TOPCON total station theodolite with a centimetre accuracy.

Recently several researches attempt to derive the grain size distribution using digital images (Butler et al., 2001; Carbonneau, 2004; Graham et al., 2005; Chang and Chung, 2012) and we also applied this technique. In a low-stage-day we took 68 digital photos placing a reference frame (40*40 cm) on the dry gravel surface. The photos were imported into the Digital Gravelometer software, then the properties of the camera were given, finally we defined the corners of the reference frame. The programme calculates the grain-size distribution of the bar surface. During the study the Wentworth scale was applied.

RESULTS AND DISCUSSION

Hydrological changes of the Dráva River

Based on the characteristics of the hydrology the dataset of 1901-2012 could be divided into three periods. The first period (1901-1917) could be considered as almost natural, as nor the floods, neither the lower stages reflected decreasing tendency. This is reflected by the overlapping frequency curves (Fig. 2). At the beginning of the 20th century floods returned in every year and they covered the floodplain for 2-3 weeks (in 1904: 54 days). Within a year floods normally were rapid and their return period was 4-6 months.

In the second period (1918-1967) the average and minimum stages show decreasing trend, as they decreased by 90-100 cm, and the frequency curves also shifted down. The stage of the floods did not change considerably, though they became shorter and in some years they did not even occur, thus their return period increased to 1.4-2 years.

In the last period (1968-2012) the above described processes became more pronounced, which became especially characteristic after the beginning of the operation of the Varasd (1976) and Donja Dubrava Hydroelectric Power Plants (1989). The average and minimum stages decreased further by 130 cm, the height of highest stages did not reach the edges of the banks (thus floods disappeared). The frequency curves shifted down characteristically, so for example in the 2000-2010 decade stages were higher than 100 cm occurred just only in 20% of the period, though they were in 100% in the 1900-1910 decade. Floods almost totally disappeared, as their return period increased to 5-15 years, and their duration decreased to 1-2 days (Fig. 3).

Long-term meander development

At the time of the Third Military Survey (1870) the studied Dráva section had braiding pattern (Fig. 4) and the flow was split between 5 islands. The width of the channel varied between 536–1813 m.

Between 1870 and 1942 the morphology of the river reach changed, as the braided pattern was replaced by meandering, and the islands melted to the banks. The channel width decreased by 85–87%, as in 1942 it was only 81–225 m. The arch-length of the meander was 1573 m, the chord length was 1489 m, the amplitude was 239 m and the radius of curvature was 931 m. According to the meander classification method of Laczay the studied meander belonged to the group of "juvenile meanders" (β=1.06). The pattern change was probably caused by the regulation works, which terminated the braiding and created a meandering single-bed river.

Until the next survey (1968) the channel became wider, as the maximum channel width (266 m) increased by 18% and the minimum width (90 m) increased by 11%. The rate of lateral bank erosion varied between 3-40 m (0.1-7.3 m/y), and its average was 3.7 m/y. All horizontal parameters meander decreased between the two surveys (1942–1968). The arch-length of the meander (1025 m) decreased by 35%, the chord length (988 m)decreased by 34%, the amplitude (95 m) became smaller by 60%, and the radius of curvature (857 m) also decreased by 8%. The meander based on its β value (1.04) still remained juvenile.

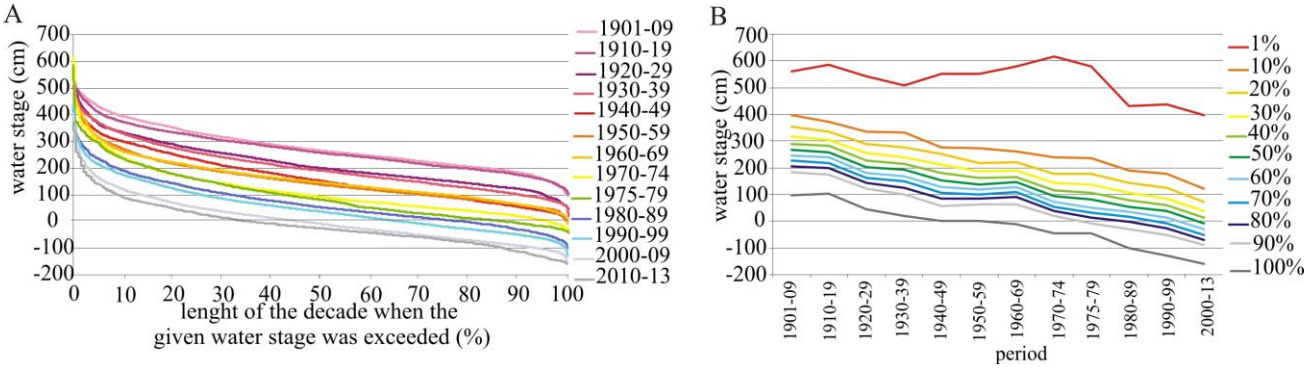

Fig. 2 Frequency distribution curves of decadal stages (A) and height (cm) of different stage frequencies (B) based on the dataset of Barcs gauging station

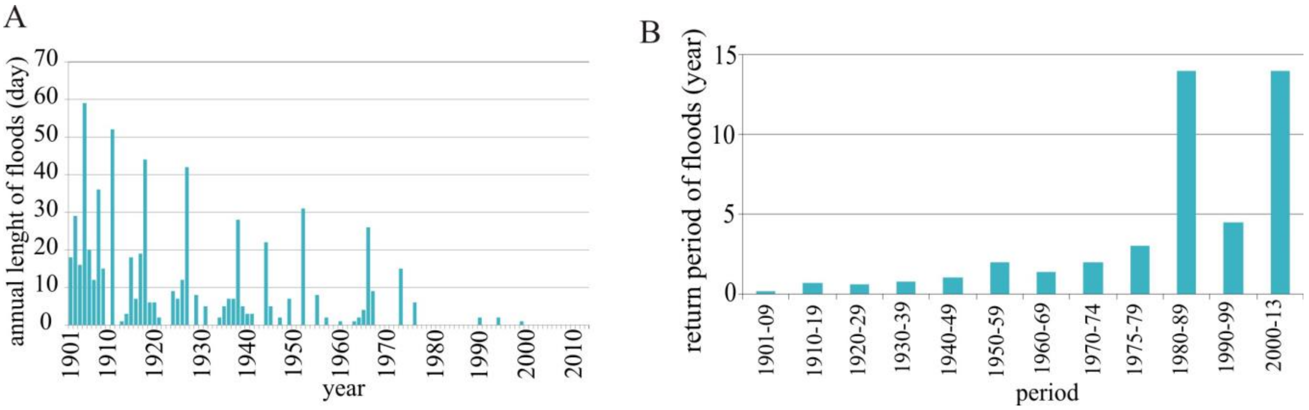

Fig. 3 Yearly number of flood (>420 cm) days (A) and the return period of floods (B) at Barcs gauging station (1901-2013)

By 1977 the studied section did not change considerably, however the meander upstream of the studied bend became sharper (decreased chord length and radius of curvature), thus it rapidly migrated downstream, thus the reach became more sinuous. The maximum width (247 m) of the studied meander decreased by 7 %, though the minimum width (108 m) increased by 20 %, thus the channel became more uniform. As the thalweg became more pronounced due to the shift of the upstream meander, the average rate of bank retreat increased to 5.6 m/y (151%). During the meander migration the erosion (11 ha) exceeded the accumulation (7 ha). All values of the horizontal parameters increased: arch-length became 1441 m (41%), chord length 1407 m (425), amplitude 140 m (47%), radius of curvature 1101 m (28%). As the parameters increased by the same rate, the shape of the meander did not change significantly (β=1.03), it remained a juvenile meander.

Between 1977 and 2001 the studied meander changed considerably, as it migrated downstream and a well-developed point-bar system evolved. The width of the channel decreased, as its maximum (216 m) and minimum (103 m) width reduced by 13% and 5% respectively. The annual rate of the lateral shift exceeded the former period by 4% (5.8 m/y). The greatest rate of the lateral migration increased by 72% (11.4 m/y) and the minimum decreased by 50% (0.1 m/y). The rate of the accummulational and erosional processes has been greatly increased, as the eroded area was 29 ha (+164%) and accumulated area was 38 ha (+443%). Most of the

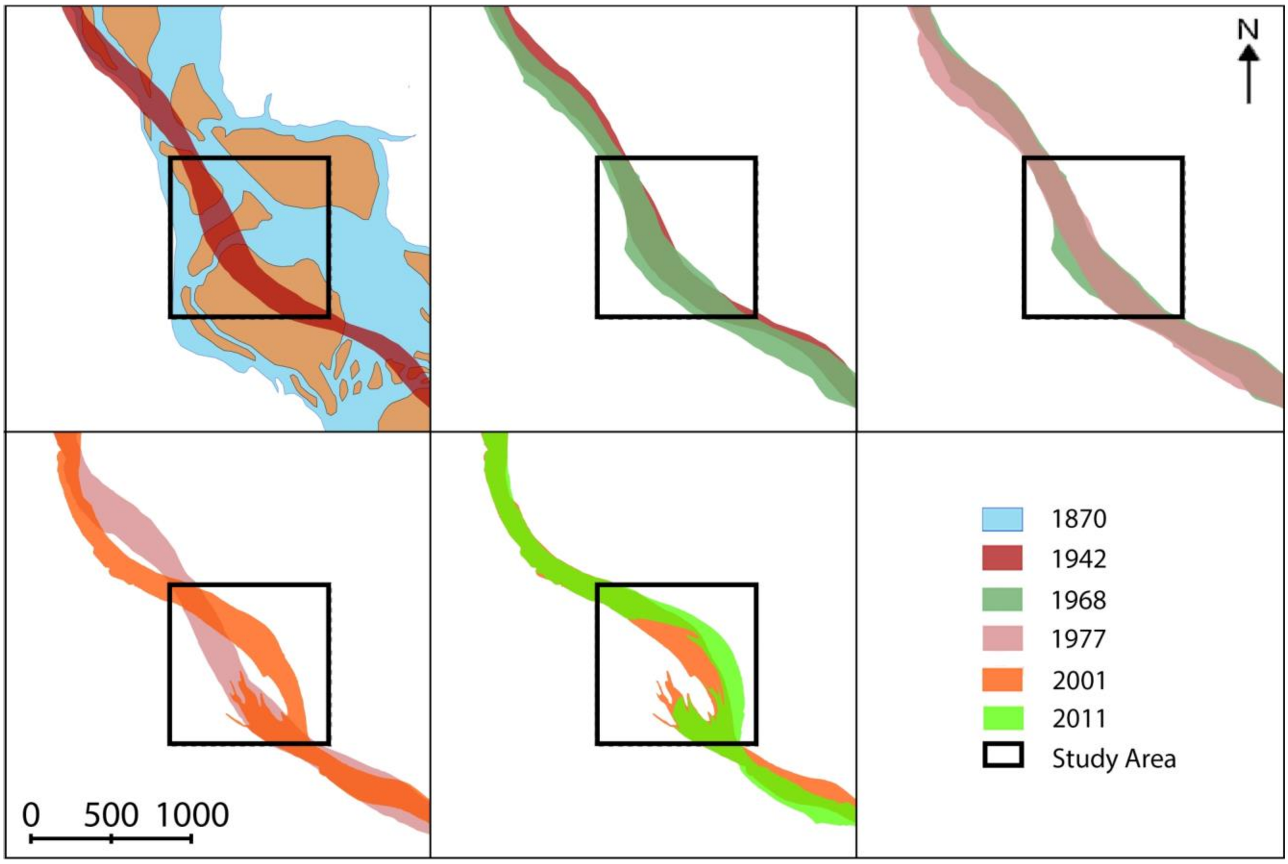

Fig. 4 Long-term meander development of the studied section

horizontal parameters decreased, for example the arch-length of the meander decreased by 13% (1254 m), the chord length by 16% (1177 m), and the radius of the curvature by 9% (999 m), meanwhile the amplitude increased by 33% (186 m). The β value increased to 1.07, indicating slow meander development.

Between the 2001 and the 2011 surveys the meander developed further on. The maximum channel width decreased by 11% (192 m) and the minimum decreased by 22% (80 m). The average rate of lateral shift was 9.5 m/y, which exceeded the former period by 64%. The maximum rate of the bank erosion was 189 m (18.9 m) and the minimum was 1 m (0.1 m/y). During the lateral migration the total amount of erosion was 14 ha, whilst the area of the point-bar increased by 18 ha, which means that the rate of these processes decreased by 52-53% and there was a net accumulation on the studied area. The former processes continued, as the arch-length of the meander decreased by 10% (1129 m), the chord length by 18% (965 m), the radius of curvature decreased by 34% (661), though the length of the amplitude increased by 24% (230 m). The meander became well-developed (β=1.17).

Short-term meander development

Between the snapshot of the ortho-photo (2011) and our first field survey (2013) the rate of the bank erosion was 2–40 m (1–20 m/y). In the following 15 months the rate of bank erosion has increased to 32 m/y (Fig. 5). Between the two field measurements (2013 and 2015) the area of eroded floodplain was 20.6 ha, which exceeds every previous data. The rate of bank erosion was spatially diverse, as it greatly increased downstream.

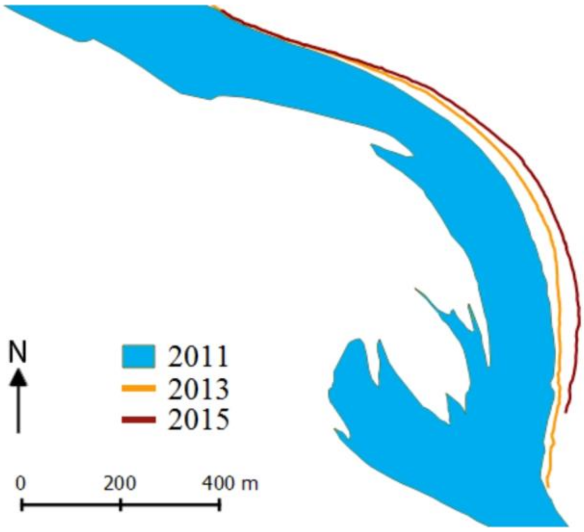

Fig. 5 Short-term bank erosion on the study area between 2011 and 2015

Grain size analysis of the point-bar

During the last almost 30 years a large point-bar system developed in the meander. The older surfaces were colonised by riparian forest, however the youngest point-bar surfaces are still bare, which enabled us to make superficial grain-size measurements. Most of the surface (73%) of the point-bar is built of pebble (4–64 mm), some areas (16%) are covered by granule (2–4 mm), 11% by sand, and only 0.1% of the area consists of cobbles (>64 mm).

The mean grain size of the whole point-bar is 6.6 mm, and the biggest cobble has a diameter of 123.9 mm. The material of the bar-system is moderately sorted (Fig. 6). Large grains appear in well defined areas, as on the upstream and central part of the point-bar, and in the secondary channel between the bank and the bar. The maximum grain-size decreases downstream: in the upstream part of the bar-system 100–120 mm large cobbles were deposited, whilst downstream the maximum sediment size decreased to 40–65 mm. This decrease does not show a linear trend, because the bigger sediment was deposited in patches and in between these patches fine-grained gravel aggraded. It suggests that the point-bar is built up of three smaller bar-heads, which were formed together.

The grain-size of the sediment is altering not only downstream, but laterally too. On the edges of the point-bar close to the thalweg the sediments are finer grained (50–90 mm) than those (60–120 mm) located closer to the bank-line. This could develop during high energy conditions, when during high stages the river could transport coarser sediments near the convex bank and in the side channel, but as the stage fall, these sediments remained in their location. However, closer to the thalweg the daily mini flood-waves generated by the power plants could transport further the coarse sediment, thus at the fall of the mini flood-waves finer grained bed armour develops.

Based on the grain-size distribution of the bare surfaces the point-bar could be divided into three parts (Fig. 6). On the upstream third of the active bar samples are coarser (mean grain-size: 7.6 mm) than the mean grain-size (6.6 mm) of the whole point-bar. The maximum grain size of this area varies between 49.7 mm and 83.4 mm, thus most of the sediment (78.5%) consists of pebbles. The material of this area is moderately sorted (S=1.7). On this area of the point-bar there is a clear tendency of decreasing grain-size toward downstream.

On the middle part of the point-bar where the mean grain size reduces to 6.7 mm, the maximum grain-size of the samples varies between 38.9 mm and 123.9 mm. Almost 74% of the sediments consists of pebbles. The material of this surface is also moderately sorted (S=1.8), but slightly better than in the upstream part. There is a decrease in grain-size towards downstream, however it is not continuous as it is in the upper part, because this central part is dissected by coarser and finer sediment patches referring to smaller bar-heads.

The mean grain size of the downstream part of the point-bar is finer (5.5–6.6 mm). The maximum grain-size is smaller (39.9–69.7 mm) than in the two upper parts, thus the proportion of pebbles decreases (70%). The material of this area is better sorted (1.9).

From the point-of view of grain-size distribution the side channel between the stabilised point-bar surfaces is diverse, as here the mean grain-size varies

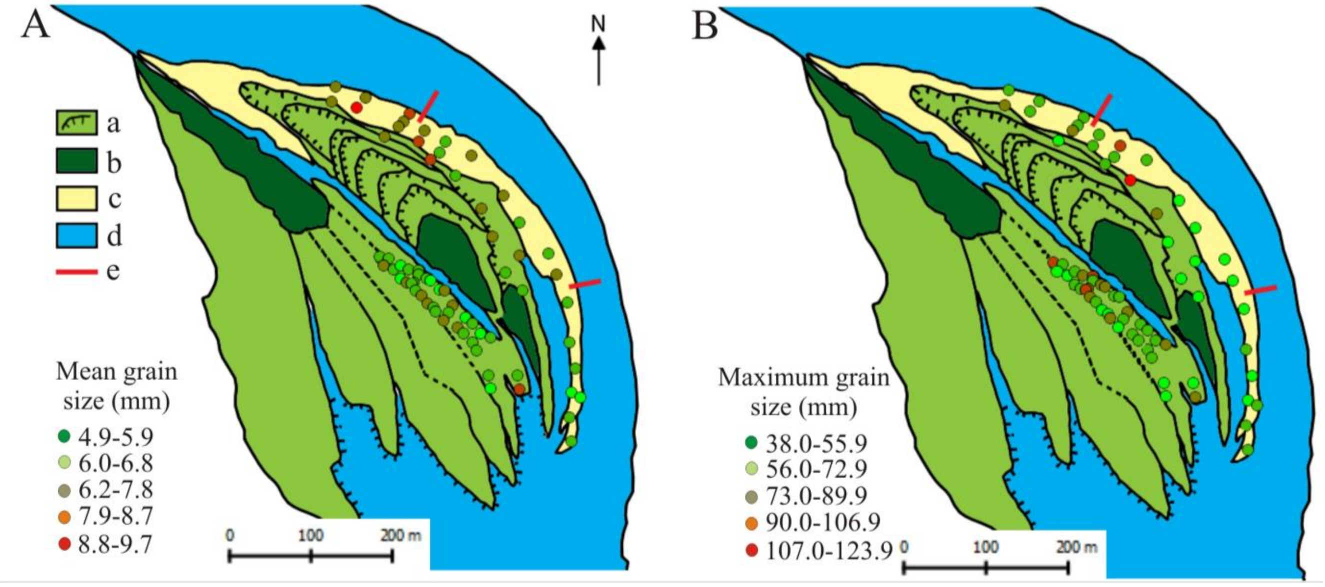

Fig. 6 Mean (A) and maximum (B) grain-size of the studied point-bar. a: slip-face of a bar; b: island-core; c: bare point-bar surface; d: water surface; e: zones of the active bar

between 4.9 mm and 7.8 mm. Here the largest particles are 44.3–103.8 mm. The maximum grain-size of the side channel decreases downstream: its upper is characterised by 70–100 mm large grains, whilst towards downstream it decreases to 50–70 mm. The material of the side-channel is 7moderately sorted (S=1.8). The varieties in grain-size distribution of the side-channel refer to high energy conditions during water cover (during the mini flood-waves), which transport large grains into the side-channel in the form of mid-channel bars. These bars slowly will aggrade the side-channel, thus the island will amalgate into the stabilised surface of the point-bar.

CONCLUSION

The hydrological analysis proved, that the floods gradually disappear from the Dráva River, thus the fluvial development of the floodplain will terminate. At the same time the stage of the mean and low stages decreases (by stabile discharge; Kiss and Andrási, 2011), which refer to rapid incision. These hydrological changes started when the first hydropower plants were constructed, but they were accelerated when the Varasd (1976) and Donja Dubrava Hydroelectric Power Plants (1989) started to operate. These hydrological changes triggered morphological changes too.

The analysis proved that the meander development and point-bar formation downstream of the Donja Dubrava Hydroelectric Power Plant is specific. In the 19th century (1870) prior the regulations the Dráva River had natural hydrological and sedimentological regime, thus braided pattern developed. However by the end of the 19th c. and in the 20th c. river regulation works became widespread, thus meanders were cut off, and side-channels were blocked. Their effects were emphasized by 20th c. dam constructions. As a result, the morphology of the river changed, as the braided river developed into a single-thread sinuous channel. The channel continuously narrowed, referring to more pronounced thalweg. Due to the sediment retention of the reservoirs clean water erosion became dominant, causing incision and simultaneous channel narrowing. As the sinuosity of the bend increased, the rate of erosional and depositional processes increased too. Because of the permanent drop in water stages, vegetation could stabilise the developed point-bars. These processes became accelerated since the end of 1970's, when the last members of the dam-reservoir system were built.

Probably due to the 1.5–1.7 m high "mini flood-waves" twice a day generated by the nearby Donja Dubrava Hydroelectric Power Plant bank erosion accelerated, despite of the fact, that real floods almost disappeared. The accelerated bank erosion is also influenced by the incision and the previous fluvial history of the area: The meander develops in the loose material of the former braided channel, thus it is easy for the Dráva to erode the young and unconsolidated material.

The incision, the development of the thalweg and the intensive bank erosion create favourable conditions for point-bar development since the end of 1970's (Fig. 7). The Dráva sorts its bed-load material downstream and laterally too. The maximum and mean grain-size decreases downstream and also laterally towards the bank. On the upstream part of the point-bar the maximum grain size was 49.7–83.4 mm and the mean sediment size was 7.6 mm, whilst on the downstream part the maximum grain size was only 39.7–39.9 mm and mean sediment size decreased to 6.1 mm. Along the bank and in the side-channel coarser sediment was deposited, as here the maximum grain size is 38.9–123.9 mm and 44.3–103.8 mm respectively.

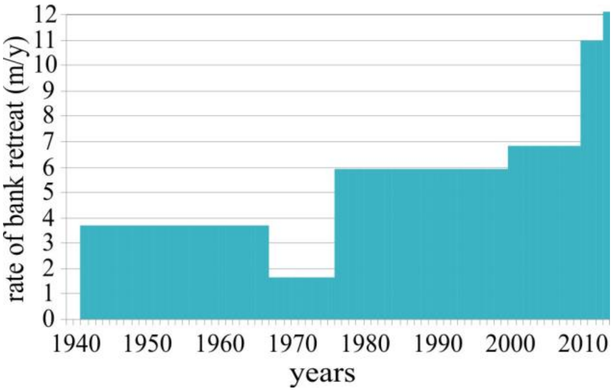

Fig. 7 Annual rate of bank erosion on the study area

Greater grains deposited in the upstream end of the point-bar, where the flow is diverted towards the main thalweg and into the side-channel, thus its energy drops. In this way the bar-system expands laterally and also towards upstream. The upstream expansion of the point-bar system is contradictory with the meander development of the sandy bed-load rivers, where the main location of the accumulation is at the downstream part of the bar (Sipos, 2006; Kiss and Blanka, 2011).

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MODELLING THE HYDROLOGICAL EFFECTS OF A LEVEE FAILURE ON THE LOWER TISZA RIVER

Tímea Kiss[1*], István Fehérváry[1], Károly Fiala[2]

[1]Department of Physical Geography and Geoinformatics, University of Szeged, Egyetem u. 2-6, H-6722 Szeged, Hungary
[2]Lower-Tisza Water Directorate, Stefánia 4, H-6720 Szeged, Hungary
*Corresponding author, e-mail: kisstimi@gmail.com

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Abstract

Along the Lower Tisza River (Hungary) the water level of the floods reached new record stages in 1998 and 2006, resulting in 80 cm increase in the peak flood level since the "great flood of 1970". Due to the gradual weakening of the levee-system caused by the several long-lasting floods, the question has arisen, that as in case of a levee breach or failure how would it modify the hydrological parameters of the river. The aim of the research is to create a hydrological model to analyse the effects (as stage reduction, slope and stream power) of two different levee breaches: one happening before the peak of the flood and another at the time of the flood level. The simulated levee breaching happened on the Tisza River at Mindszent, and the data-set of the 2006 flood was used for the modelling (at that time no levee failure happened in Hungary, and it was the greatest flood in history).

In the simulation the levee was broken at a point, where the channel is very close and intensively eroding, thus there is a real risk of a levee failure. If the levee would be broken a well defined area (reservoir) would be flooded, surrounded by the secondary levees and the rim of the high floodplain. During the simulation the HEC-RAS 4.1. ArcGIS 10.1 and HEC-GeoRAS software were applied.

The greatest changes in the hydrology of Tisza occurred in the cross section where the levee breached, though the effects propagated upstream and downstream too. Due to the water outflow from the Tisza the greatest stage reduction effect was 1.54±0.1 m. The slope conditions changed too, as it increased from 4 cm/km to 6.5 cm/km in the upstream reach, while downstream of the failure point it decreased from 3.5 cm/km to 1.9 cm/km. At the same time the stream power increased from 4 W/m to 5.5 W/m in the upstream section, while it decreased from 3.5 W/m to 1.5 W/m in the downstream reach. Comparing the results of the simulations at different stages (one at the highest stage and one at 1.0 m lower stage) it seems that the hydrological parameters did not change considerably (1%), though in a case of a levee failure at higher the reservoir reached the maximal water level sooner, though less water was stored in it, as the fall of the river was continuous.

Keywords: levee failure, flooding, HEC-RAS, flood modelling, hydrologic parameters

INTRODUCTION

Nowadays floods are the most common in natural hazards, and they cause the greatest economical losses, moreover they endanger the life of millions of people living on the flood-prone areas along rivers, especially if the inundation is a result of unexpected incidences, for example a levee or a dam failure (Yalcin and Akyurek, 2004). Every levee breach or failures carries human tragedies and considerable losses, therefore it is important to develop detailed plans for flood-prevention and to carry out hydro-dynamic modelling of catastrophes.

On the Tisza River, which is the greatest tributary of the Danube, the flood levels have been dangerously raised on several sections since the "great flood of 1970", thus the flood hazard and risk increased. The seriousness of the problem is well-demonstrated by the fact that between 1998 and 2010 period the peak flood level reached new records twice, increasing the record stage by 80 cm compared to the 1970 peak flood. According to the engineers the solution of the problem of the decreasing high water levels could be the construction of flood control reservoirs that can decrease the peak flow of floods (Szigyártó and Rátky, 2010).

The Cigánd Reservoir (storage capacity: 94 million m^3) was the first flood storage reservoir built on the Upper-Tisza. If it would be opened and filled up to its maximum capacity, it would decrease the flood stage by 0.25 m [1]. Concerning the plans and the construction of this reservoir Szigyártó (2012) expressed several critiques, as the inflow capacity of the storage lake reaches only 65 % of the required capacity. Another flood reservoir was built between the Szamos and Kraszna Rivers (capacity: 126 million m^3) in 2014, and the Bereg Reservoir is planned to be finished at the end of 2015. The Upper Tisza flood control system continues in the Middle Tisza too, where the Tiszaroff (97 million m^3), the Nagykunság (99 million m^3) and the Hany-Tiszasüly Reservoirs (247 million m^3) were built. As the sum-effect of the operation of all these reservoirs the flood level could be reduced by 0.5-0.6 m along the river according to model calculations [1]. However, considering the flood level increase (0.8 m) since 1970, it is not enough to reduce the flood hazard effectively. Thus, we believe, that this would only be a partial solution of the problem, since the management of the floodplain (decreasing the vegetational roughness) and the widening of the tight sections are also needed.

The application of models in hydrology has been started in 1960's, by simulating the flow conditions in a channel and the seepage in porous materials (Whisler and Watson, 1968). By the 1990's software groups were developed, that can model complicated hydrological systems and situations, and they have been widely applied in water management issues. Nowadays the developed models able to simulate most of the hydrological processes in various conditions, but it still remains a question, what is the relation between the results and the real nature, since numeric models provide correct results, if the initial conditions and the border conditions were chosen properly. However some empirical parameters (e.g. vegetational roughness, morphological roughness) cannot be determined easily and properly, though they have significant role in modelling, which can greatly modify the results.

One of the most widespread model in hydrological modelling is HEC-RAS (Hydrologic Engineering Center-River Analysis System). This is an one dimensional and linear model which is able to produce pseudo 3-D image with the correct ordering of cross-sections. The software is suitable to make calculations for sub-critical (Froude number <1) or for super-critical (Froude number >1) hydrodynamic situations besides this it is possible to build in the model detailed hydraulic constructions and structures. Novelty of the HEC-RAS software is that it divides the cross-sections into main channel, left and right floodplain zones and it calculates the velocity and discharge for these zones, and the program finally summarizes the data. The model calculate is able to calculate water level for each cross-sections, so in the separate branches not appear locally evolved higher or lower water levels (HEC-RAS Hydraulic Reference 2010). The input datasets of the HEC-RAS model are the following: geometric data of the riverbed, of engineering structures (bridges, culverts etc.), water level and discharge curves, roughness parameter (Pregun, 2009) which can be determined by empirical, mathematical or statistical methods (Kamanbedast and Esfandiar, 2011).

Between the HEC-RAS and ArcGIS software the connection is established by HEC-GeoRAS, a toolset of ArcMap program. It combines the digital elevation data with spatial analysis, thus the visualization of flood-depth and velocity characteristic becomes possible. The toolset could display the flooded areas on the digital elevation model, flood losses could be estimated, maps and illustrations cold be combined.

The MIKE hydraulic modelling family has been developed since the 1970's. The input data are similar to HEC-RAS's (MIKE 11; Józsa, 2001; Karatzas et al., 2012), but it is appropriate to study the Manning roughness in time and space, and it enables inundation simulation in 1D and 2D (MIKE 21) even various environments, as in rivers, cities, sewer systems, coastal areas and dam breaches. Moreover the models can be used at different scales from local to regional [2].

The aim of our research is to model and analyze the hydrological effect of a levee failure by Mindszent on the Lower Tisza River. The possibility of a levee breaching or failure is increasing by time, because (1) the repeated and long-lasting floods weaken the levee; (2) the water level of floods will probably increase further, thus it may cause overtopping; and (3) mass-movements endanger the levees, as where the levee was built too close to the channel, revetments were created to stop the lateral erosion, however during the last 50-80 years the channel intensively incised (Kiss et al., 2008) and the revetments were partially destroyed, thus the lateral erosion could endanger the levees. The simulated levee failure took place where in reality it is the most probable: at the given point (at Mindszent) the levee is very close (20-25 m) to the river channel, and the revetment is destroyed by landslides. In the HEC-RAS model we used the data of the 2006 flood as a basis, as it was the last record flood in the region. During the research we aimed to simulate and compare the hydrological effects (as stage reduction, slope and stream power) of two different levee breaches: one happening five days before the peak of the flood and another at the time of the peak flood level. The results that are gained by the modelling of a levee failure could provide useful information for the flood control reservoir that is planned on the Lower Tisza too.

STUDY AREA

The Tisza River is the second largest river in Hungary (L: 962 km, A 157.200 km^2; Lászlóffy, 1982), its lower reach was chosen for the study (Fig. 1). The regime of Tisza is influenced by the diverse climatic characteristic of the catchments and the tributaries with frequently extreme regime. Floods mostly develop at early spring due to snow melt and rainfall, and at the beginning of summer (Lászlóffy, 1982). On the study area the swelling effect of Danube could also be detected (Vágás, 2003; Bezdán, 2011). The characteristics of the study area is that the measured water level record in 1970 has been exceeded in 2000 (1000 cm) and in 2006 (1062 cm) too, and the durability of floods continuously increases (Kovács, 2007; Sándor, 2011). The low stages also last longer, but along the Lower Tisza this phenomenon is moderated by the Törökbecse Barrage. The difference between the lowest (70 m^3/s) and the greatest (4200 m^3/s) discharges is sixty-fold.

During the simulated levee failure the flood flowed outside of the present-day active floodplain, into the western protected side (it is called storage area/lake in the text below). The storage area has well defined borders: secondary artificial levees are found in north and south, in east is the main levee of the Tisza, and in west the natural rim of the high floodplain could be found. Thus, the flooded area is actually a natural low floodplain, which was evolved in the Pleistocene and Holocene. There is 3-5 m difference between the low and high floodplains (Her-

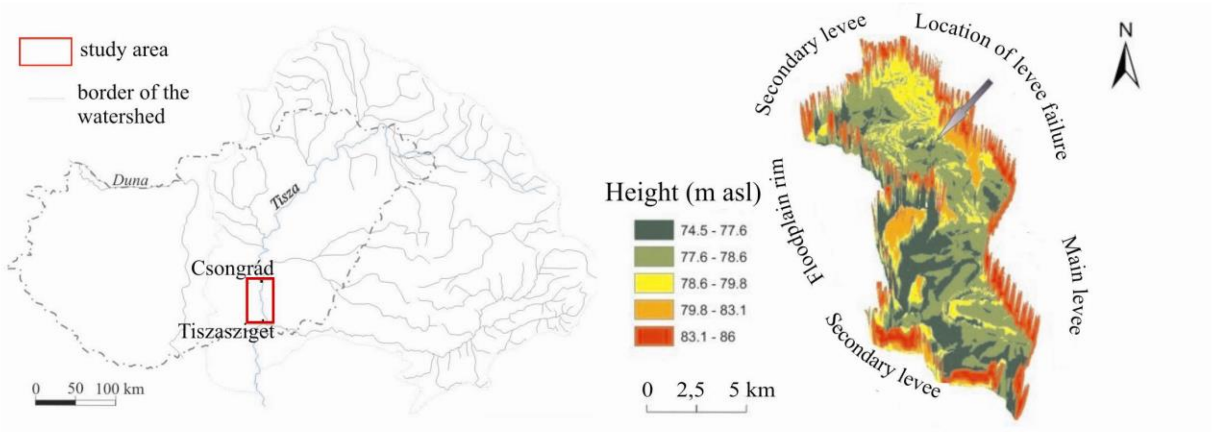

Fig. 1 The study area is located on the Lower Tisza. In the model the flood would destroy the levee and inundate a flood protected area (reservoir)

nesz and Kiss, 2013). On the surface of the storage lake 1.5-2 m deep paleo-channels are which could lead the flood wave into the storage area and out, however after the regression of the flood stagnant water would remain in these forms for a while. Point-bars, crevasses and floodplain islands rise from the low floodplain also characteristic of this area (Kiss et al., 2012). Before the 19th c. regulation works the low floodplain was periodically flooded, therefore settlements have been established just on the high floodplain or on floodplain islands. The levees in the area were built in the 1880’s and were raised several times (Schweitzer, 2003).

The inundated area used in the model could serve as real a flood storage reservoir, however the levees around should be heightened up to a uniform level.

METHODS

For the research we used the dataset of the 2006 flood, which was calibrated by the Lower Tisza Hydrological Directorate under HEC-RAS software. This flood was the highest flood in history, when the water level reached 1062 cm, thus 5.0-5.5 m deep water covered the floodplain for over 80 days.

The model was uploaded by large amount of data: hydrological and morphological data of the main channel and the tributaries, cross-sections, bridge data, roughness values and the data of Törökbecse Barrage. The boundary conditions of the model had to be set out of the study area, because the simulated levee should not affect the boundary conditions and the starting calculation failures could be corrected. When the boundary of the model was set, it had to be considered, that (1) the Tisza has very low slope in the study area (1-6 cm/km; Kovács, 2007), and (2) during a previous levee failure in 1879 the flood level was reduced by 1 m. Thus we assumed that the levee breach by Mindszent (218 fkm) would have an affect at least on a 50-50 km-long reach downstream and upstream. Therefore, the upper boundary of the model was set by Szolnok (334.6 fkm) and the lower boundary by Titel (11.6 fkm). Along the modelled reach the Körös and Maros Rivers flow into the Tisza, therefore their data were aldso built in the model. The boundary of the Maros River reach set Makó (24.3 fkm) of the Körös River by Gyoma (79.1 fkm).

For the simulation we had to add the cross-sections of the channel. It was surveyed by the Lower Tisza Hydrological Directorate at every 100 m. However in order to model the levee breach the intervals between the cross-sections around the breach had to be decreased, using the *XS inerpolation* tool in HEC-RAS. We added 30-30 interpolated cross-sections both in upstream and downstream along a 200 m-long reach. After setting the geometrical parameters the hydrological boundary conditions in the *Unsteady Flow Simulation* menu point had to be adjusted. The stage data were measured hourly, while the discharge data were mostly calculated from the water stages and some were actually measured. The gate operational data of Törökbecse Barrage (at 61.79 fkm) were also filled into the model.

In the next step the inundated storage area had to be defined surrounded by the levees and the floodplain rim. We used the digital elevation model of the area with 2*2 m resolution with HEC-GeoRAS toolset. The HEC-RAS software able to calculate the inundation of the area, creating its volume curve extracted with the help of *Elevetion Range* and *Elevation Volume Data* tools found in the HEC-GeoRAS toolset. The *Elevation Range* tool determines the altitude of the deepest and the highest points. The *Elevation Volume Data* tool contains volume values related to different elevation categories (Table 1). After creating these data the storage area had to be exported using the RAS Data tool, and then the storage area had to be imported into the HEC-RAS geometry dataset.

The levee was built into the model as a lateral structure, because in this way a levee breach could be initiated. The geometry data of the levee were uploaded, and we set on that reach and the river kilometre on which the starting point of the levee should have been placed. Furthermore, we joined the levee with the right bank and set the water would flow into the storage area on the protected side in case of levee breach. The width and the height of the levees were set in the *Lateral Weir Embankment* menu point and the distance from the upstream cross-section in the *Weir Stationing* menu point.

Table 1 Required data for filling up the storage area

Height (m asl)	Volume (m^3)	Area (ha)
–74.5	0	10890
74.51–74.56	522.70	10890
74.57–74.64	1317.47	13335
74.65–74.72	2227.90	16895
74.73–74.83	3814.74	21065
74.84–74.96	6242.60	26005
74.97–75.11	9773.72	32625
75.12–75.30	14956.79	38285
75.31–75.52	22415.91	68235
75.57–75.78	39571.46	97765
75.57–76.10	122167.22	885775
76.11–76.48	474995.47	1484965
76.49–76.94	2279174.25	6473645
76.95–77.49	8573056	19036124
77.50–78.15	30234490	64933576
78.16–78.94	86709024	109962880
78.95–79.89	182364640	132163272
79.90–81.03	307073664	140241056
81.04–82.39	460514816	141567792
82.40–84.03	646742528	142157424
84.04–86.0	870831232	142212288

The modelled levee breach or failure was created by Mindszent (218 fkm), where the levee is very close to the river (20-25 m), the revetment have been partly destroyed and the levee is threatened by landslides. Besides, the area behind is the deepest part of the simulated storage lake, thus the paleo-channel which starts exactly at the levee failure point could control the inflow and outflow of the flood. The simulated levee breach would totally destroy the levee along its 60 m length within 6 hours with an even rate. The steepness of the breached surface is 1-1° on the left and on the right side therefore the breached surface has trapezoid shape. The coefficient of the levee material was set to 2.6, considering that it was built of soil and loose sediments. As we aim the simulation of two levee failures, in the first case the levee breach occurred at 958 cm flood level (equals to 84.4 m altitude, or 1 m before the peak stage) and in the second case by the levee failure happened at the highest stage at 1058 cm (85.3 m altitude).

After adjusting the boundary and the initial conditions the *Plan Data* was compiled by selecting that geometry and unsteady simulation file that should have been used during the simulation. The initial (2006.03.22. 7:00) and the final (2006 5.31 7:00) dates were also set in the Plan Data window. This period cover the whole duration of the 2006 flood.

The *Hydrograph Output Interval* menu records water stage and discharge values into a file in given time intervals. As the water level measured in every hour at the gauging stations, 1-hour interval for the output was selected.

The results of the model were validated using the measured data of the 2006 flood. During the process the values calculated by the model and the real measurement data were exported into an EXCEL table. The accuracy of the model was ±0.1 m within the studied period, however during the last ten days of the falling stage the error became as high as ±1.0 m, which could be explained by the special characteristics of the 1-D model.

RESULTS

Levee failure prior the peak flood (at 958 cm)

If during the 2006 flood the levee would have been breached at Mindszent at 958 cm stage, and the flowing water would erode a 60 m wide opening on the levee in six hours, the maximum discharge of the out-flowing water would be 1255 m^3/s (Fig 2). The flood storage area (113,7 km^2) on the protected side of the levee would be filled up to 84.5 m asl. At the end of the process ca. 700 million m^3 water would flow into the reservoir. The greatest volume would be stored on the 13th day after the levee breach, as afterwards the water would start to flow backwards to the Tisza.

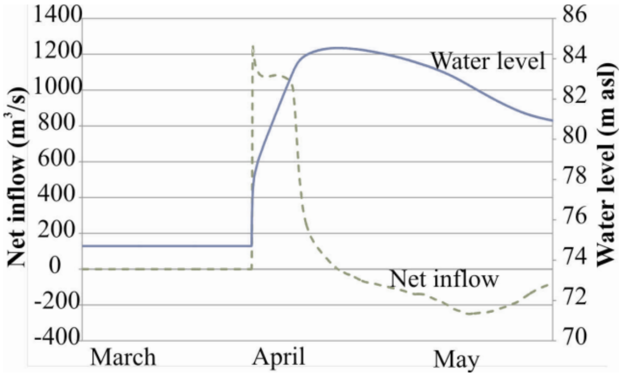

Fig 2 The water level and the water inflow curves of the reservoir in the case when the levee breached before the peak-flood at 958 cm stage

Comparing the simulated water stages of the neighbouring gauging stations to the 2006 stage data (without levee failure) it could be stated, that the maximum stage-reduction effect is 1.54±0.1 m at the Mindszent (218 fkm) gauging station (Fig 3). At the Tiszasziget gauging station (167 fkm) ca. 50 km downstream from the levee failure this effect decreases to 1.2 ±0.1 m, while upstream at Csongrád (246 fkm) it is only 0.68±0.1 m respectively. The greatest degree of stage-reduction appears on almost all gauging stations on the same day, 6 days after the levee failure.

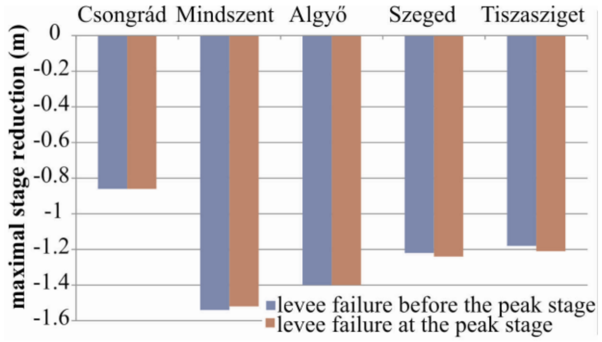

Fig 3 Maximal stage reduction effect of the two simulated levee failures

The simulated hydrograph reflects stage drop by approximately 50 cm on the day after the levee failure, though after 6 days the stage increases again and reaches a peak at 965 cm, which level is 7 cm higher than the water level when the levee breached (Fig 4). The maximum height difference between the simulated hydrograph and the real stage curve of the 2006 flood is the greatest at Mindszent (0.78±0.1 m), and it decreases upstream and downstream, in the function of distance from the point of the levee failure.

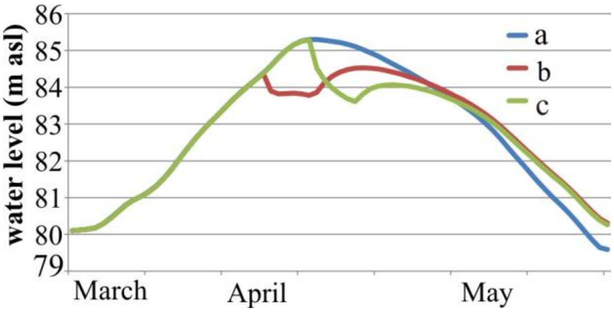

Fig 4 Hydrographs of the 2006 flood (a), of the simulated flood with levee failure at 958 cm stage (b), and of the simulated flood with levee failure at 1058 cm stage (c)

After the peak stage the water level drops. Simultaneously, the water level in the reservoir falls too, due to back-flow towards the Tisza. This increases the stage of the Tisza by up to 0.79±0.1 m at the cross-section where the levee failure occurs. In the last 10 days of the simulation the model counted by greater error (±1.0 m), therefore only the existence of the phenomenon of water level rising could be proved, but exact values of the process and the emptying of the reservoir within the simulated time interval could not be studied in detail.

Based on the calculations of the simulated levee failure the average slope of the Tisza increases from 4 cm/km to 6.5 cm/km on the upstream section between Csongrád and Mindszent, while on the downstream section it decreases from 3.5 cm/km to 1.9 cm/km (Fig. 5). At the same time the stream power of the river on the upstream section increases from 4 W/m to 5.5 W/m, while it decreases on the downstream section. The greatest decrease from 3.5 W/m to 1.5 W/m was calculated by Mindszent (Fig. 6).

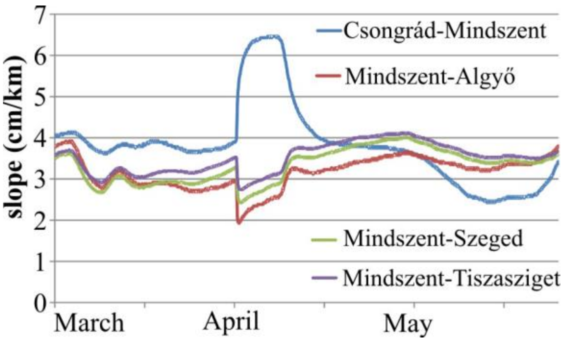

Fig 5 Slope changes of the Tisza River after a levee failure at Mindszent

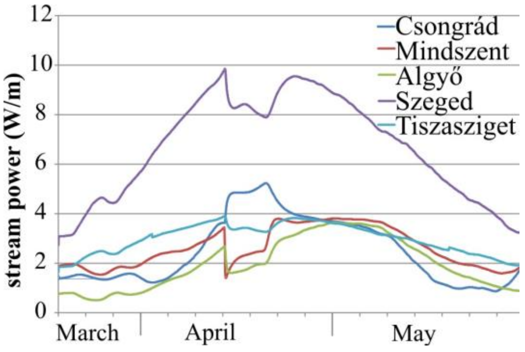

Fig 6 Stream power changes of the Tisza River after a levee failure at Mindszent

Levee failure at the peak of the flood (1058 cm)

In the second simulated case the levee failure would occur at the peak of the flood (1058 cm), and the levee would be destroyed along a 60 m long section. In this case the maximum discharge of the outflow (Fig. 7) would be much higher (1698 m^3/s) than in the previous case (1255 m^3/s), therefore the reservoir would be filled up in 11 days (shorter by 2 days) up to 84 m asl, which is 0.5 m lower than in the first case. Altogether 650 million m^3 water would be stored in the reservoir, less by 50 million m^3 than during the first simulated levee failure. It could be explained by the different hydrographs of the two cases: in the first case the levee breaches 1.0 m before the peak flood, thus the outflow got high amount of water supply for another 6 days, until the flood starts to fall. However, in the second case the levee failure occurs at the peak of the hydrograph, thus the falling limb of the flood supplies less water, thus the amount of outflow decreases too.

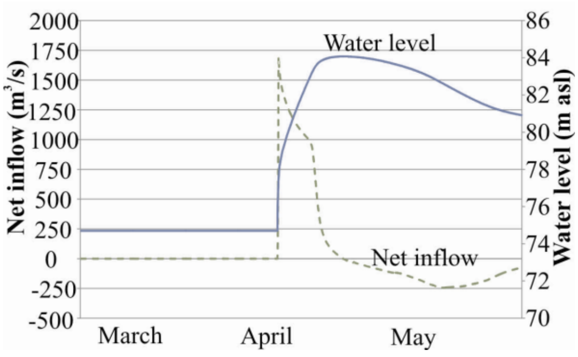

Fig. 7 The water level and the water inflow curves of the reservoir in the case when the levee breached at peak-flood

The maximum values of the diminution effect of the two simulated levee failures do not change significantly (1%), so the diminution effect would be 1.54-1.52 m (Fig. 4). During the second simulation the maximum value of diminution appears 5-6 days after the levee failure, which is one day shorter than in the first simulation case. The backflow into the Tisza would be very similar as in the first simulated case.

Comparing the simulation of the levee breach at the peak of the flood with the simulation of the levee failure at 1.0 m lower stage, it seems that the changes in slope are not significant (<1%). Although the slope on the upstream (Csongrád–Mindszent) section increases to 6.3 cm/km, which is slightly lower than it was during the former simulation. On the downstream section between Algyő and Mindszent the slope decreases to the same value (1.9 cm/km). Considering the stream power the trends in both cases are similar, as it increases considerably on the upstream section from 3.3 W/m to 5.5 W/m, while downstream of Mindszent it reduces significantly from 4.1 W/m to 1.4 W/m.

DISCUSSION

Usually levee failures occur due to levee overtopping, as it happened during the most disastrous Hungarian floods of the Tisza: in 1879 Szeged was destroyed by the flood, or in 2001 a levee failure by Tarpa destroyed several settlements in the Upper Tisza region. So in the second simulation we supposed overtopping, however in the first case we simulated a levee failure that occurred at 958 cm water stage, so at 1.0 m lower stage than the peak of the flood. In this simulated case overtopping is impossible, but the slide of the levee is very probable, as landslides endanger the levee due to very active incision of the channel. Besides, the results of this simulation could be applied if the levee would be opened consciously with flood-protection purposes, so the protected side could be used as a flood control reservoir.

After the levee failure the filling up of the reservoir area would be controlled by the hydrology of the flood wave and the characteristics of the relief. In the model the initial point of the filling up is the deepest point of the area, however it could be considered as the gross error of the model, since in reality the filling up does not begin at the deepest point, but at the site of the levee failure. Thus, applying the HEC-RAS only the hydrological changes of the Tisza could be simulated.

The water outflow into the protected floodplain area changes significantly the hydrological parameters of the Tisza. The greatest changes occur at the cross-section of the levee failure (Mindszent, 218 fkm), as the largest flood diminution effect (1.54±0.1 m) could be observed here. Towards downstream the effect would decrease, so at Tiszasziget (50 km far from Mindszent) the maximum diminution effect would be just 1.22±0.1 m (Fig. 3–4). The small difference could be explained by the small slope (1.9-3.5 cm/km) of the river. The levee breach also causes flood diminution towards upstream, however its degree is reduced by the arriving flood wave.

Comparing the hydrographs with and without levee breach the date and the degree of the maximum diminution effect could be determined. The simulated levee breach (at 958 cm stage) occurred on April 16th and the greatest diminution effect ensued six days afterwards along the middle section of the river (Mindszent–Algyő–Szeged), but it developed one day later at the further gauging stations (Csongrád and Tiszasziget). The temporal coincidence of the maximal diminution effect on the gauges could be explained by two reasons. First of all the effect of the levee breach is pronounced for 6-8 days until the outflow-discharge (towards the reservoir) is over 1000 m^3/s, thus great part of the floodwater supply coming from the upstream is drained off. On the other hand, the peak of the 2006 flood occurs exactly 6-8 days after the levee breach so the diminution effect coincides with the duration of the rising limb of the arriving flood-wave.

The date of the peak of the 2006 flood without levee breach (at Mindszent April 22nd) precedes the date of the peak of the flood with levee breach at 958 cm stage (at Mindszent April 28th). It could be explained by the fact that the out-flowing water from the Tisza is able to decrease the water stages of the river only at a particular discharge (in this situation 1000 m^3/s) and only for a certain time (in this case for 6-8 days) against the water supply from upstream. After the reservoir is filled up, the amount of inflow water decreases, and the diminution effect terminates.

The occurrence of a levee failure has the greatest probability at the peak of a flood. Comparing the values of the two simulations it seems, that in case of the peak-stage levee failure the processes are more rapid. Thus, (1) the out-flowing discharge increases by 35%, (2) the filling up of the reservoir lasts 2 days shorter, (3) the water level in the reservoir is 0.5 m lower due to the falling stage of the Tisza and the resulted decreasing water supply, and (4) in the reservoir the amount of stored water is less by 50 million m^3. These processes are reflected on the hydrographs of the out-flowing water (Fig. 2 and 7): the hydrograph of the out-flowing water of the levee failure at peak-flood decreases steeper, since the water supply from the river is becomes limited. However, between the two simulations the values of the greatest stage reduction does not change significantly, probably because in both cases almost the same amount of water flows out to the protected side. The maximum stage reduction occurs one day earlier in case of the second simulation (at peak-flood), which is probably in connection with the higher stage (thus higher local slope) and the greater out-flowing discharge.

The slope conditions within the main channel are greatly affected by the levee failure and the out-flow, though there are only slight differences between the two scenarios. This similarity could be explained by that the stage reduction in the two cases reached almost the same degree.

The stream power highly depends on slope and discharge. Thus in case of a levee failure the slope increases on the upstream section of the levee failure, therefore the stream power increases considerably, whilst on the downstream section it decreases. (In the case of Szeged the Maros River also influences the stream power locally, therefore the simulation resulted much higher stream power values.) The changes in slope and stream power values are in connection with distance from the location of the levee failure, as by increasing distance the effect decreases.

CONCLUSIONS

The aim of the presented research was to analyze the hydrological effect of a possible levee failure by Mindszent, when the western levee would breach (or opened consciously) along 60 m length and the flood would inundate a confined flood-bay or reservoir. As the basis of the simulation a HEC-RAS model was applied using the data of the 2006 flood from March 22 until May 31. During the study we assumed, that the reservoir has uniform border (levee) heights. We ran the model for two cases: (1) the levee failure occurs at a stage 1.0 m lower (958±10 cm) than the peak flood, and (2) the levee failure happens at the peak of the flood (1050±10 cm). The results of these simulations were compared.

In the first case the maximum out-flowing discharge would be 1255 m^3/s, whilst in the second case it is 1698 m^3/s. The reservoir (113,7 km^2) would be filled up to 84.5 m asl in the first case, while in the other case just to 84.0 m asl, because in the latest the falling limb of the Tisza could supply less water into the reservoir. Consequently in the first case the reservoir would be filled up in 13 days by 700 million m^3 water, while if the levee failure occurred at the peak-flood only 650 million m^3 water would out-flow to the reservoir in 11 days, and after that would the water would flow back to the Tisza from the reservoir.

The greatest changes in the hydrology of the Tisza occur in the close vicinity of the levee failure, but there are only 1% difference between the two levee failure scenarios. In both cases the greatest stage reduction (1.52-1.54±0.1 m) appears at Mindszent. On the downstream section at Tiszasziget (50 km far from Mindszent) the stage reduction is only 1.18-1.22±0,1 m, whilst on the upstream section at Csongrád (30 km far from Mindszent) it is even smaller (0.84-0.86±0.1 m). On the upstream section the stage reduction effect is lessen by the water supply from further upstream. If the levee breached at a stage 1.0 m lower than the peak of the flood the maximum of the stage reduction would appear 6-7 days after the levee failure, though it would be faster by 1 day in the second case, due to higher initial water out-flow. Yu (2013) also studied levee failures at various water levels applying laboratory experiments, and he found that if a levee failure occurred at higher stage the processes are faster.

In case of levee breach at lower stage, the date of the peak-flood shifted in time, for example the peak of the flood at Mindszent occurred 6 days later and at lower stage by 0.78±0.1 m than the original 2006 flood-wave. Both simulations prove that the water flowing backwards form the reservoir to the Tisza increases the water level of the falling Tisza by maximum 0.74 m. However in this period the accuracy of the model decreases, therefore the dynamics and the effect of the backflow were not examined in detail.

As a result of the levee breach the slope conditions of the Tisza alters significantly by the same degree regarding both simulations. On the upstream section, between Csongrád and Mindszent the slope increases from 4.0 cm/km to 6.5 cm/km while downstream of the levee failure it decreases from 3.5 cm/km to 1.9 cm/km. The degree of the slope change decreases proportionately by distance from the point of the levee failure. The levee breach influences the stream power too. At the first simulation (at 958 cm stage) the stream power increases from 4.0 W/m to 5.5 W/m on the upstream section at Csongrád, while downstream of Mindszent it decreases significantly from 3.5 W/m to 1.5 W/m. In the second case (at 1058 cm stage) the stream power increases from 3.3 W/m to 5.0 W/m on the upstream and decreases from 4.1 W/m to 1.4 W/m on the downstream section. The alteration of slope conditions and the stream power could effect the channel formation. On the upstream sections due to the 50% rise in these values intensive bank erosion and incision could take place, and as the sediment transport could become more intensive, the overbank floodplain aggradation will accelerate. Meanwhile the values on the downstream section halves, so the transportation of the sediment slows down, thus in the channel accumulational processes and intensive mid-channel bar and point-bar formation could be characteristic.

The results of the study could be applied in flood management, since in case of a levee failure or during a controlled levee opening similar hydrological processes could be expected. However, every flood is unique and our model was based on the record high flood of 2006, thus the model should be calibrated and run on another floods, so the results could be generalized.

The construction of the “Szeged Flood Reservoir” is among the plans that would increase the flood safety of the nearby areas of the Tisza, however its planned area (67 km^2) is less by 40% than the reservoir area we used during the simulations. Therefore, it would reduce the flood levels only by 0.4 m (Bódis, 2010), though in our model the flood level decrease would be at least three times greater. In order to verify which plan would be more profitable, the economic value of the reservoir area should be calculated.

The levee failure in 1879 ensued at lower water level (806 cm) by Petres, but the location of the levee failure was only few km far from the simulated location. The flood inundated the same reservoir, but after breaking several secondary levees it flowed further south and destroyed Szeged. During this levee failure the stage of the Tisza was dropped by ca. 1.0 m (Dégen, 1969), which is quite similar to the simulated event, showing the validity of the model. Applying the SWAN program Borza (2008) also simulated the effects of a levee failure based on the data of the 2006 flood, and he found that the discharge of the outflow could be 1300-1400 m^3/s and the water level would be dropped by 1.1 m, which are very similar to our values and it confirms the utility of the HEC-RAS model.

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COMPARATIVE GRAIN-SIZE MEASUREMENTS FOR VALIDATING SAMPLING AND PRETREATMENT TECHNIQUES IN TERMS OF SOLIFLUCTION LANDFORMS, SOUTHERN CARPATHIANS, ROMANIA

Raul David Serban[1*], György Sipos[2], Mihaela Popescu[1], Petru Urdea[1],
Alexandru Onaca[1], Zsuzsanna Ladányi[2]

[1]Department of Geography, West University of Timisoara, V. Parvan Str. 4, RO-300223Timisoara, Romania
[2]Department of Physical Geography and Geoinformatics, University of Szeged, Egyetem u. 2-6, H-6722 Szeged, Hungary
*Corresponding author, e-mail: raul.serban88@e-uvt.ro

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Abstract

Grain-size distribution has become in the last years an important indicator in the analysis of periglacial processes and landforms. However, as they exhibit a complex sedimentology, careful sampling is required to draw meaningful conclusions. The aim of the present study was therefore to validate the sampling procedure carried out on solifluction forms and to evaluate the effect of sampling pretreatment during grain size analysis. A comparison between multiple measurements of grain size distribution using the laser diffraction method (LDM) was performed on 54 sediment samples collected from different solifluction landforms at different depths in the alpine area of the Southern Carpathians. The results of parallel measurements were compared using textural and statistical indicators. The received distributions reinforced the properness of field sampling procedure in most of the cases. The results of textural classification and fractional composition showed a high consistency between the two parallel measurements made on untreated and pretreated samples. An overall fining as a matter of etching was identified. Relative deviation increased and correlation decreased as pretreatment advanced. HCl etching resulted a greater deviation and variability in case of the sand fraction, H_2O_2 rather affected the silt fraction. The greatest deviations were experienced in case of landforms developed on crystalline limestone. Pretreatment of samples introduced a major uncertainty to further comparison and interpretation. Thus, multiple LD measurements on a representative group of samples from the entire sample set were suggested before the geomorphological or environmental interpretation of results to decrease the uncertainties and to validate the processes.

Keywords: laser diffraction method, grain size distribution, acid pretreatment, solifluction landforms, Southern Carpathians

INTRODUCTION

Grain size distribution is one of the most important sedimentological parameters (Ryżak and Bieganowski, 2011), representing the percentage of the total dry weight of sediment grains of a given size fraction. Grain size distribution influences other properties such as pore distribution, water retention, water conductivity, soil nitrification, thermal and absorption properties etc. (Ryżak and Bieganowski, 2011), which in turn highly influence alpine solifluctional processes and landforms.

In the last years several new methods were developed for grain-size analysis, including electroresistance counting, photometrical techniques, X-ray attenuation, optical determination using image analysis, time of transition and laser diffraction (McCave and Syvitski, 1991; Beuselinck et al., 1998; Goossens, 2008; Di Stefano et al., 2010). All these new methods generally have the advantage of covering a wide range of grain sizes, using less quantity of sediments, speed in analysis, reproducibility and fewer possibilities for operator failure (Di Stefano et al., 2010; Kun et al., 2013). Among these the use of the laser diffraction method (LDM) seems to be the most widespread, as it is cost effective, its precision and reproducibility are high. LDM is basically based on the dispersion and diffraction of a laser beam on the measured particles. The scattered laser light is recorded on sensors and the diffraction angle in which the beam is scattered is inversely proportional to particle size. The software of the equipment recalculates the information from the sensors into volumetric grain size distribution (Ryżak and Bieganowski, 2011).

The accuracy of the measurement is influenced by many factors, e.g. the color of the suspension, the mineral composition and opacity of particles, or by organic and carbonate content (Kun et al., 2013). Considering that grain size measurements are affected by the applied pretreatment method, there has been a debate on what procedures should be applied. Some researchers still underline the necessity of using acids when the organic content is high (Murray, 2002) while others found this unnecessary (Beuselinck et al., 1998) and stating that ultrasonic dispersion can replace chemical pretreatment and dispersion methods (Ryżak and Bieganowski, 2011).

In earth sciences LDM has mainly been applied on soil samples, loess, lacustrine, marine and, fluvial sediments (Loizeau et al., 1994; Konert and Vandenberghe, 1997; Buurman et al., 2001; Arnaud, 2005; Di Stefano et al., 2010; Ryżak and Bieganowski, 2011; Forde et al., 2012; Kun et al., 2013), and just in the last years starte to be applied on solifluction landforms (Ridefelt and Boelhouwers, 2006; Oliva et al., 2009; Ridefelt et al., 2011).

Grain-size analysis carried out on solifluction landforms so far has beene made on untreated samples, without evaluating the necessity of pretreatment or the sampling strategy.

Applications in alpine environments require more attention regarding that the material from solifluction lobes is disordered and overlapped by slow mass soil moving (Harris et al., 2008). In these circumstances representative and reproducible field sampling can be an important issue and must be validated before drawing further sedimentological or geomorphological conclusions.

The aim of this study thereby was to attest the correctness of sampling in case of Southern Carpathian solifluction landforms using multiple laser diffraction measurements and to evaluate the effect of sample pretreatment on the results.

STUDY AREA AND METHODS

Solifluction sediment samples were collected from the alpine area of Southern Carpathians, Romania, from different mountain ranges (Fig. 1). The Southern Carpathians are the highest sector of the Romanian Carpathians (Moldoveanu Peak – 2544 m a.s.l.) with seasonal freezing conditions in more than 6 months annually (Urdea, 1993). In the alpine area the climatic conditions are rather cold, with negative mean annual air temperature above 2000 m a.s.l. (-0.5°C at Ţarcu - 2180 m a.s.l and -2.4°C at Omu -2505 m a.s.l.) and precipitation over 1000 mm. Above the tree line (1700-1800 m a.s.l.) extensive areas are affected by solifluction, whereas other periglacial landforms (block streams, rock glaciers, talus cones and scree slopes, block fields, patterned ground, ploughing blocks, earth hummocks, etc.) are also common.

The Southern Carpathians are in general composed of crystalline schists with granite intrusions, especially in Cindrel and Făgăraș Moutains. Whereas the Tarcu Moutains is primarily built up of granitoides (northern part), limestones (central part) crystalline schists, sandstones and conglomerates. In terms of lithology, Cindrel and Sureanu Moutains belong to the Getic Fabrics (paragneiss, micaschists and amphibolites), while Parâng Moutains are part of the Danubian Unit (granitoides, amphibolites, and limestones). Characteristic soil type in the area is alpine meadow umbrisol, from the typical to cambic, lithic and skeletal subtypes.

A wide variety of solifluction landforms occur in the alpine environments based on their genesis. Most common and widespread are turf-banked solifluction lobes, while so called ploughing blocks are less frequent (Fig. 2). The term solifluction include all the processes (gelifluction, frost creep, frost heaving and frost sorting, periglacial elevation) contributing to slow mass soil movement in a periglacial environment and leading to the formation of solifluction lobes and terraces (Harris, 2007).

Solifluction lobes have a frontal height ranging from several cm to more than 1 m and length from several cm to more than 10 m (Hugenholtz and Lewkowicz, 2002; Matsuoka et al., 2005).

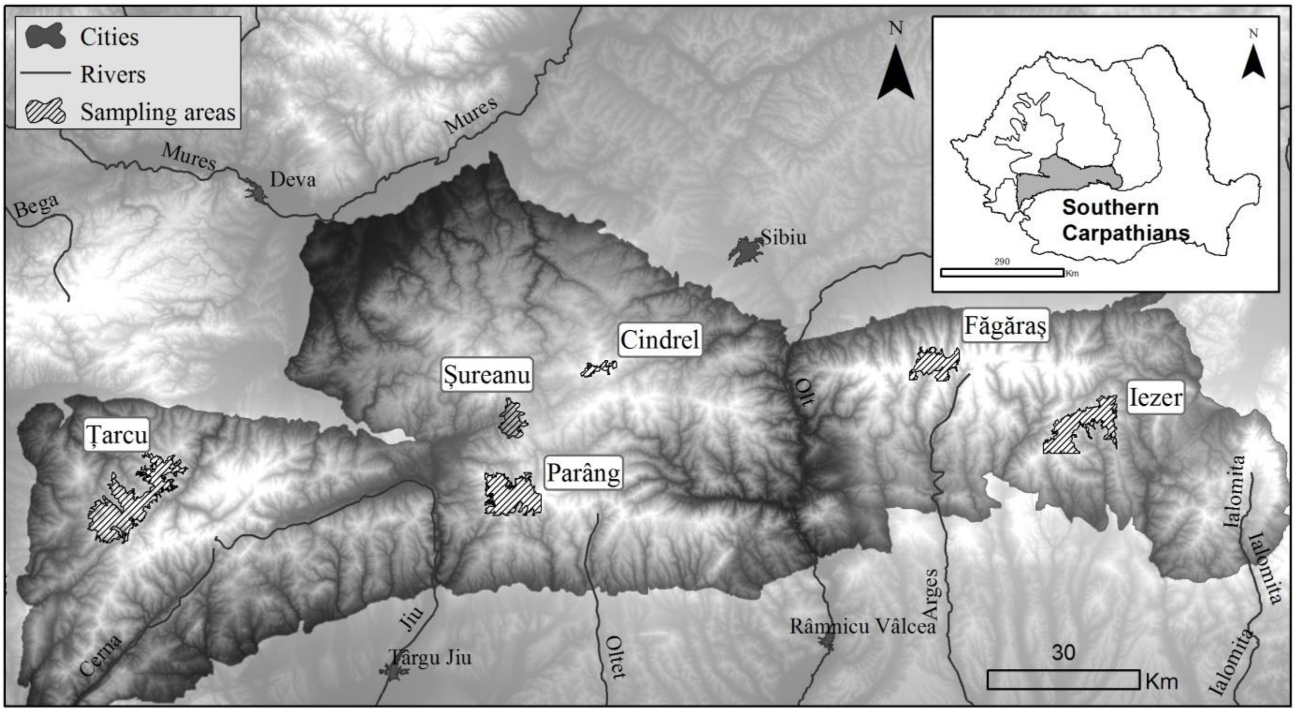

Fig. 1 The location of sampling areas

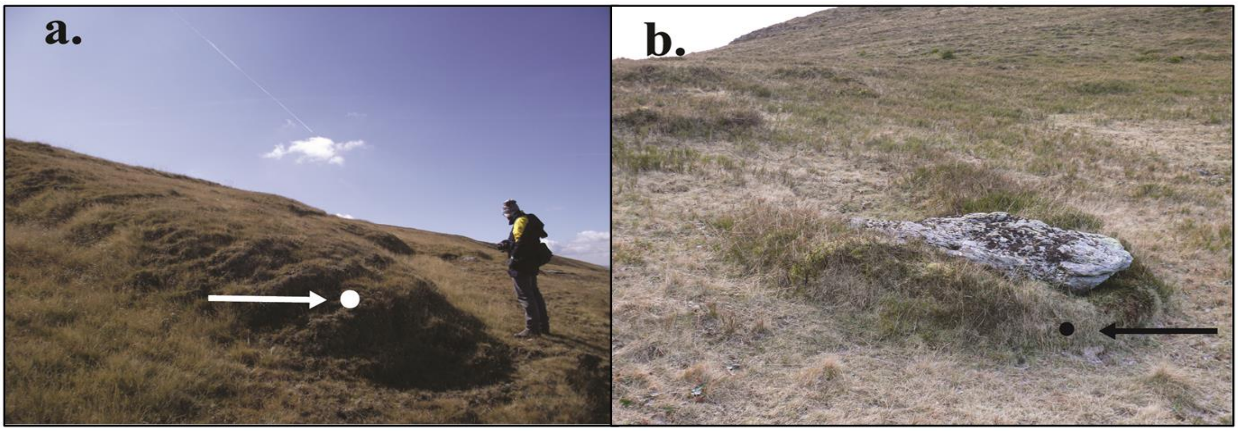

Fig. 2 Sampling of solifluction landforms: a. turf-banked lobe, b. ploughing block

Ploughing blocks represent a form of mass movement when a block moves downslope faster than the surrounding material, resulting a mound on the front and lateral sides of the block, and a depression behind (French, 1996). Occurence of ploughing blocks is associated with areas of active solifluction and frost-susceptible soils with low plasticity and liquidity limits (Ballantyne, 2001). Their size varies from several cm to almost 5 m (Hall et al., 2001) and alongside the solifluction lobes they represent an indicator of current periglacial phenomena (Ballantyne, 2001; Berthling et al., 2001).

Sampling sites were selected based on their elevation, aspect and geographic location. In all 54 sediment

Table 1 Field and laboratory coding and origin of samples (a - ploughing block, b - turf-banked lobe)

Field ID	Depth (cm)	Lab. ID	Type	Mountain Range	Field ID	Depth (cm)	Lab. ID	Type	Mountain Range
ST136_a25	25	1.	a	Tarcu	C4_25	25	28.	b	Fagaras
T36_a20	20	2.	a	Tarcu	V1_25	25	29.	b	Fagaras
T36_b20	20	3.	a	Tarcu	C2_25	25	30.	b	Fagaras
T36_c20	25	4.	a	Tarcu	P1_25	25	31.	b	Fagaras
T36_d25	25	5.	a	Tarcu	C18_25	25	32.	b	Fagaras
T42_a25	33	6.	a	Tarcu	Pa_D20	20	33.	b	Fagaras
T22_a33	23	7.	a	Tarcu	P8Da_20	20	34.	b	Fagaras
MMlob_23	25	8.	b	Tarcu	P8Da_80	80	35.	b	Fagaras
LC8_25	25	9.	b	Cindrel	P8D_riser2	20	36.	b	Fagaras
LC8_45	45	10.	b	Cindrel	P8Da_60	60	37.	b	Fagaras
LC1_20	20	11.	b	Cindrel	P8Db_25	25	38.	b	Fagaras
I_25	25	12.	b	Iezer	P8Da_40	40	39.	b	Fagaras
I3_35	35	13.	b	Iezer	P8D_riser1	20	40.	b	Fagaras
BRLA12_A28	28	14.	a	Fagaras	Pa19Da_40	40	41.	b	Fagaras
BRLA12_B28	28	15.	a	Fagaras	Pa19Da_60	60	42.	b	Fagaras
BRLA12_C40	40	16.	a	Fagaras	Pa19Da_80	80	43.	b	Fagaras
BRLA12_D15	15	17.	a	Fagaras	Pa19Db_25	25	44.	b	Fagaras
BRLA12_E18	18	18.	a	Fagaras	Pa19Db_50	50	45.	b	Fagaras
S1_25	25	19.	b	Sureanu	Pa19Db2_25	25	46.	b	Fagaras
S1_45	45	20.	b	Sureanu	Pa19Da2_40	40	47.	b	Fagaras
P8_25	25	21.	b	Fagaras	Pa19Da2_80	80	48.	b	Fagaras
Pa18A_25	25	22.	b	Fagaras	Pa19Da_110	110	49.	b	Fagaras
Pa18B_25	25	23.	b	Fagaras	Pa19Da_100	100	50.	b	Fagaras
Pa19Db_riser	20	24.	b	Fagaras	P8Da2_40	40	51.	b	Fagaras
Pa19Da_20	20	25.	b	Fagaras	P8Da_75	75	52.	b	Fagaras
Pa19Db_45	45	26.	b	Fagaras	P8Da2_80	80	53.	b	Fagaras
Pa19Da_105	105	27.	b	Fagaras	LP_25	25	54.	b	Parang

samples were extracted from 17 turf-banked solifluction lobes and from the front mound of 5 ploughing blocks for grain size and other sedimentological analyses (Fig. 2). Sampling depth ranged from 20 to 110 cm for turf-banked lobes and 15 to 40 cm for ploughing block mounds (Table 1.). Samples of approx. 0.5 kg were extracted by digging, thus samples were considered representative for later geomorphological comparisons, but might not be representative for stratigraphic analysis within the form.

All the laboratory work was performed in the sedimentology laboratory of the Department of Physical Geography and Geoinformatics, University of Szeged, Hungary. From each sampling bag two subsamples (Set A and Set B) were extracted from different positions, weighing approximately 35 g, in order to test the representativeness of field sampling and to verify if the sample was collected from the same sediment layer. For every set of sample the same workflow was followed (*Fig. 3*).

Samples were dried on 105°C, gently crushed, homogenised and dry sieved at a 2 mm mesh size for removing larger clasts and organic constituents. The fraction below 2 mm was analysed with a Fritsch Analysette 22 MicroTec laser diffraction equipment with a 0.08-2000 μm measurement range and 108 measurement channels. Instrumental settings and protocols described by Kun et al. (2013) were used throughout the measurement process. Analyses were made in 3 steps for each parallel set of samples (Fig. 3). Firstly, the original untreated subsamples were analysed (Step 1). Subsequently, samples were treated with 10 % H_2O_2 for 1 day and a second run of measurements was performed after drying (Step 2). Finally, after a 1 day long 10 % HCl treatment a third run was also executed (Step 3). Acid treatment was aimed to ensure the complete removal of organic material, carbonates and to minimise the presence of aggregates.

Consequently, each sample was measured 6 times in all, the different measurements were identified by adding suffixes marking the set of samples and the steps of measurements (Fig. 3).

In the beginning of measurements the efficiency of ultrasonic treatment, made within the wet dispersion unit of the measurement device, was tested on 3 clayey, untreated samples, prone to be affected by aggregation. Ultrasonification is very efficient in removing clay coatings, but it can also brake up quartz grains if the exposure is too long (Di Stefano et al., 2010). Three sequential measurements were made, each preceded by 12s of treatment, then the results were compared.

Raw grain size data were exported and processed by software Gradistat v8. Grain size classes were identified following the Udden-Wentworth scale (Udden, 1914; Wentworth, 1922). For comparing different sets of samples and different steps of measurements cumulative distribution and the median diameter (D50) were primarily considered.

Textural properties were compared using the graphical method and the triangular diagram of Folk (1954) and Folk and Ward (1957). Subsequently the mean D50 value of different sample groups were analysed in order to reveal general tendencies and differences related to parallel sampling and sample pretreatment. Results were also compared on the level of major grain size fractions (clay, silt, sand). Finally, D50 data of different measurements were plotted against each other and correlation coefficients (R^2) were calculated in relation to a 1:1 linear function in order to determine the variability of the data and to provide further insight to factors modifying the measurement results.

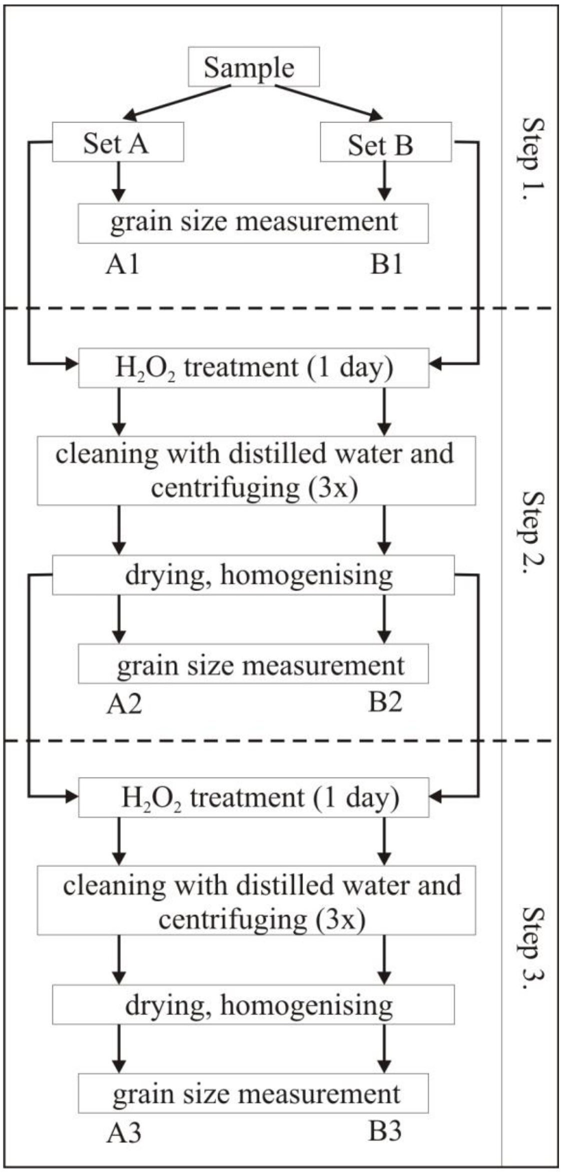

Fig.3 The steps of the measurement process and the identification of the different group of samples compared in the study

RESULTS AND DISCUSSION

Ultrasonic pretreatment

Regarding the median diameter of samples the mean relative difference between the first and third measurement cycles was 1.6 %, while maximum deviance was 3.3% (Fig. 4). Results were similar to those of Kun et al.

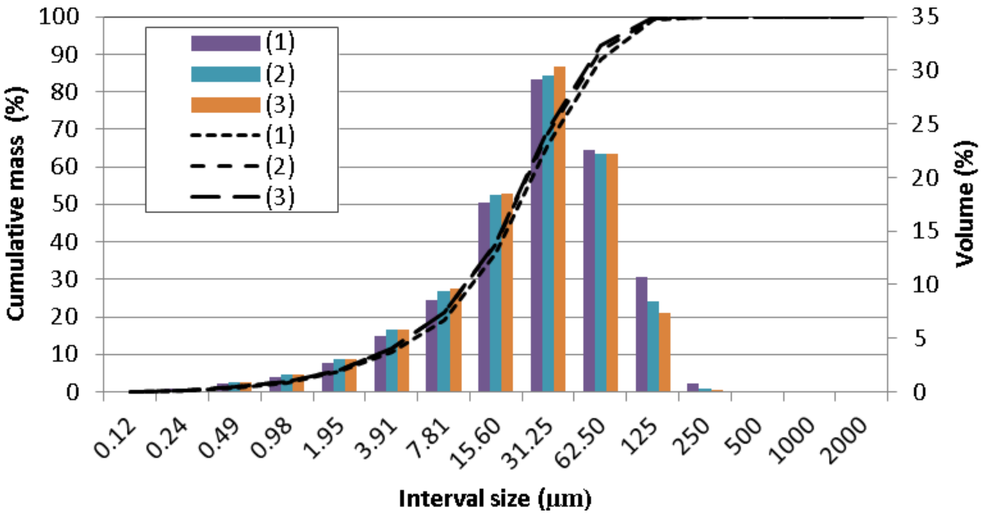

Fig. 4 Cumulative (dashed lines) and frequency (columns) particle size distribution of sample C4, using an increasing length of ultrasonic dispersion (1): 12s; (2): 24 s, (3) 36 s

(2013), using the same equipment, however, also corresponded well to the observations of Di Stefano et al. (2010), applying a longer ultrasound treatment. Based on the above, the data of the third measurement cycle, preceded by a total 36s of ultrasonification, were used for further comparisons.

It is assumed therefore that the applied treatment was adequate for the dispersion of clay aggregates and considering the results of Chappell (1998) the breaking up of individual grains could be also avoided.

Textural properties and main fractions

Based on the measurements on untreated samples, all belonged to two textural groups: sandy mud and muddy sand (Fig. 5.), representing 56 and 44% of the samples in case of Set A and 59 and 41% in case of Set B, respectively. If Step 2 and Step 3 results are taken a clear textural shift, i.e. fining due to disintegration can be noticed. As a matter of H_2O_2 treatment in case of both sets the proportion of the coarsest samples decrease by around 20%, and a new, finer textural group, mud also appears. Following HCl treatment fining is still remarkable on a textural level, and finally 30 and 24% of samples from Set A and Set B can be described as mud, respectively. Nevertheless, this time fining mostly affects sandy muds, and the proportion of muddy sands hardly changes.

These trends are reinforced if results are compared concerning the main fractions, being very similar at both sets of samples throughout the whole measurement process (Fig. 6). Fining is evident in this case too: the proportion of sand continuously decreases while the proportion of silt increases, and the proportion of clay first increases then remains stable. It is also obvious already at this stage of the comparison that as pretreatment advances the difference between the results of set A and set B samples is increasing (Fig. 6). These findings are in accordance with the results of Kun et al. (2013) and Di Stefano et al. (2010).

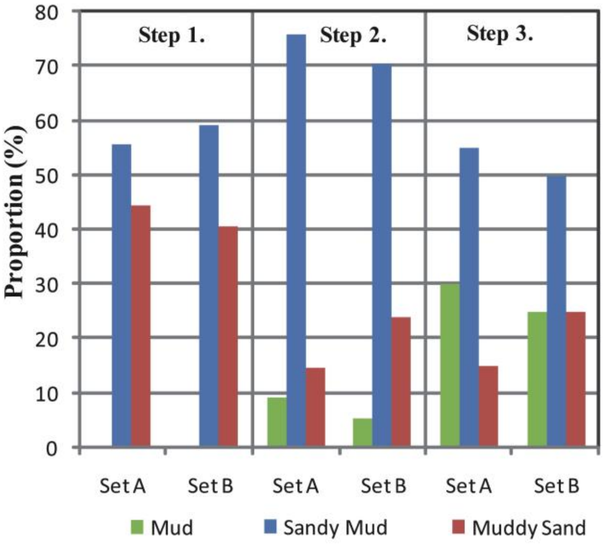

Fig. 5 Textural classification of samples at different steps of the analysis

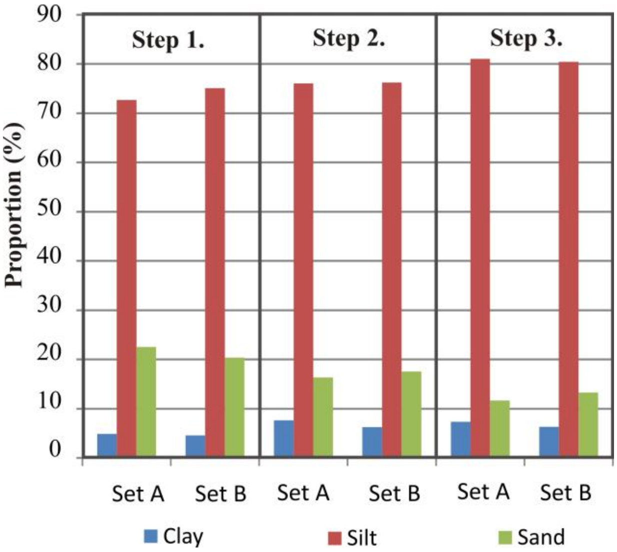

Fig. 6 Mean proportion of main fractions (clay, silt, sand) in both sets of samples at the different steps of the analysis

Consequently, acid pretreatment can significantly change even the textural properties of samples. At this stage of the analysis it is assumed that the removing of organic constituents rather affects the classification of coarser samples, while removing carbonates rather influences finer samples.

Nevertheless, it must be noted that textural shift is mainly because many of the samples are situated on the threshold between textural classes. In general the textural properties of the two parallel sample sets remained very similar throughout the measurement process.

Percentage deviations in median grain size

Concerning the entire dataset mean difference between the D50 value of A1 and B1 samples is 6.8% (0.53µm) in average. By pretreatment these values increase considerably and reach 23.7% (5.9µm) in case of A2 and B2 samples, while concerning A3 and B3 samples it drops back to 7.8% (1.9µm).

Differences are greater if the same set of samples are compared but with different pretreatment. For example in case of A1 and A2 samples the difference in D50 values is 33.7% (9.7µm) in average, while the same data for A1 and A3 samples are 14.3% (4.1µm). Concerning the two acid treatment steps it seems as if samples were more sensitive for H_2O_2 (A1-A2 and B1-B2), showing a 33.7% and a 14.6% difference than for HCl etching (A2-A3 and B2-B3): 22.7% and 9.3%. This emphasizes again the significance of acid pretreatment in changing the measured grain size distribution.

If results are separated on the basis of morphology, in the case of ploughing blocks and turf-banked lobes the average difference between A1 and B1 samples is 0.5% and 8.4%, respectively. However, after pretreatment the two groups swap, and the difference between A3 and B3 samples changes to 36% and 2.3% (Table 2). Thus, in the case of ploughing blocks acid treatment ruined the coherence of the results, while in case of turf-banked lobes it improved significantly. It has to be resolved in the future if there is any genetic explanation to this phenomenon: higher organic matter or carbonate content, or greater spatial variability in grain size composition for example.

When the main fractions are considered on their own, obviously the situation gets slightly better. Concerning raw samples (A1 and B1) differences remain below 3%. As a result of acid treatment the greatest difference is experienced in the case of the clay fraction (Table 2), being 23.4% and 15.8%. By the end of the measurement cycle the proportion of silt proved to be the most stable (3.7%) when the two sets of samples (A3 and B3) are taken.

A similar relationship is seen if the different steps of measurements are compared within the same set of sample, namely the highest variability can be attributed to the clay fraction (42.1% and 32.2%), while silt provides the most steady data if the raw and fully treated samples (A1-A3 and B1-B3) are compared. However, if the two steps of treatment are considered separately (A1-A2 and A2-A3 for example) it seems as if the sand fraction was less sensitive to acid pretreatment. The discrepancy is probably because the change in the sand fraction (decreasing abundance) is unidirectional at each step of treatment, while in the case of silt relative loss (silt particles turning into clay) and relative gain (sand particles turning into silt) can also occur, making the final result more comparable to the raw data. Finally, in general it seems as if samples, with the exception of the sand fraction, were more sensitive for H_2O_2 treatment (A1-A2 and B1-B2) than for HCl treatment (A2-A3 and B2-B3).

Correlation analysis

In order to check the consistency of comparative results correlation coefficients were calculated by plotting against the results of parallel measurements. Values of R^2 supported and also supplemented the conclusions made on the basis of mean percentage deviations (Table 3).

If the full set of samples is considered, then R^2 is the highest between untreated A1 and B1 samples (0.71) and as pretreatment went on its value significantly decreased (Table 3). If compared to changes in mean differences it must be noted that concerning the A3-B3 pair lower mean difference is not followed by the increase of the R^2 value, i.e. HCl treatment did not improve the comparability of the samples in the end (Table 3). It is also noteworthy that the correlation de-

Table 2 Mean percentage deviation of median diameter (D50) between different sample groups

% difference	median diameter (D50)			main fractions		
	all	blocks	lobes	clay	silt	sand
A1-B1	6.8	0.5	8.4	1.4	2.9	0.8
A2-B2	23.7	36.2	5.8	23.4	16.0	1.3
A3-B3	7.8	11.2	2.3	15.8	3.7	6.8
A1-A2	33.7	40.9	28.1	43.6	25.0	8.6
A2-A3	22.7	9.5	0.3	2.6	22.8	13.6
A1-A3	14.3	34.7	27.9	42.1	2.9	21.1
B1-B2	14.6	6.9	16.7	27.5	13.3	6.7
B2-B3	9.1	20.6	7.7	6.5	4.6	8.5
B1-B3	22.4	26.1	23.1	32.2	9.1	14.6

Notes: set A and B: untreated (step1: A1 and B1), pretreated with H_2O_2 (step2: A2 and B2) and with HCl (step3: A3 and B3)

Table 3 Correlation coefficients of median diameter (D50) between different sample groups

R^2	median diameter (D50)			main fractions		
	all	blocks	lobes	clay	silt	sand
A1-B1	0.71	0.93	0.69	0.96	0.94	0.82
A2-B2	0.49	0.24	0.72	0.80	0.47	0.60
A3-B3	0.42	0.37	0.78	0.87	0.72	0.47
A1-A2	0.81	0.22	0.86	0.75	0.32	0.63
A2-A3	0.39	0.34	0.37	0.70	0.24	0.16
A1-A3	0.26	0.12	0.17	0.62	0.28	0.08
B1-B2	0.46	0.62	0.50	0.77	0.57	0.56
B2-B3	0.80	0.93	0.92	0.77	0.50	0.09
B1-B3	0.60	0.70	0.61	0.55	0.23	0.08

Notes: set A and B: untreated (step1: A1 and B1), pretreated with H_2O_2 (step2: A2 and B2) and with HCl (step3: A3 and B3)

creased mostly after H_2O_2 treatment, the subsequent HCl etching just slightly affected the comparability of the samples.

When correlations within the same set of samples are taken, the values of the two sample groups are significantly different. In the case of Set A samples H_2O_2 treatment influences much less R^2 values compared to Set B samples, conversely, the HCl step introduces a much greater discrepancy (lower R^2) in case of Set A samples than the other group. If raw and fully treated samples are considered (A1-A3 and B1-B3) the deviation in correlation coefficients is also striking (Table 3), which might mean either that the mineral composition of subsamples was different, or acid treatment was not entirely consistent, however the same procedures were applied in each case.

The discrepancy above can be further analysed if the different solifluction forms are considered separately. Similarly to percentage deviations in median diameter ploughing blocks show a very good comparability on the level of the A1-B1 pair, which drops abruptly after the H_2O_2 step (A2-B2) (Table 3). In case of turf-banked lobes R^2 values are very similar throughout the whole process, referring to more uniform mineral composition. If the two sets of samples are considered separately, a great variation can be seen in the effects of pretreatment, just as in case of percentage deviations described above.

Correlations were calculated for the main fractions as well. Highest values were received for clay (0.96) and silt (0.94), for sand the R^2 value was somewhat lower (0.82) (Table 3). In case of the clay fraction correlation coefficients between different sets of samples remained reasonably high throughout the whole analysis, which seemingly contradicts the trend experienced for percentage deviations (Table 2). This might be because a slight change in median diameter can cause a significant difference in percentage deviations, while the R^2 value is less sensitive to this effect. Based on the coefficients, the variability in the silt fraction increases significantly after H_2O_2 treatment, which is in harmony with the results received for percentage deviations. Although R^2 values received for the sand fraction of untreated samples (A1-B1) is reasonably high, with the advance of pretreatment the largest variability is introduced by far here. Actually, in the end, when results are plotted against within the same subsample group, no functional relationship can be identified (Table 3). This phenomenon is primarily due to the disintegration of particles as a result of HCl etching (A2-A3 and B2-B3).

CONCLUSIONS

In the present paper we investigated the representativeness of sampling in case of different solifluctional landforms, and the effect of acid pretreatment on LD grain size measurements.

If the textural classification and fractional composition of subsamples is considered, the results show a high consistency between the two parallel measurements let they be made on untreated or pretreated samples. An overall fining as a matter of etching is evident. Based on the experienced shifts between textural classes, fining as a result of H_2O_2 treatment is a greater issue in case of muddy sands, while fining as a result of HCl treatment is rather significant in case of sandy muds. This implies a compositional difference between samples falling to coarser and finer textural groups.

Either considering mean percentage deviations or correlation coefficients the comparability of the parallel measurements is best if samples remain untreated (A1-B1). In this sense the sampling strategy in general is validated, however considering different landforms clear differences were experienced. While parallel untreated samples yielded very similar results in case of ploughing blocks, in case of turf-bank lobes a more careful and detailed sampling is proposed for further geomorphological comparisons, as probably large samples include more than one structural or stratigraphic elements of the landform.

In case of the present samples pretreatment introduces a major uncertainty to further comparison and interpretation. In general relative deviation increases and correlation decreases as pretreatment advances. Based on the analyses, HCl etching results a greater deviation and variability in case of the sand fraction, in turn H_2O_2 rather affects the silt fraction. This can partly be traced back to the geological background and composition of samples, namely the greatest deviations are experienced in case of landforms developed on crystalline limestone, and finer fractions are more likely to contain organic constituents of their size range.

Nevertheless, in several cases Set A and Set B samples exhibited different tendencies during the pretreatment process. This might imply either that organic and carbonate content could be different at parts of the relatively large samples, or the etching process was not entirely consistent. Both possible reasons require further analysis. High variability of organic content can be explained by the stratigraphic observations of Hugenholtz and Lewkowicz (2002), Kinnard and Lewkowicz (2006), Oliva et al. (2009), who revealed buried organic horizons, overlapping and deformed layers in solifluctional forms. Consequently, organic matter and carbonate content determination as well as additioal mineralogical analyses can add further insight to the interpretation of discrepancies. Meanwhile, by changing the parameters of acid pretreatment and making further comparative measurmeents the methodology of etching can be refined.

Finally, based on the results of the above research, we advise to make always multiple LD measurements on a representative group of samples from the entire sample set before the geomorphological or environmental interpretation of results. This way both sampling and sample processing can be validated, and the uncertainties of conclusions can be decreased.

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MODELLING RUNOFF ON A SMALL LOWLAND CATCHMENT, HUNGARIAN GREAT PLAINS

Tamás Právetz[1*], György Sipos[1], Balázs Benyhe[2], Viktória Blanka[1]

[1]Department of Physical Geography and Geoinformatics, University of Szeged, Egyetem u. 2-6, H-6722 Szeged, Hungary
[2]Lower-Tisza Water Directorate, Stefánia 4, H-6720 Szeged, Hungary
*Corresponding author, e-mail: pravetz@gmail.com

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Abstract

The lowland region of the South-Eastern Carpathian Basin faces extreme hydrological conditions, therefore the more detailed understanding, monitoring and predicting of the hydrological regime on catchments have high importance. However, in the region only few measured data are available in terms of evaporation, runoff, infiltration and water retention, and this is especially true concerning small catchments. In the meantime these areas support extensive agriculture, therefore more information is needed to manage future drying and irrigational demands. In the present research runoff and discharge were modelled for a ten year period and compared to at-a-station measurement data on the Fehértó-majsa Canal, a sub-catchment of the Tisza River, in order to test the predictability of hydrological changes related to future climate change. Modelling was made by applying a coupled MIKE SHE/MIKE 11 model and integrating all available topographic, pedologic, climatic, hydrologic and vegetation data. Consequently, another motivation of the research was to assess the suitability, data demand and limitations of the MIKE modelling environment on lowland catchments. As from all available data sources soil data seemed to be the least accurate, sensitivity tests were made by changing different soil parameter. Based on the results, the developed model is highly suitable for the estimation of annual and monthly runoff. Nevertheless, concerning daily data a general overestimation of discharge was experienced during low flow periods, and a time lag appeared between measured and modelled discharge peaks during high flow periods. In all, the results of the study can greatly support the realization of water management and planning projects in the drought prone sand land catchments where only a few directly measured data are available.

Keywords: modelling, runoff, MIKE, lowland catchments

INTRODUCTION

Water resources has become more and more important in the last decades in many regions of the world due to the increasing water demand of agriculture, industry and population and also due to climate change. The main difficulties with resources arisen from their great spatial and temporal variability. Therefore sustainable water management require detailed and accurate information about the processes of the hydrological cycle (e.g. spatial and temporal variation of runoff, infiltration, soil moisture). The growing significance of this issue led to the development of hydrological models, since simulated results of hydrologic models are useful in water and land resource management (Sahoo et al., 2006). Hydrological models were developed for understanding and quantifying the factors of the complex hydrological cycle by mathematic, physical or empirical functions on a well-defined hydrological system or catchment. The components of the hydrological system (surface and subsurface waters, urban drainage or sewage systems) are in close connection and this system involves complex, incompletely understood interactions among flow, sediment transport and channel form (Rodrigez et al., 2004). Thus a well-designed hydrological modelling software should take into account these components (Singh and Frevert, 2001). Hydrological models can be 1) conceptual: rough simplifications of reality, conceptualising the ideas of important processes and simulating internal variables or 2) physically based: processes are described by detailed physical equations. Based on spatial resolution, they can be 1) lumped, representing the entire catchment by a few boxes and no spatial differentiations are considered, and “) distributed models dividing the catchment into a large number of cells (Lundin et al., 2000).

Physically distributed hydrological models use parameters related directly to the physical characteristics of the watershed (e.g., distribution of topographic, geologic, soil and vegetation parameters) and spatial variability in both physical characteristics and meteorological conditions (Sahoo et al., 2006). The applied MIKE SHE hydrological modelling software is a widely used physically distributed hydrologic model, suitable for modelling different components of a hydrological system e.g. rainfall–runoff (Makungo et al., 2010; Odiyo et al., 2012), evapotranspiration (Vázquez and Feyen, 2003), groundwater movement (Demetriou and Punthakey, 1999), rivers stage (Panda et al., 2010), soil hydraulic properties (Romano and Palladino, 2002), or the complete hydrological system of a catchment (Singh et al., 1999; Liu et al., 2007; Doummar et al., 2012).

On hydrologically extreme areas, such as the lowland small catchments of the Carpathian Basin, more accurate description and forecast of the water balance is a very important objective, since only a few exact data are available about evaporation, runoff, infiltration and water storage conditions of the area. The aim of the research was to model runoff and discharge for a ten year period on the Fehértó-majsa Canal, a sub-catchment of the Tisza River, in order to test the predictability of hydrological changes related to future climate change. Modelled data were compared to at-a-station measurement data in order to verify the modelling process. In the meantime the applicability and data demand of the MIKE environment was also assessed.

STUDY AREA

The modelling was carried out on the catchment of the Fehértó-majsa Canal (SE Hungary), a 290 km^2 sub-catchment of the Tisza River. The Canal has 9 tributary canals and canal density is 0.68 km/km^2 on the basis of the total length of canals managed by water directorate (Fig. 1). The major part of the catchment (the western, upstream section) is located on the Dorozsmai-majsai Sand Ridge, while the eastern, downstream section of the catchment is located on the South-Tisza Valley *(*Dövényi 2010*)*.

Low slope conditions exist on the catchment, despite the ridge-like character of the area. The slope of the major canal is 0.78-1.16 m/km on the upper reach and 0.27-0.78 m/km on the lower reach. The maximum relief of the major canal is 24.4 m. The vertical fragmentation of the catchment is relatively high compared to lowland landscapes (the relative relief is 3-6 m/ km2) due to the system of the residual ridges and blown-out depressions, arranged into northwest-southeast direction, defining also the main runoff direction of the major and tributary canals (Marosi-Somogyi 1990).

The climate of the region is humid continental, facing drying in the past decades. Based on meteorological data, this drying tendency means that the precipitation distribution was increasingly uneven, characterised by less frequent and decreased amount of summer precipitation. In the region of the studied catchment, the annual mean temperature and the average annual duration of sunshine is the highest in the country (Pálfai, 1990), and the annual precipitation amount is quite low (520-570 mm), thus the climatic water stress is an important factor in this region (the average annual water scarcity is 520-570 mm –OMSZ 2001). The aridity of the region is enhanced by the unfavourable moisture regime of the dominantly sandy soils, because the water retention capacity of these soils is low. Based on the climatic and physical geographical parameters the area faces with moderate inland excess water hazard and high drought hazard (Fiala et al., 2014; Mezősi et al., 2014). Due to the regionally elevated situation of the upper-catchment, the groundwater regime is different on the lower-catchment (near to Szatymaz), –where the average groundwater level is 115-155 cm below the surface – and on the upper-catchment (in the sand ridge area), where the average groundwater level is 200-300 cm below the surface (ATIVIZIG).

DATA AND METHODS

The modelling of water balance on the Fehértó-majsa Canal was carried out by using a coupled MIKE SHE/MIKE 11 model. Setting up the model requires the input of a number of data sets, explained in detail below.

The modelling software

From the wide range of MIKE software products, MIKE 11 and MIKE SHE were used. MIKE 11 is a one dimension (1D) river and channel modelling software, while MIKE

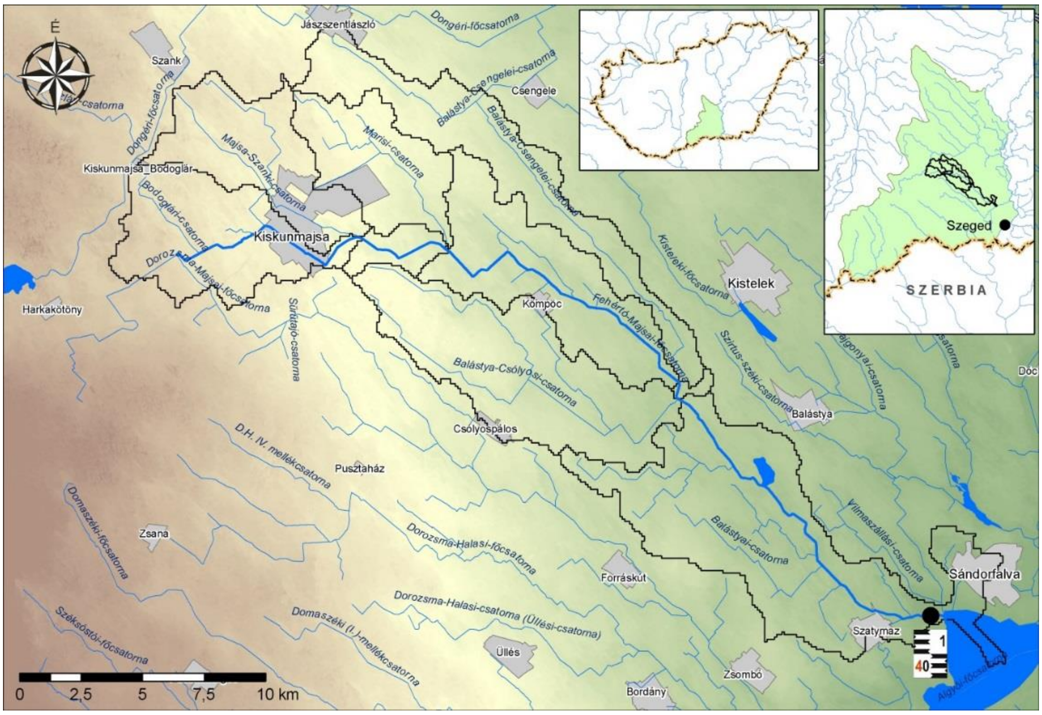

Fig. 1 Location of the studied catchment

SHE is 2D integrated catchment modelling software. The two modelling environments can be coupled, thus the interactions between the water flow and the catchment could also be interpreted. The MIKE 11 is an implicit finite difference model for computation of one dimensional unsteady flow with free surface. MIKE 11 applied with the fully dynamic descriptions solves the vertically integrated equations of conservation of volume and momentum (the 'Saint Venant' equations), based on the assumptions that the water is incompressible and homogeneous.

The MIKE SHE is a deterministic, fully distributed and physically based modelling system for modelling the major processes of water flow in the land phase of the hydrological cycle, including a range of numerical methods for modelling each hydrological processes. Each of these processes can be represented at different levels of spatial distribution and complexity, according to the goals of the modelling study and the availability of field data. The advantage of the MIKE SHE is the high integration of the elements of the hydrological process, in which the interrelations between these processes are counted. Due to the modular approach implemented in the MIKE SHE, each of the hydrologic processes are calculated separately and integrated on the basis of the interrelations between these processes (Graham and Butts, 2005).

The integration of different input data into the model

Land cover data

To evaluate the effect of vegetation cover of the modelled catchment, 1:100.000 scale Corine Land Cover (CLC) database was applied. The parameters of the different land cover types has importance in modelling surface runoff, since land cover type define the runoff factor of the precipitation. On the analysed catchment, 17 different land cover types were identified, thus defining the parameters for each land cover type is important (Fig. 2.).

Land cover affects overland flow and Evapotranspiration Component during modelling. The calculation of overland flow is based on the Manning's roughness coefficient (Chow 1959) in the MIKE software. The Manning's roughness values for the CLC land cover types are indicated in Table 1. For calculating the Evapotranspiration Component MIKE SHE requires the leaf area index (LAI) and the root zone depth for each land-use type. These values were defined based on the CLC classes (Table 1).

Soil data

The soil data can be integrated into the model as polygon features. For the modelling the effect of soil on the, the parameters of the unsaturated soil are important (depth of the soil layer, water retention parameters, hydraulic conductivity). The parameters of the unsaturated soil zone were described for the model on the basis of the 1:100 000 scale Agrotopographical map (Agrotopographical Database, 1991) (Fig. 2). The water retention parameter of the soil can be defined by the pF curves of the different soil types to estimate the soil moisture balance. These pF curves were described by Stefanovits et al. (2010) for the main soil texture classes (sand, loam, clay), thus the soils of the study area were categorised into these classes:

1. Sand: blown sand, humic sandy soil, chernozem type sandy soil
2. Loam: meadow chernozem, solonetzic meadow chernozem, meadow soil
3. Clay: solonchak solonetz, meadow solonetz, Solonetzic meadow soil

Table 1 Parameters related to the Corine Land Cover (CLC) classes used in the model (Zhao et al., 2012; Chow, 1959*)*

Corine Code	Type	LAI index	Root zone depth (m)	Roughness
112	Discontinuous urban fabric	0	0	0.1
121	Industrial or commercial units	0	0	0.1
131	Mineral extraction sites	0.98	0.5	0.04
142	Sport and leisure facilities	0.98	0.5	0.05
211	Non-irrigated arable land	1.375	0.5	0.04
221	Vineyards	1.5	1	0.05
222	Fruit trees and berry plantations	1.5	1	0.05
231	Pastures	1.76	0.5	0.035
242	Complex cultivation	1.375	0.5	0.04
243	Land principally occupied by agriculture, with significant areas of natural vegetation	1.375	0.5	0.05
311	Broad-leaved forest	2.33	2	0.09
312	Coniferous forest	2.45	2	0.09
313	Mixed forest	2.53	2	0.09
321	Natural grassland	1.76	0.5	0.035
324	Transitional woodland shrub	1.97	1	0.07
411	Inland marshes	1.82	0.5	0.07
512	Water bodies	1.81	0	0

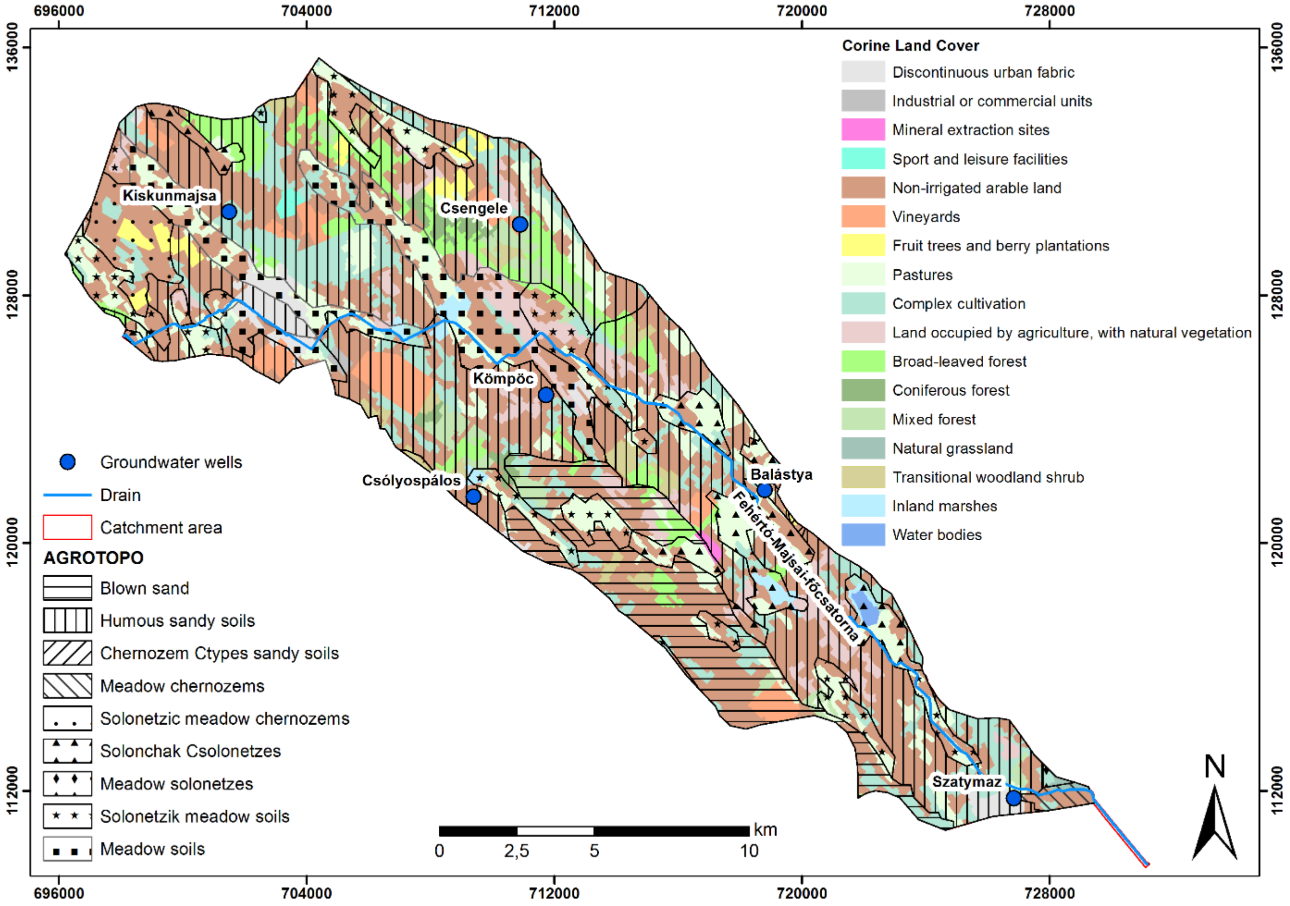

Fig. 2 Soil and land cover types on the studied catchment

The hydraulic conductivity can be defined by several methods e.g. Averjanov, van Genuchten, Campbell/Burdin. Important input parameters in the calculation of hydraulic conductivity are the saturated hydraulic conductivity (Ksat), saturated soil water content (Ɵsat), residual soil water content (Θ_{res}) and empirical values of the inverse of the air entry value (α) and the shape parameters of the van Genuchten (n). MIKE SHE needs these parameters to estimate the water content of unsaturated soil during the simulation, however the evaluation of these parameters are very complex, requiring extensive field and laboratory measurement, thus the catchment-scale evaluation is problematic. Therefore the reference values, defined by Cook (2012) for different soil texture types (Table 2) were used in the modelling.

Topography

The runoff directions throughout the catchment were evaluated using surface topographical data. The topography input data was obtained from a 5 m resolution digital elevation model (DEM). The MIKE SHE re-

Table 2 Hydraulic parameters for soil texture types (Cook, 2012)

Type	Θ_{res}	Θ_{sat}	α, cm^{-1}	n	K_{sat} ft/day
Sand	0.045	0.43	0.145	2.68	23.39
Loamy Sand	0.057	0.41	0.124	2.28	11.49
Loam	0.078	0.43	0.036	1.56	0.82
Silt Loam	0.067	0.45	0.02	1.41	0.35
Sandy Clay Loam	0.1	0.39	0.059	1.48	1.03
Clay Loam	0.095	0.41	0.019	1.31	0.2
Silty Clay Loam	0.089	0.43	0.01	1.23	0.06
Loam	0.078	0.43	0.036	1.56	0.82
Sandy Clay	0.1	0.38	0.027	1.23	0.09
Silty Clay	0.07	0.36	0.005	1.09	0.02
Peat	0.1	0.7	0.05	1.1-1.3	0.05-1

quires a special raster dataset, a (.dsf2) grid point file. Hence the original DEM requires some transformation procedures. Firstly, a point file was created using ArcGIS and the elevation data of the DEM was linked for each point. The resulted point shape file can be used as input and a digital elevation model can be generated by interpolation in the model.

Water flows (canals)

To evaluate the canal network and the features of the canals, a MIKE 11 model was developed. The canal network was implemented using polyline GIS maps and cross-sectional and longitudinal section data were joined to the canals. The description of the canals was achieved through the specification of cross-sections of the canal. In defining the cross-section geometry, the maximum elevation is specified in such a way that the cross-section will accommodate the maximum expected water levels. The placed markers of the canal bank define the horizontal boundary of the hydraulic area. If, during a simulation, the water level rises above the maximum elevation in the processed data table, the hydraulic area is calculated by assuming the river banks extend vertically upward. This is not realistic, however the computation of the runoff is simpler, moreover the model cannot compute horizontal flooding as a 1D model. Important parameter is the channel bed roughness (n), since it has an impact on the runoff velocity. The roughness factor is defined by the shape of the channel and the vegetation type and density. In this study, a uniform n value of 0.035 was used, which is consistent with values proposed by Chow (1959) for streams with hydraulic characteristics similar to the studied canals. As boundary condition, prescribed infow and outfow points and initial boundary conditions also have to be defined. Here, the inflow boundary conditions at the upstream end of the branch was closed end (Q=0), since there is no inflow at the upstream end of the modelled canal. As the outflow boundary conditions at the downstream end of the branch stage-discharge relation or a simple water level (in meter above sea level).

Groundwater data

To describe the effect of the saturated zone on the system relative groundwater depth data was used. The depth of the groundwater has effect on the runoff and water level of the canal in two ways: if the groundwater level is higher than the bottom of the canal, groundwater inflow represents additional water within the system; if the groundwater level is lower, water outflow from canal represents water loss within the system. The model processes the groundwater level changes over time, starting with a preliminary defined initial value. This value can be one value representing the whole catchment or an elevation model of the relative or absolute groundwater level. In this study elevation model was interpolated from the data of 6 groundwater wells (Fig. 2) and this elevation model (Fig. 3) was the input data for modelling. Beside ground water data, properties affecting subsurface activities include saturated hydraulic conductivity of the saturated zone layers and special geologic properties of the soil profile (e.g. less permeable lens). The inclusion of geologic data is op-

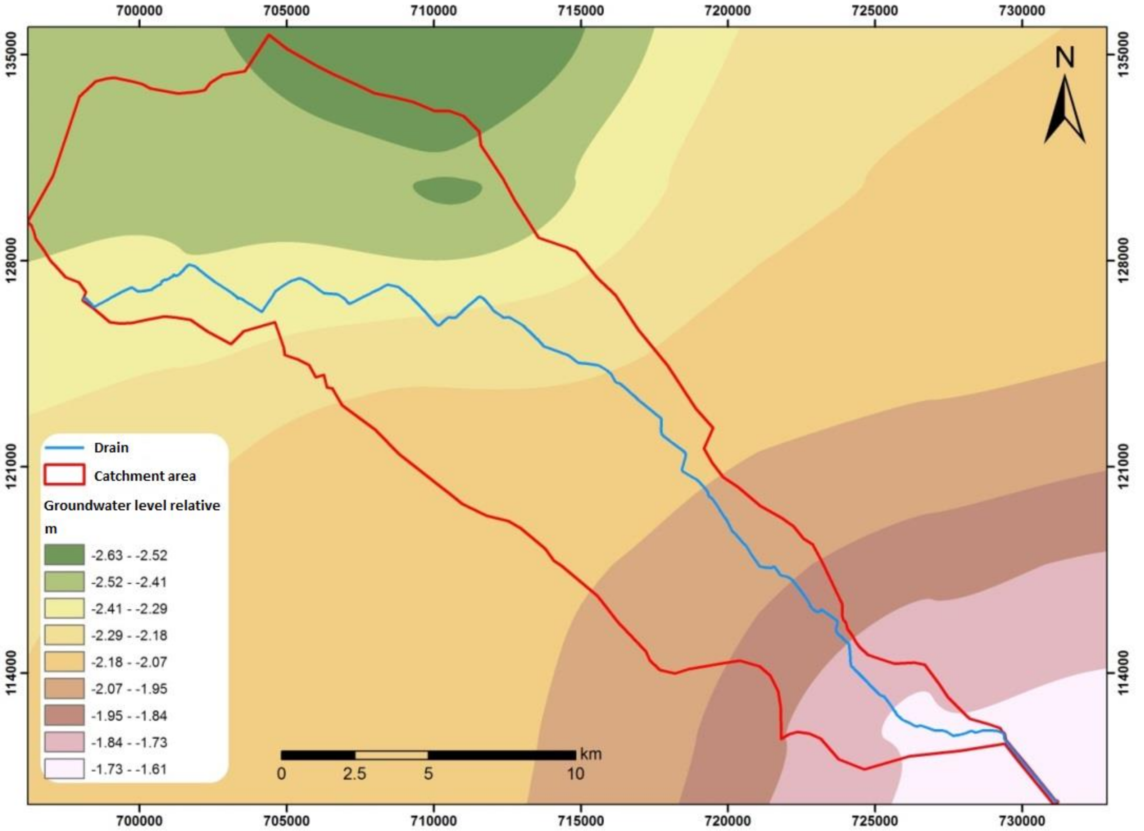

Fig. 3 Initial relative groundwater depth on the study area (01.01.2003)

tional in the model. The subsurface system was defined by closed boundary condition in the model, thus the horizontal inflow and outflow is not allowed during the modelling.

Meteorological data

To integrate the climatic conditions, MIKE SHE model requires three main inputs: precipitation rate air temperature and reference evapotranspiration. One of the most important meteorological input data of runoff models is the precipitation amount, since the precipitation is the main water input in the system. For the study area observed daily data of 4 meteorological stations was available in the simulated period (2003-2012). Into the model, the average data of the 4 stations was calculated and this value was applied for the whole area. In the model, the precipitation can runoff, infiltrate or temporarily store in the soil. The storing capacity (mm) is an input parameter of the model and this value defines the thresholds of infiltration or runoff. The model is very sensitive to this parameter, significantly influencing the model results, thus preliminary testing is essential (Frana, 2012). The infiltration and runoff are defined by the vegetation and roughness of the land cover and the parameters of the unsaturated soil zone.

The physical state of the precipitation (rain, snow) is also important, thus the data series of temperature is also necessary for the simulated time period. Temperature has influence on the model result because of the water storing in case of frost periods or the increased evapotranspiration in case of high temperatures. In the model, daily average temperature data was used. The most problematic meteorological parameter is the evapotranspiration. Detailed catchment scale evapotranspiration data are not available for the study area, only large scale yearly average values. This yearly average could be used in the model by calculating daily values, however this constant value is not realistic due to the significant temperature variation during the year and this would resulted in large errors in the model result. To provide more accurate values for the model, the evapotranspiration data should be corrected with the daily temperature variation using the correction values. For this correction, data of FAO (2015) was used.

The modelling process

After uploading the necessary data simulation was run for a 10-year period between 2003 and 2012. In all 9 model variations were generated. The first is termed as the initial model, containing the data in the form detailed above. Since from among the input datasets soil parameters can be attributed with the greatest uncertainty as a consequence of their relatively poor resolution (1:100 000) and the lack of measured data concerning physical properties, in the following variations the sensitivity of the model to the variation of these were tested. Primarily, parameters related to hydraulic conductivity and storage capacity, influencing infiltration and ground water flow were changed by considering possible minimum and maximum values concerning loamy soils.

In all 9 different model variations were set up (Table 3). In the first two variations specific storage was increased and decreased by 50%, in the following two variations specific yield was modified similarly. In case of model variation No. 6 and 7 hydraulic conductivity was increased and decreased by an order of magnitude. Subsequently, the detention storage parameter was increased to 2 and 5 mm. Concerning the final variation the calculation method of the water retention parameter was modified and instead of soil pF curves the Van Genuchten formula was applied with empirical values for α and *n* (Cook, 2012). All model variations were run and discrepancies between the simulated and the measured discharges were analysed.

Model variations were validated against discharge data recorded near the outlet of the catchment at the Szatymaz gauge station. The station records the discharge of the canal daily at 7:00 am since the 1990s, therefore simulated discharge data were retrieved from the model also for this time of the day. For comparisons the differences (in m^3/s and %) between calculated and the measured daily data were averaged for the entire period, and also on a yearly and a monthly base. The agreement between modelled and measured data was also analysed by calculating correlation coefficients.

Table 3 Modified input parameters in the different model variations

Model variations	Specific Storage (1/m)	Specific Yield	Hydraulic Conductivity (m/s)	Detention Storage (mm)	Retention Curve
Initial	0.2	0.2	2.8e-005	0	pF curve
1.	0.3	0.2	2.8e-005	0	pF curve
2.	0.1	0.2	2.8e-005	0	pF curve
3.	0.2	0.3	2.8e-005	0	pF curve
4.	0.2	0.1	2.8e-005	0	pF curve
5.	0.2	0.2	2.8e-006	0	pF curve
6.	0.2	0.2	2.8e-004	0	pF curve
7.	0.2	0.2	2.8e-005	2	pF curve
8.	0.2	0.2	2.8e-005	5	pF curve
9.	0.2	0.2	2.8e-005	0	van Genuchten

Data were also compared in terms of dry (low water) and humid (high water) periods. The distinction was made by calculating the mean of the measured data series (0.208 m^3/s). Consequently, values below and above this value were considered as low water and high water data.

RESULTS

Concerning the initial model the average discrepancy of the simulated data for the whole period (2003-2012) was +0.027 m^3/s, meaning a 12% overestimation of the measured discharge (Table 4). The simulated data of the initial model were in a good agreement with the measured data in low flow periods. On the other hand in more humid periods the model overestimated runoff and simulated peak discharges were in delay to the measured data (Fig. 4). The maximum difference experienced in the daily data series was -2.5 m^3/s and occurred during the 2006 excess water period. The correlation coefficient between the daily data of the simulated and modelled series was extremely poor as a consequence of overestimation and time lags between the two datasets. Naturally, if monthly and annual means are compared the results improve. On a monthly and annual basis the value of R^2 is 0.51 and 0.94 (Table 4).

Concerning the entire modelling period the lowest differences were experienced in case of the initial model and in case of model variation No. 3 and 4 (discrepancy: +0.026-0.027 m^3/s and 12-13%), where the specific yield parameter was modified. The highest discrepancy was found in case of model variation 8, run with a 5 mm detention storage value (discrepancy: +0.314 m^3/s and 502%).

Each of the modified model variations overestimated runoff during low flow periods. The fitting of the modelled data series to the control data was varying. Based on the tests, the modification of the specific yield parameter hardly caused any change in the results compared to the initial model (Table 4). In these variations the overestimation was 43%, being only 0.07-0.08 m^3/s, which is reasonable if we consider that during low flow mean discharge is only 0.128 m^3/s. Greater differences were seen when changing the values of the specific storage parameter. Nevertheless, the largest discrepancy was experienced in case of model variation No. 5 and 8, when hydraulic conductivity was considerably decreased and detention storage was increased. In these cases modelled discharges were in averages 5 times higher than the control values (Table 4). When hydraulic conductivity was increased in model variation No. 6, low water values were still considerably higher than in case of the initial model, probably as a result of increased ground water yield to canals.

Concerning high flows both underestimation and overestimation occurred in comparison to the measured data series. Best correspondence was experienced in case of the initial model (-0.115 m^3/s, -17%), and model variation No. 7 (+0.103 m^3/s, +15%). Tests showed that high flow results are again hardly sensitive to changes in the specific yield parameter just like in the case of low flow data (Table 4). When specific storage is modified more considerable deviations occur. In model variation No. 5 and 6 the modification of

Table 4 Mean absolute and relative deviation of models compared to the measured data. The best three results are highlighted by bold letters

	Low water period			High water period			Complete period				
Model variations	Mean absolute difference (m^3/s)	Mean relative difference (%)	Mean discharge (m^3/s)	Mean absolute difference (m^3/s)	Mean relative difference (%)	Mean discharge (m^3/s)	Mean absolute difference (m^3/s)	Mean relative difference (%)	Mean discharge (m^3/s)	R^2 - monthly mean values	R^2 - annual mean values
initial	+0.075	**+43**	0.128	-0.115	**-17**	0.547	0.027	**+12**	0.235	**0.51**	**0.94**
1.	+0.094	+80	0.146	-0.157	-23	0.506	0.031	**+15**	0.238	**0.48**	0.78
2.	+0.136	+160	0.188	+0.186	+28	0.848	0.148	+71	0.356	0.31	**0.89**
3.	+0.075	**+43**	0.127	-0.121	**-18**	0.542	0.026	**+13**	0.233	**0.51**	**0.94**
4.	+0.076	**+45**	0.128	-0.119	**-18**	0.543	0.026	**+13**	0.234	**0.51**	**0.93**
5.	+0.311	+496	0.363	+0.327	+49	0.991	0.315	+152	0.523	0.14	0.41
6.	+0.202	+287	0.253	-0.264	-39	0.399	0.083	+39	0.291	**0.63**	0.54
7.	+0.148	+184	0.199	+0.103	**+15**	0.766	0.136	+65	0.344	0.28	0.82
8.	+0.314	+502	0.366	+0.358	+53	1.021	0.325	+156	0.533	0.11	0.41
9.	+0.205	+293	0.257	-0.128	-19	0.535	0.119	+57	0.328	0.17	0.39

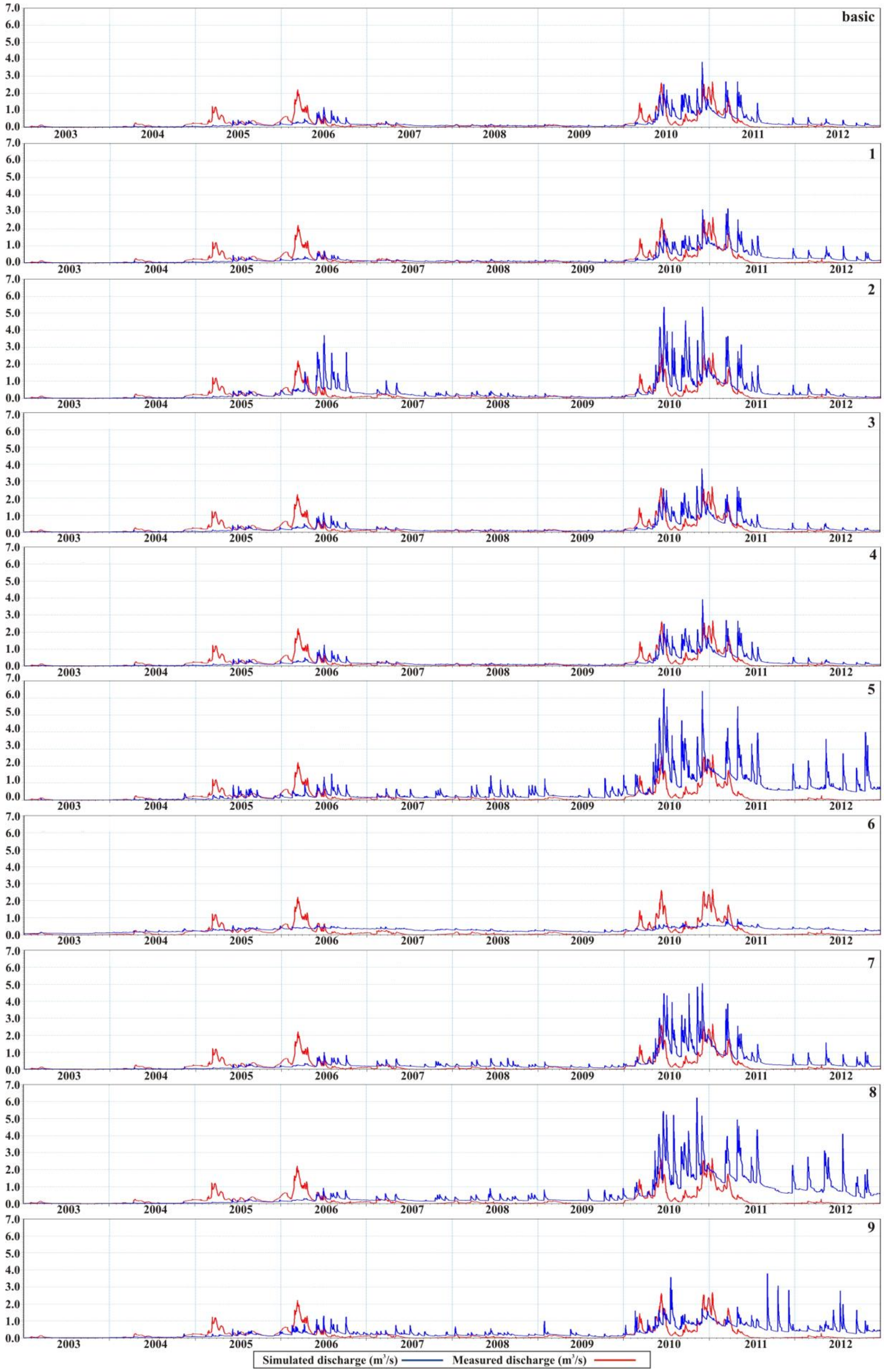

Fig. 4 Simulated discharge (m^3/s) curves of the different model variations compared to the measured data series

hydraulic conductivity resulted high deviations, the model seems to be sensitive to this parameter. It is also obvious that changing the value of detention storage the outcome of the model at high flows can be greatly affected. In case of periods with higher precipitation the use of the Van Genuchten method instead of the pF will not make a significant difference if average deviations are considered (Table 4).

Correlation coefficients calculated by plotting against modelled and measured data show that a daily based precise prediction of discharge data is not possible at the present state of the model. In terms of monthly means the highest R^2 (0.63) was received in case of model variation No. 6, with a low hydraulic conductivity (Table 4). However, as it was seen earlier this variation resulted high deviations in both low water and high water periods, therefore, the relatively high correlation in monthly data is rather the result of an averaging effect of positive and negative deviations. The second highest correlation (0.51) was experienced in case of the initial model and model variations No. 3 and 4, reinforcing previous results (Fig. 5a). The lowest correlation coefficient (0.11) was received for model variation No. 8 which is in harmony with expectations based on absolute and relative deviations.

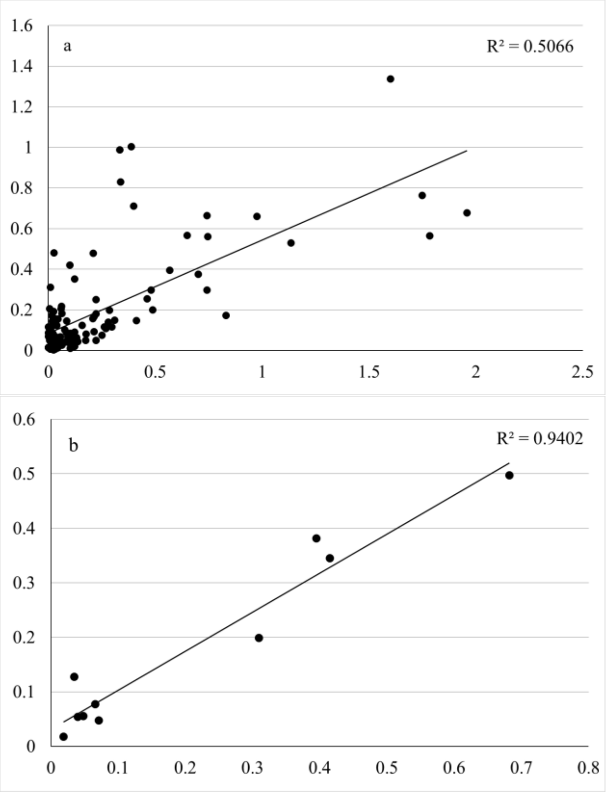

Fig. 5 Correlation of modelled and control data on a monthly (a) and on an annual (b) base in case of the initial model variation

The values of R^2 naturally improve if annual means are considered. In this case coefficients were as high as 0.94 in terms of the initial model and model variation No. 4 (Table 4). This means that predictions can have a high accuracy on a yearly basis (Fig. 5b). Coefficients above 0.80 were received for model variations No. 2, 4 and 7. Thus, at an annual resolution most of the model variations are well applicable.

Another key issue of the model is the time lag between measured and modelled peak discharges. This can explain the relatively low R^2 values in terms of monthly values. In case of the 2010 high flow period the first peak of the flooding was missed by most of the model variations, and only those showed some overlay, which anyway performed poor during the deviation and correlation analysis. Nevertheless, the second wave was captured well by the initial model and those variations where specific yield and specific storage were modified (Fig. 4). The overlap with the following 2-3 peaks is variable, and in certain cases fake peaks also appear in the modelled data series.

The situation in terms of the 2006 peak is even more interesting, as in this case actually none of the models captured the flood wave and increasing discharge values appeared with a several month delay (Fig. 4). This phenomenon might be explained by human interventions on the catchment, namely in this period there was an extensive inland excess water cover on agricultural areas, which was managed by draining and pumping the water directly into the main canal. As exact data on the amount of the drained water was not available, this effect could not be integrated to the model. Similar issues may affect the time lags experienced in terms of the 2010 flood period.

CONCLUSIONS

After performing several runs with modified soil parameters we found that the initial model, comprising average values advised by the literature and values retrieved from low spatial resolution data, proved to be relatively accurate in predicting monthly and annual discharges.

The model is not sensitive in general to the modification of the specific yield parameter and slightly sensitive to the modification of the specific storage parameter. Much higher deviations were experienced as a matter of changing hydraulic conductivity and detention storage.

Concerning low flow periods in relative terms a significant overestimation was experienced, and not any of the model variations could improve deviations. The modification of sensitive parameters listed above caused dramatic changes in the results and ruined comparability to the control data. As most of the modelled period is comprised of low flow events, the field assessment of the above listed parameters, especially hydraulic conductivity would be crucial in the future to improve the output of the model.

In terms of high flows relative differences between modelled and control data are lower. Best performing models underestimate discharge, which can be significantly improved by modifying the detention storage parameter. Consequently, in the future dry (low flow) and wet (high flow) periods of the model should be fine tuned by adjusting different parameters.

The overall validation of the model is significantly hindered by the observed time lags between measured and modelled peak discharges. This problem is partly caused by artificial draining activity on the catchment, especially during the spring period. The issue could be overcome, and correlation between measured and modelled data could be increased if measured or calculated data of draining were introduced to the model.

As far as the above measurements and estimations are not completed and integrated to the calculations, the model is rather applicable to predict monthly and annual runoff and discharge. Nevertheless in terms of a lowland catchment with such a low relief this can still provide valuable data for water management. Moreover, applying the above introduced methodology and input data the runoff on other small catchments in the Lower Tisza Region could also be modelled.

The initial model variation at its present stage can also be applied to predict general changes in runoff related to climate change. Based on the performance of the present model, if the simulation data of regional climate models are applied annual changes can supposedly be predicted at a high accuracy.

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