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CHANGES IN FLOODPLAIN VEGETATION DENSITY AND THE IMPACT OF INVASIVE *AMORPHA FRUTICOSA* ON FLOOD CONVEYANCE

Judit Nagy[1], Tímea Kiss[1]*, István Fehérváry[2], Csaba Vaszkó

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

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Abstract

Flood conveyance of floodplains is significantly influenced by the riparian vegetation cover, since vegetation affects flow velocity, therefore has a considerable impact on flood height and rate and pattern of sedimentation. However, climate change promotes the spread of invasive species, and their rapid growth results in dense vegetation stands, thus they have a significant impact on floodwater hydraulics. The aims of the present study are (1) to analyse the long-term changes in land-use and vegetation density on the Lower Tisza River, (2) to evaluate the role of the invasive *Amorpha fruticosa* in increasing vegetation density, and (3) to model the effect of dense floodplain vegetation on flood level and flood conveyance. Long-term (1784-2017) changes of land-use suggest that in natural conditions the study area was occupied by wetlands (92%), thus water covered the area for almost the whole year. In the 19th century, after levee constructions the wetlands were replaced by meadows and pastures (94%), then by the end of the 20th century planted and riparian forests replaced these land-covers. As a result, the mean roughness (0.14) of the floodplain has increased threefold until the early 21st century. Today forests are invaded by *Amorpha fruticosa*, which increases the vegetation density by 3% in riparian forests, by 23% in forest plantations, and by up to 100% in abandoned pastures and arable lands. According to the results of HEC-RAS *(Hydrologic Engineering Center's River Analysis System)* and CES *(Conveyance Estimation System)* models, if floodplain vegetation was managed and *Amorpha fruticosa* was cleared from the floodplain, peak flood level would decrease by 15 cm. Due to dense vegetation, the flood conveyance decreased by 4-6%, and the presence of *Amorpha fruticosa* reduced the flood flow velocities by 0.014-0.016 m/s. Accordingly, clearance of the floodplain from *Amorpha fruticosa* would have positive effects on flood protection, since peak flood stages would decrease and flood waves would shorten.

Keywords: vegetation, roughness, floodplain, forests, *Amorpha fruticosa*

INTRODUCTION

The climate change and the resulted hydro-climatological extremities facilitates the spread of invasive species, thus they appear in large number and due to their rapid growth they form very dense vegetation stands, thus they have a significant impact on the ecosystem (Didham et al., 2005) and on vegetation density (Delai et al., 2018), resulting in changes in floodwater hydraulics.

One of the most important elements of effective floodplain management and flood protection is providing unobstructed flood conveyance on floodplains (Samuels et al., 2002). Flood conveyance of floodplains is influenced by several local factors, e.g. water surface width, the floodplain's surface roughness, built-in structures, and floodplain aggradation (Rátky and Rátky, 2009). The roughness of the floodplain's surface is significantly influenced by vegetation, as plants could alter flow conditions and affect flow velocities (Osterkamp and Hupp, 2010; Takuya et al., 2014; Devi and Kumar, 2016). As a result, dense vegetation significantly reduces flow velocity, which combined with accelerated sedimentation, deteriorates the flood conveyance on floodplains (Chow, 1959). This could result in increased flood levels, thus increased flood risk (Wang et al., 2015).

The impact of vegetation on flow conditions is complex, as it depends on the density and height of the vegetation, on its phenological phase, morphological and structural characteristics (Chow, 1959; Wang et al., 2015; Vargas-Luna et al., 2015). Vegetation density is primarily determined by the species (Antonarakis et al., 2010), the number and rigidity of stems (Freeman et al., 2000; Galema, 2009), and the density of foliage (Ree and Crow, 1977; Järvelä, 2004; Antonarakis et al., 2010), thus it can vary by season (Burkham, 1976; Coon, 1998). The denser vegetation and more rigid stems create greater obstructions to flood flow, resulting in reduced flow velocity. In extreme cases (very dense vegetation and low water slope) the flow velocity can be reduced to 0 m/s (Sándor and Kiss, 2007). Decrease in flow velocity depending on the height of the vegetation cover, as if the height of inundation exceeds the height of the vegetation, the flow velocity can recover to normal, since there is no obstruction in the flow direction (Galema, 2009).

Floodplains provide optimal conditions for the spread of invasives, since these species survive periodical inundations, and their seeds can travel large distances by the floods invading farther areas (Pyšek and Prach, 1994). Invasive species tolerate burial by deposits (Schnitzler et al. 2007), extreme hydrological conditions, and they favour sunlight (Dumitraşcu et al., 2012). Human activities on floodplains also promote their dispersal, as new invasive species are often introduced, besides deforestation and abandonment of lands could help their invasions too (Pyšek and Prach, 1993; Planty-Tabacchi et al., 1996; Szigetvári, 2002; Mihály and Botta-Dukát, 2004).

High and long-lasting floods could be such a high magnitude of disturbing effects, that native species cannot necessarily tolerate (Catford and Jansson, 2014; Garssen, et al. 2015). On the Lower Tisza River in Hungary, for instance, floodplains can be inundated by 6-8 m high floods for 1-3 months, which has promoted the dispersal of invasive species, such as *Amorpha fruticosa*, *Echinocystis lobata* and *Vitis vulpina*. Nowadays, these species form very dense, impenetrable shrubbery in many areas on the floodplain (Fig. 1).

Fig. 1 (a) Mainly invasive species form impenetrable shrubbery and (b) Amorpha fruticosa bushes under a Poplar plantation (Lower Tisza River, Hungary)

Along the Tisza River *Amorpha fruticosa* causes the greatest problems, as it spreads very aggressively on the floodplain (Mihály and Botta-Dukát, 2004), thus its presence reduces flood conveyance considerably (Sándor and Kiss, 2007; Delai et al., 2017). *Amorpha fruticosa* originates from south-eastern North America, and it was introduced in Hungary at the end of the 19th century in order to stabilize riverbanks and to protect them from intensive erosion (Simonkai, 1893; Szigetvári and Tóth, 2012). The *Amorpha* forms 3-4 m high shrubbery (Mihály and Botta-Dukát, 2004), and according to previous measurements in these very dense shrubbery the flood flow velocity decreases to 0 m/s (Sándor and Kiss, 2007). Former researches were limited to the estimation of vegetation density (Chow 1959; Barnes 1967; Acrement and Schneider, 1989), they did not consider the role of invasive species, and they did calculated the influence of different floodplain management methods on flood conveyance, on peak flood levels, and did not model the role of invasive species on increasing flood hazard.

The aim of the present study is (1) to determine the long-term land use changes on the floodplain of the Lower Tisza River, and the effect of these changes on vegetation density; (2) to evaluate the role of the invasive *Amorpha fruticosa* in increasing vegetation density, and finally (3) to calculate the extent of flood level increase caused by the dense floodplain vegetation. The ultimate goal is to model the effect of two floodplain management scenarios on flood conveyance, thus what would happen if *Amorpha fruticosa* was cleared from the floodplain vegetation. The results of two different models (HEC-RAS and CES) will be compared to evaluate the reliability of the results.

STUDY AREA

The Tisza River is the second longest river in Hungary (length: 962 km, catchment area: 157,200 km^2). Since the middle of the 19th century the river has been significantly regulated, the formerly 5-10 km wide natural floodplain have been confined by artificial levees, thus today the active floodplain is just 1-4 km wide. Some bends have been cut off shortening the Tisza River by 457 km (32%). These affected the hydrology ad hydraulics of the river, the slope of the channel and the land-use of the floodplains.

The Tisza River is characterized by two floods, caused by early spring snow-melt and early summer rainfalls. The mean discharge of the Tisza River at Szeged gauging station is 810 m^3/s (maximum 4,346 m^3/s; Lászlóffy, 1982). As a result of the regulation works, flood levels have increased by 200-350 cm (Rakonczai and Kozák, 2009). The duration of floods on the Lower Tisza River is 54 days/year on average (Kiss 2014). Since the Tisza is a lowland river, its flood can be simultaneous with the floods of the tributaries or of the Danube, and they can block each other, thus long-lasting ad high floods could develop.

The mean water slope of the Tisza River is only 2.9 cm/km in the Hungarian section (Lászlóffy, 1982; Kiss, 2014). The bedload is fine sand (9,000 t/year; Lászlóffy, 1982), and the river transports a great amount of suspended silt and clay sediment (18.7 t/year; Lászlóffy, 1982). The average flow velocity is 0.1-0.15 m/s (Kiss, 2014).

The changes in vegetation density and flood conveyance were analysed on a 10 km long section (180-190 rkm) of the Lower Tisza River, north from the city of Szeged, at Algyő. The boundaries of the study area are not the borders of the natural floodplain, but the artificial levees built in the 19th century (Fig. 2). The mean channel width is 160 m, while the mean water depth is ca. 14 m, but during floods it could be as much as 19-20 m (Lászlóffy, 1982).

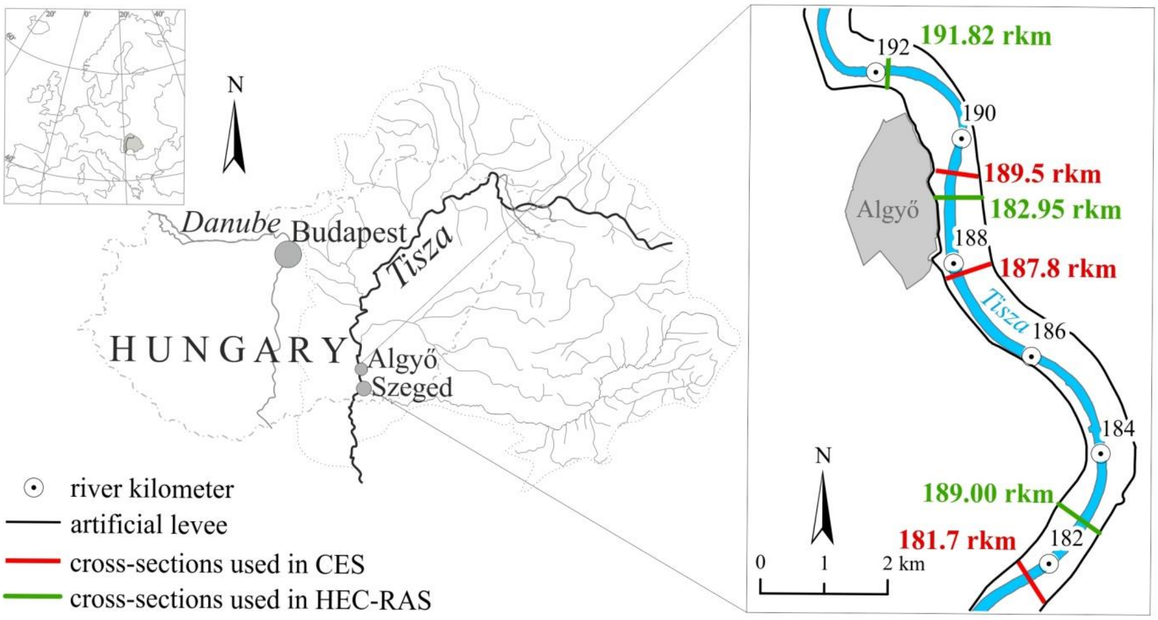

Fig. 2 Study area and the location of cross-section used in HEC-RAS and CES models

METHODS

The long-term land-use changes of the study area were analysed since the end of the 18th century, based on 1:28,000 scale maps of historic Military Surveys (1784, 1861-1864 and 1881-1884), a 1:10,000 scale topographic map (1980s), and Google Earth image (2017) were used. As a first step, the territory of the different land-use categories was determined on the geo-corrected spatial database. To evaluate the long-term impact of vegetation on surface roughness, the average roughness values ($n_{1\text{-}n}$) determined by Chow (1959) were assigned to each land-use category (Table 1). Then the average vegetation roughness of the study area at a given year (n_{year}) was weighted by the territory of each land-use category ($A_{1\text{-}n}$):

$$n_{year} = \frac{(A_1 \times n_1) + (A_2 \times n_2) + \cdots (A_n \times n_n)}{100} \qquad \text{Eq. 1}$$

Table 1 Applied land-use categories and their mean roughness values (Chow, 1959)

vegetation roughness category	land-use category	roughness coefficient
n_1	wetland	0.017
n_2	bare surface	0.018
n_3	forest	0.100
n_4	meadow, pasture	0.030
n_5	meadow, pasture with sparse trees and shrubs	0.050
n_6	orchard	0.050
n_7	arable land	0.040
n_8	artificial surface	0.013

As there are no previous data on the extension and density of the invasive *Amorpha fruticosa*, we mapped its density during the winter of 2017/2018 in three woody land-use categories: in forest plantations, in riparian forests and in abandoned arable lands, meadows and pastures where *A. fruticosa* has started to spread aggressively. The selected 15 plots represent the three land-use category quite well.

To determine vegetation density we used Warmink's (2007) photograph based Parallel Photographic (PP) Method, which could be used to calculate the area occupied by vegetation in a given volume. During the measurements photographs were taken in a quadrate (2 m x 3 m) in front a 2 m high and 3 m wide white screen (Fig. 3a), thus in a given quadrate the dark stems were well separated from the white background (Fig. 3b). After converting the photographs into black and white images (Fig. 3c), the area occupied by vegetation in front of the screen was be calculated. Inserting these calculated values into Equation 2 the vegetation density *(Dv_{PP})* in each quadrate was calculated (Warmink, 2007):

$$Dv_{PP} = -\frac{1}{L} * ln(1 - A_{tot}) \qquad \text{Eq. 2}$$

where L is the length of the white screen (3 m), and A_{tot} is the ratio of black pixels represented by vegetation. The Dv_{PP} is a non-dimensional value between 0.0 and 1.0. The vegetation density was calculated for two conditions: representing (1) the actual vegetation with *A. fruticosa*, and (2) an ideal, well-maintained condition without *A. fruticosa*. To calculate the latest, the *Amorpha fruticosa* stems were erased from the black and white images (Fig. 3d), and then vegetation density was re-calculated using Eq. 2.

The calculated vegetation density values were used in HEC-RAS (Institute for Water Resources, U.S. Army Corps of Engineers) and CES (UK Environmental Agency) models. The aim was to determine how flood conveyance would change in relation with vegetation density. During the modelling, we used the data of the 2006 record high flood (max. height: 1,062 cm; max. discharge: 2,720 m^3/s).

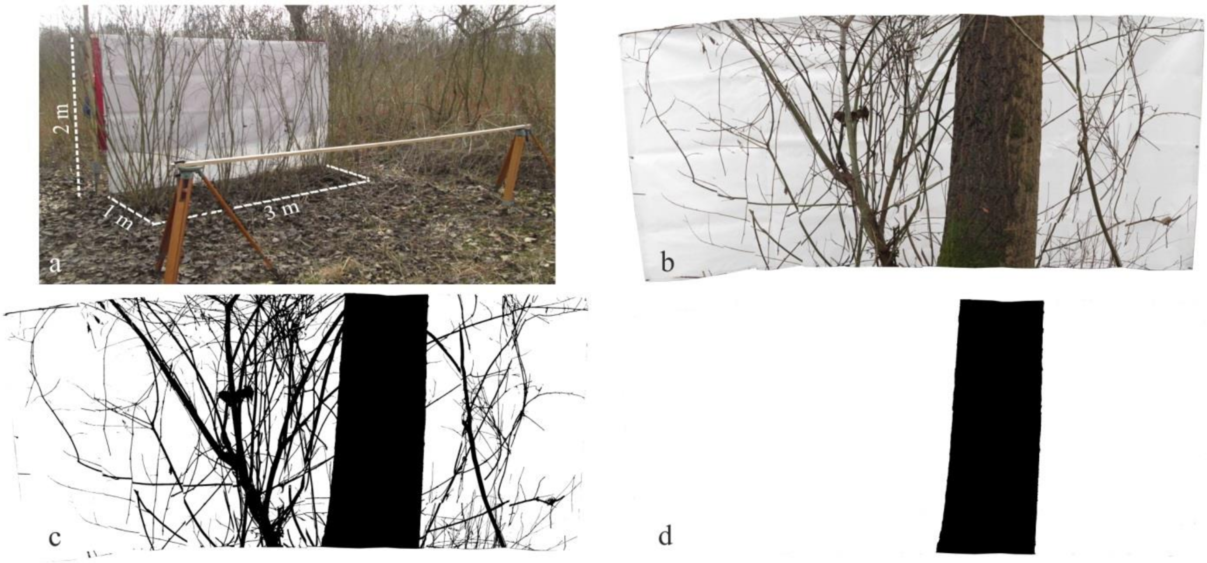

Fig. 3 Photographs of vegetation were taken from a track in front a whitescreen (3a), then the photos were mosaiced (3b). Finally black and white images were used to evaluate the vegetation density with Amorha (3c) and without it (3d*).*

In HEC-RAS, during the first run, the actual vegetation density values (n=0.23) were used to model flood levels, with ±10 cm accuracy. In the second run the vegetation density data of "ideal, well-maintained condition without *A. fruticosa*" was applied in the 10 km long section of the floodplain. This ideal conditions equals to *'pastures with high grass, cultivated areas with mature row crops, scattered brush, and cleared land with tree stumps and no stumps'*, where n=0.035 (Chow, 1959). The hydraulic effects of the decreased surface roughness were calculated at three cross-sections, at the upstream end, at the middle and at the downstream end of the 10 km long reach (Fig. 2). Finally, the temporal and spatial changes of the flood wave were analysed.

In the CES model the hydraulic changes also at three cross-sections were analysed, however no temporal analysis could be made, thus the model run just during the peak of the flood. The selected cross-sections were close to the ones in HEC-RAS (Fig. 2), but they were not identical. The surface topography was extracted from the 1:10,000 scale topographic map, while channel topography was provided by the Lower Tisza District Water Directorate (ATIVIZIG). The CES model – similarly to HEC-RAS – was run for two scenarios, (1) with the actual vegetation roughness with *Amorpha*, and (2) with ideal conditions without it.

RESULTS

Land-use of the floodplain along the Lower Tisza River has changed considerably in the last two hundred years (Fig. 4-5). At the time of the first survey (1784) the conditions refer to almost natural state, as it reflects the environment before the river regulation works and

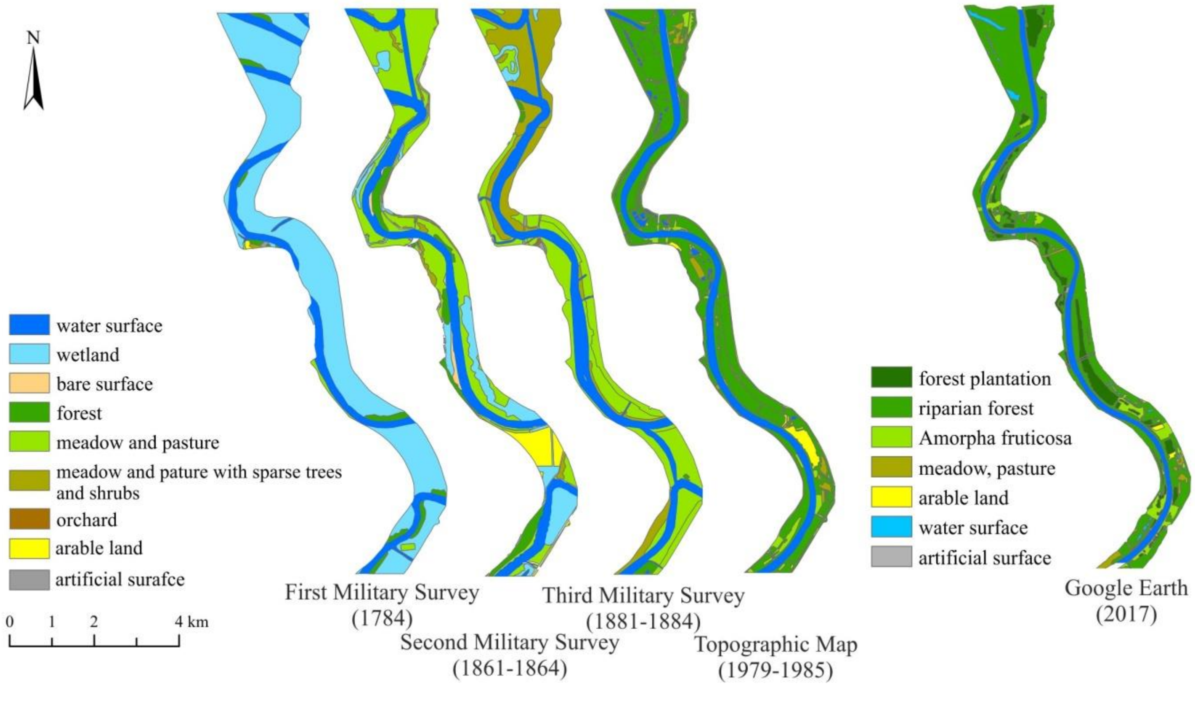

Fig. 4 Land-use changes of the study area since the late 18th century

artificial levee constructions. Most of the area (92%) was occupied by wetlands, where water covered the area almost permanently. The proportion of forests was only 5%, and their patches grow along the channel, where the overbank aggradation created higher surfaces. In the mid-19th century channel regulation works started. By the time of the second survey (1861-1864) two meanders were already cut off in the upstream part of the study area, though the third one in south was still untouched. Therefore, the artificial levee system at that time was not located at the same place as the present-day system. The proportion of wetlands decreased drastically (22%), and they were replaced by meadows and pastures (56%). The forests expanded moderately (9%), but they were still located along the riverbanks. Longer flood-free periods enabled some areas to be cultivated (proportion of arable lands: 7%). Two decades later (1881-1884) most of the wetlands had already disappeared (2%). Almost the whole study area was occupied by meadows and pastures (94%), but almost on half of their area trees started to grow. In contrast, the proportion of forests had decreased to 2%. One hundred years later (1980s) the vegetation cover of the study area had changed considerably, as the area of pastures and meadows became afforested, therefore their proportion decreased to 11%. Because of extensive poplar plantations, the proportion of forests increased to 78%. Nowadays (2017) the forested area of the floodplain increased further on (86%). Only some arable lands and grasslands remained (8%), however, according to our field survey three fourth of them have been abandoned and they are densely covered by *Amorpha fruticosa*.

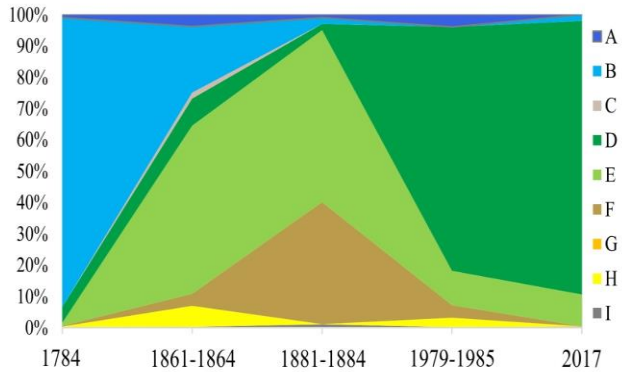

Fig. 5 Proportional changes of land use-categories since the late 18th century. I: 1784; II: 1861-64; III: 1881-84; IV: 1979-85; V: 2017; A: water surface; B: wetland; C: bare surface; D: forest; E: meadow and pasture; F: meadow and pasture with sparse trees and shrubs; G: orchard; H: arable land; I: artificial surface

Roughness values defined in the literature weighted by the proportion of land-use categories (see Table 1) reflect that the vegetation roughness of the floodplain has been increased since the late 18th century (Fig. 6). The vegetation roughness increased especially in the 1980s due to forest plantations, and nowadays because of the presence of *Amorpha fruticosa*. Overall, the mean vegetation roughness of the study area has increased from n=0.021 to n=0.14, thus it increased by seven times since the late 18th century.

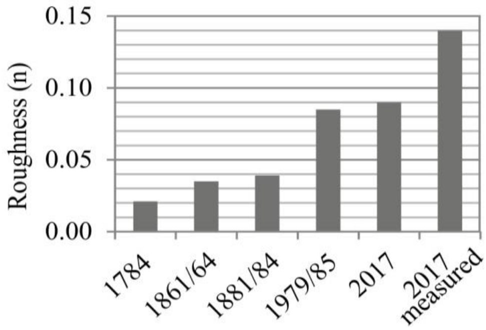

Fig. 6 Mean vegetation roughness of the study area based on land-use categories (1784-2017) and on PP-method (2018)

The role of Amorpha fruticosa in increasing vegetation density: results of Parallel Photographic Method

In the study area three woody vegetation types were identified and studied in detail. At present, riparian forests cover 71% of the study area. Due to the shading effect of the older trees, the abundance of *Amorpha fruticosa* is the smallest in these forests. Therefore, the invasive species increases vegetation density only by 3% on average (0-10%), depending on the amount of sunlight reaching the surface and the rate of disturbance. In these almost natural riparian forests the vegetation roughness is 0.13 on average (min: 0.06, max: 0.22), but without *Amorpha fruticosa* it would be 0.12.

Forest plantations occupy 15% of the floodplain, with trees of different age. Generally, in the first years after the plantations the undergrowth vegetation is managed to support the growth of the trees, but when the poplars grow above 3-4 m, the undergrowth is not managed any longer. Since the coverage of the foliage of planted forests is less closed, more sunlight could reach the surface, therefore older plantations, depending on the lack of management, could be invaded by non-native species. In the study area, *Amorpha fruticosa* increases vegetation density by 23% on average. The vegetation roughness of these forests is 0.10 (min: 0.07, max: 0.15), while without *A. fruticosa* vegetation roughness would decrease to 0.08.

In the floodplain of the Lower Tisza River *Amorpha fruticosa* increases vegetation density by the greatest degree on abandoned arable lands, meadows and pastures. The abandonment of these areas accelerated after the flood in 2006, when the floodplain was covered by ca. 6-8 m height water column for one week, and the inundation itself lasted for 104 days (Kiss 2014). This high and long flood destroyed the agricultural crops and destroyed some of the natural undergrowth. In addition, the flood period had started in 1998; therefore, farmers gave up cultivating these floodplain lands because of the returning annual loss. On these abandoned lands *Amorpha fruticosa* increases the vegetation density by up to 100%, but in less-invaded areas it contributes to vegetation density by 76% on average (min. 50%). Due to the presence of *A. fruticosa* the average vegetation density of abandoned lands is 0.12 (min: 0.09, max: 0.16), while without invasive species this value would be only 0.03.

Flood conveyance as a function of vegetation: results of HEC-RAS and CES modelling

The results of the two scenarios (unmanaged floodplain with n=0.23, and managed floodplain with n=0.035) run in HEC-RAS model suggest that the most significant changes in water levels appeared in the upstream cross-section (191.82 rkm; Fig. 7) of the 10 km-long study reach. In case of the No. 2 scenario the vegetation of the 10 km-long floodplain section is managed (cleared from *Amorpha*), thus the floodplain vegetation creates fewer obstacles (resistance) against flood flow. Therefore, the velocity of the flood is accelerated. In this case, the peak flood level decreases by 15 cm compared to the "unmanaged" scenario (n=0.035). The greatest difference between the hydrographs was 18 cm in the falling limb of the floodwave.

At the downstream cross-section (182.95 rkm) of the modelled 10 km-long reach, the processes are different from those of the upstream cross-section (Fig. 8). In the No.2. scenario this cross-section is located at the downstream end of the managed section, at the border between the managed and unmanaged vegetation (n=0.23). Thus the flood flow collides with the dense vegetation, and forced to flow through it. The resistance is combined with the small slope of the river and the backwater effect of the Danube. Though the flood peaks of the two scenarios slightly differ (±1-2 cm), during the falling stage the differences in stages increases (6 cm), though it is within the error of the model (±10 cm).

The cross-section (189.00 rkm) located in the middle of the study area is in the middle of the managed floodplain section in case of No.2. scenario. Here the processes described at the upstream and downstream cross-sections are combined (Fig. 9). Water level changes are similar to the ones at the upstream cross-section, but the peak water level decreases just by 6 cm in No.2. scenario. The greatest difference (9 cm) between the hydrographs was detected also in the falling limb of the flood.

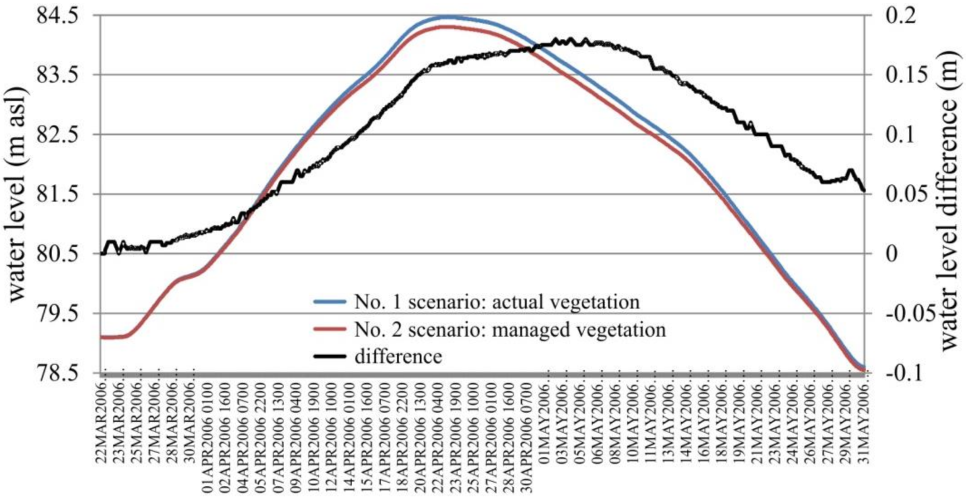

Fig. 7. Changes in water level at the upstream cross-section of the 10 km-long studied floodplain. The model was calibrated to the 2006 flood. The hydrograph of the No. 1. scenario (blue line) refers to the actual situation with unmanaged floodplain vegetation, while the No. 2. scenario refers to managed vegetation cover (red line)

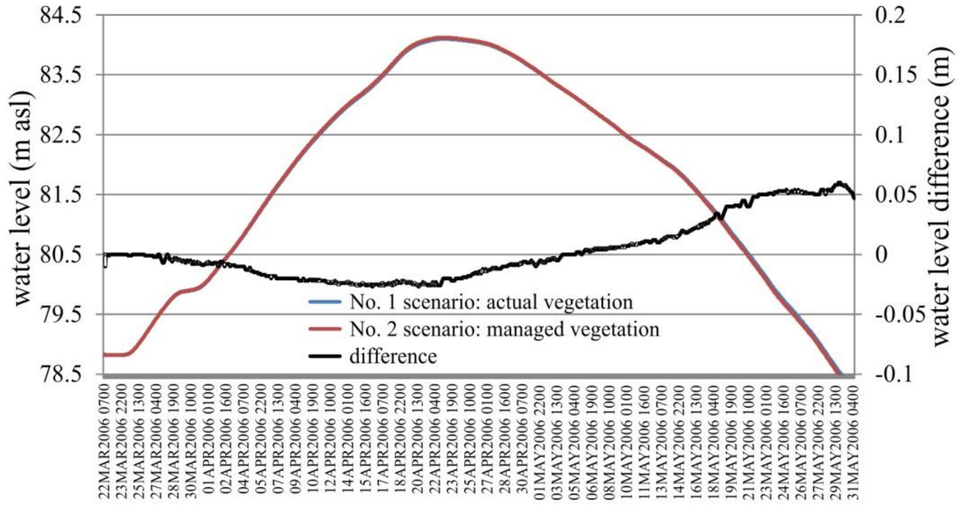

Fig 8 Changes in water level at the downstream cross-section of the 10 km-long studied floodplain. The model was calibrated to the 2006 flood. The hydrograph of the No. 1. scenario (blue line) refers to the actual situation with unmanaged floodplain vegetation, while the No. 2. scenario refers to managed vegetation cover (red line)

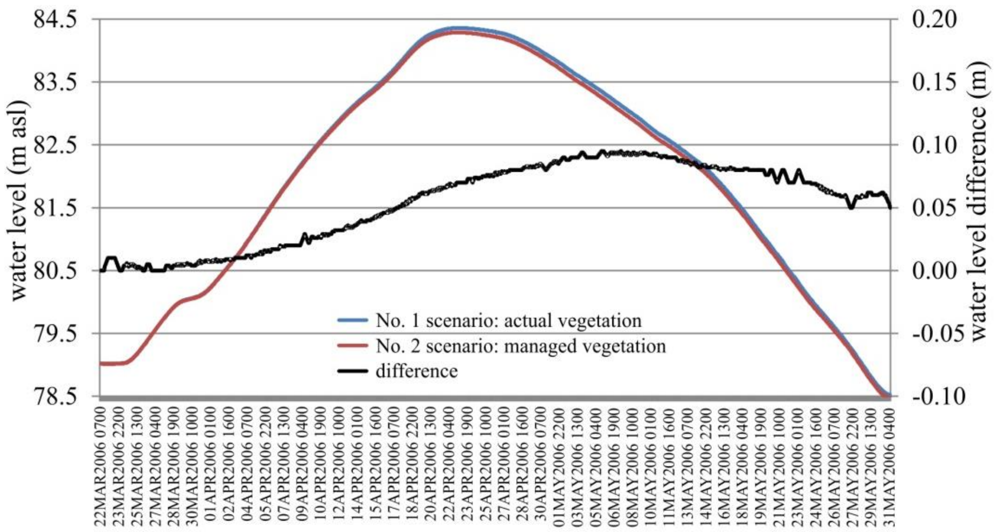

Fig 9 Changes in water level at the middle cross-section of the 10 km-long studied floodplain. The model was calibrated to the 2006 flood. The hydrograph of the No. 1. scenario (blue line) refers to the actual situation with unmanaged floodplain vegetation, while the No. 2. scenario refers to managed vegetation cover (red line)

The temporal differences in hydrographs are the greatest in the falling limb of the flood wave. It could be explained by the characteristic of the flood: the modelled 2006 flood has been the highest on the Tisza River and its peak lasted nearly for a week. This special characteristic was caused by back-water effect of the Danube, thus the flood wave of the Tisza River could fall just after the flood on the Danube had passed. Thus, the impoundment and the reduced flow velocity was just partly caused by the vegetation, but probably it was surpassed by the impounding effect of the Danube, Therefore the effect of vegetation roughness on flood flow could only became obvious in the falling limb of the flood wave, when the Danube had no longer had significant effect on the Tisza River.

The CES model gave similar result to the HEC-RAS model (Table 2; Fig. 10). The results of the three cross-sections slightly differed, because the rate of invasion by *Amorpha fruticosa* varied and the width of the floodplain was different too. At all three cross-sections *Amorpha fruticosa* contributed to vegetation density by the same rate (Dv_{PP} increased by 0.03). Because of the presence of *Amorpha fruticosa* the peak discharge of the flood resulted in higher water stage by 15.3 cm at the upstream and downstream cross-sections, while it was only 12 cm at the middle cross-section. Based in the CES model calculations the presence of *Amorpha fruticosa* decreased the mean flow velocity by 0.016 m/s. There is a slight difference in the decrease of discharge at a given (highest) water stage: at the upstream cross-section the discharge of the peak stage was decreased by 5.7% by the presence of the *A. fruticosa*, while at the downstream cross-section it was decreased by 6% respectively. The difference could originate from the floodplain width, as the floodplain is wider along the downstream section (770 m) than upstream (680 m). At the middle cross-section the invasive species decreased the mean flow velocity by 0.014 m/s, reduced the discharge of the peak stage by 4 %, and resulted in higher water stage by 12.1 cm of the same peak discharge.

DISCUSSION

In the present study we analysed the changes of vegetation cover on the floodplain of the Lower Tisza River, determined the role of the invasive *Amorpha fruticosa* in increasing the vegetation density of the floodplain, and modelled its role in reducing flood conveyance.

Long-term changes (1784-2017) of land-use on the floodplain of the Lower Tisza River suggest that at the end of the 18th century, before the river engineering works, most of the surface was covered by wetlands (92%). As a result of 19th century river regulation works the channel

Table 2 Main characteristics of the studied cross-sections, and the drop of water stages on case of managed floodplain, thus the clearance of Amorpha fruticosa (A.f.). HECpeak: during the peak flood modelled by HEC-RAS, HECfall: during the falling stage of the flood modelled by HEC-RAS, CES: during the peak of the flood modelled by CES

Cross-section (rkm)	floodplain with (m)	channel slope (cm/km)	land-use (%)		vegetation roughness (Dv_{PP})		decrease in water levels (clearing A.f.)		
			forest	meadow, pasture	with A.f.	without A.f.	HEC peak	HEC fall	CES
189.5	680	4	100	0	0.13	0.10	15	18	15
187.8	750	4	100	0	0.13	0.10	6	9	12
181.7	770	4	61	23	0.13	0.07	0	6	15

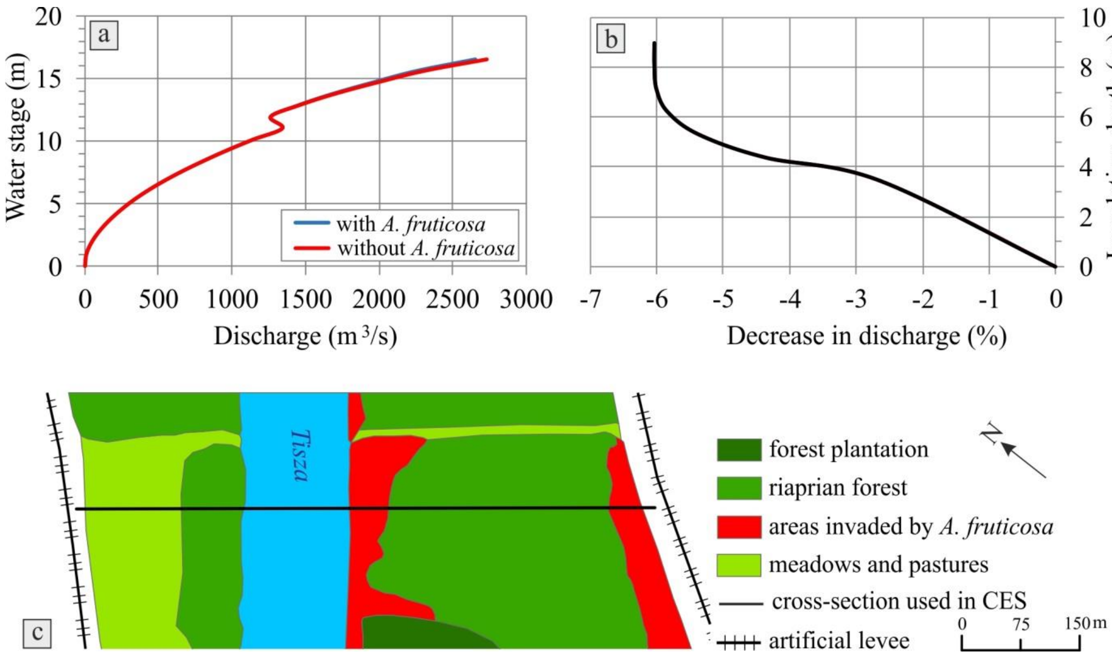

Fig. 10 Results of the CES modelling at the downstream cross-section (181.7 rkm). a) Discharge change at a given water level (from the lowest point of the channel bed) in the case of vegetation with and without Amorpha fruticosa; b) decrease in discharge on the floodplain due to the presence of Amorpha fruticosa; and c) land-use categories along the cross-section

incised, thus low water stages decreased (by 260-280 cm; Lászlóffy, 1982), which resulted in drier floodplain surfaces. Therefore, since the mid-19th century the wetlands were replaced by meadows and pastures (94%), and riparian forests (9%). Nowadays, most of the floodplain is covered by natural or planted forests (86%), while the proportion of meadows decreased to 2%. The vegetation roughness of the study area has increased fourfold since the late-18th century. This increased vegetation roughness has a significant impact on flood conveyance. Since similar land-use changes were observed on other floodplain areas of Hungary (Gábris et al., 2004; Sándor and Kiss, 2008; Oroszi and Kiss, 2006), it could be assumed that the vegetation has influenced hydrological conditions in a similar way.

However, the actual surface roughness is greater (0.14) than it was calculated from the land-use categories, due to the presence of invasive species, and because in the literature the impact of invasive species on vegetation density was not considered. Most of the meadows, pastures and arable lands are strongly invaded by *Amorpha fruticosa*, therefore 8% of floodplain surfaces are covered exclusively by *A. fruticosa*, but it has spread in riparian and planted forests as well.

Results of vegetation density calculations were used in HEC-RAS and CES models, to determine the role of two different floodplain management methods on flood conveyance. In the No.1. scenario the actual vegetation density (with *Amorpha fruticosa*) was applied, while in the No.2. scenario the Amorpha was cleared from the area, thus the floodplain vegetation was managed. The comparison of the two scenarios in HEC-RAS suggests that if the floodplain was managed properly and it was cleared from *Amorpha fruticosa* on the studied 10 km long reach of the river, at the upstream section water flow would accelerate because of reduced surface roughness, which would decrease water levels. Therefore, the level of the peak flood could be reduced by 15 cm according to the HEC-RAS and by 12-15 cm according to the CES. The downstream section of the managed floodplain is followed by an unmanaged area, therefore, its increasing vegetation roughness could decrease the flood conveyance and flow velocity by impounding the flood, thus at this section higher peak levels could occur (but it was under the error limit of the model). At the middle section the effects described above (i.e. increased and decreased flood conveyance) combined, therefore here the flood conveyance would be just slightly better, thus the drop of peak flood level is moderate (9 cm).

CONCLUSION

In the present study, we analysed vegetation density and its effects on flood conveyance with different methods. The Parallel Photographic (PP) Method was used to calculate the actual vegetation density in different land-use categories. The resulted vegetation roughness values are 1.5-fold higher than values given in the literature for the given land-use category. This can be explained by the very dense population of invasive species, since these species were not taken into account in the vegetation roughness values defined in the literature (Chow 1959), they gave only empirical values for natural vegetation cover. With the PP method, however, the vegetation density could only be measured in a small quadrate (6 m^2) and up to a height of 2 m; although during floods the floodplain is inundated by 6-8 m high water column. Further disadvantages of the PP method are low time efficiency and errors occurring during taking the photographs. In sunshine, the shadows of the stems and branches can modify the ratio of black and white pixels, the white screen can lean in wind, and the snow cover on the branches (since photographs were taken in winter) can also modify the number of black pixels. During photoprocessing errors can occur when the non-vertical stems are photographed from different angles, therefore after the photos are assembled these stems can appear several times on the photos. Based on our experience, however, these errors do not cause significant differences in the results.

Flood conveyance was analyzed in two hydraulic models. The advantage of the HEC-RAS model is that a real flood event could be modelled, and the spatial and temporal effects of various floodplain vegetation on flood conveyance could be analysed. Disadvantage of the model is that its setting up is time and data consuming. Besides, the characteristics and roughness values of the floodplain and of the channel, the hydrographs of a particular flood event are also needed along a long river reach (in our case it was 200 km) to keep the model stable.

Great advantage of CES model is that it is very easy to use, and it does not require large amount of input data. The hydrological processes on the floodplain, however, could be analysed only at during the flood peak and along one section, thus temporal and spatial changes in the processes could not be studied. Accordingly, the selection the most suitable cross-section on the floodplain is very important.

From the point of view of floodplain management it can be stated that by adequate vegetation management (i.e. removing invasive species, restoration of land-use with lower surface roughness) of longer floodplain sections flood stages could be decreased. The length of the managed area, however, may vary depending on the slope of the floodplain and the areal extension of impounded flow, since in short managed sections the effect of impoundment may distinguish the effect of better flood conveyance. Accordingly, clearing vegetation in patches would not have any detectable effect on flow conditions. The analysis, however, should be repeated on floodplain sections with different hydrological conditions, since the effect of vegetation on flood conveyance may vary based on slope, floodplain width and flood characteristics. Overall, reducing vegetation roughness coefficient by properly managing floodplains would have a positive impact on flood hazard, since flood waves would accelerate and peak flood stages would decrease.

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References

Acrement, G.J., Schneider, V.R. 1989. Roughness coefficients for densely vegetated flood plains. U. S. Geological Survey, Water-Resources Investigations Report 83–4247. DOI: 10.3133/wri834247

Antonarakis, A.S., Richards, K.S., Brasington, J., Muller, E. 2010. Determining leaf area index and leafy tree roughness using terrestrial laser scanning. *Water Resources Research* 46, W06510 DOI: 10.1029/2009wr008318

Barnes, H. H. 1967. Roughness characteristics of natural channels. USGS Water Supply Paper 1849, 213 p. DOI: 10.3133/wsp1849

Burkham, D.E. 1976. Hydraulic effects of changes in bottom-land vegetation on three major floods, Gila River in south-eastern Arizona. Geological Survey Professional Paper, 655-J, 17 p. DOI: 10.3133/pp655j

Catford, J.A., Jansson, R. 2014. Drowned, buried and carried away: effects of plant traits on the distribution of native and alien species in riparian ecosystems. *New Pythologist* 204(1), 19–36. DOI: 10.1111/nph.12951

Chow, V.T. 1959. Open channel hydraulics, McGraw-Hill, New York, United States. 364 p.

Coon, W.F. 1998. Estimation of roughness coefficients for natural stream channels with vegetated banks. United States Geological Survey, Water-Supply Paper 2441. DOI: 10.3133/wsp2441

Delai, F., Kiss, T., Nagy, J. 2018. Field-based estimates of floodplain roughness along the Tisza River (Hungary): The role of invasive Amorpha fruticosa. *Applied Geography* 90, 96–105. DOI: 10.1016/j.apgeog.2017.11.006

Devi, T.B., Kumar, B. 2016. Flow characteristics in an alluvial channnel covered partially with submerged vegetation. *Ecological Engineering* 94, 478–492. DOI: 10.1016/j.ecoleng.2016.06.018

Didham, R.K., Tylianakis, J.M., Hutchison, M.A., Ewers, R.M., Gemmell, N.J. 2005. Are invasive species the drivers of ecological change? *Trends in Ecology & Evolution*, 20(9), 470–474. DOI: 10.1016/j.tree.2005.07.006

Dumitrașcu, M., Grigorescu, I., Kucsicsa, G., Dragota, C., Năstase, M. 2014. Non-native and native invasive terrestrial plant species in Comana Natural Park. Case-studies: Amorpha fruticosa and Crataegus monogyna. *Romanian Journal of Geography* 55, 81–89

Freeman G.E., Rahmeyer W.H., Copeland R.R. 2000. Determination of resistance due to shrubs and woody vegetation. Technical Report, ERDC/CHL TR-00-25, US Army Engineer Research and Development Center, Vicksburg, MS. DOI: 10.21236/ada383997

Gábris, Gy., Timár, G., Somhegyi, A., Nagy, I. 2004. Árvízi tározás vagy árvízi gazdálkodás a Tisza mentén. (Flood storage of flood management on the Tisza River) II. Magyar Földrajzi Konferencia (CD kiadvány), 1–18.

Galema, A. 2009. Evaluation of vegetation resistance descriptors for floodplain management. Mater Thesis, University of Twente, Hollandia. 114 p.

Garssen, A.G., Baattrup-Pedersen, A., Voesenek, L.A.C.J., Verhoeven, J.T.A., Soons, M.B. 2015. Riparian plant community responses to increased flooding: a meta-analysis. *Global Change Biology* 21, 2881–2890. DOI: 10.1111/gcb.12921

Järvelä, J. 2004. Determination of flow resistance caused by non-submerged woody vegetation. *Intl. J. River Basin Management* 2 (1), 61–70. DOI: 10.1080/15715124.2004.9635222

Kiss, T. 2014. Fluviális folyamatok antropogén hatásra megváltozó dinamikája: egyensúly és érzékenység vizsgálata folyóvízi környezetben. (Changing dynamics of fluvial processes due to anthropogenic effects: assessment of equilibrium and sensitivity in fluvial environment) Academic doctoral thesis, Szeged, 164 p.

Lászlóffy, W. 1982. A Tisza. Vízi munkálatok és vízgazdálkodás a Tisza vízrendszerében (Tisza. Engineering works and water management in the Tisza river system). Akadémiai Kiadó, Budapest, 610 p.

Mihály, B., Botta-Dukát, Z. 2004. Özönnövények I. (Invasive species I.), Természet BÚVÁR Alapítvány Kiadó, Budapest, 366 p.

Oroszi, V., Kiss, T. 2006. Területhasználat-változás a Maros egy hullámtéri öblözetében a XIX. századtól napjainkig (Land use change on a floodplain section of the Maros River since the 19th century). *Tájökológiai Lapok* 4(2), 309–316.

Osterkamp, W.R., Hupp, C.R. 2010. Fluvial processes and vegetation – Glimpses of the past, the present, and perhaps the future. *Geomorphology* 116, 274–285. DOI: 10.1016/j.geomorph.2009.11.018

Planty-Tabacchi, A.M., Tabacchi, E., Naimann, R.J., Deferrari, C., Decamps, H. 1996. Invasibility of species-rich communities in riparian zones. *Conservation Biology* 10(2), 598–607. DOI: 10.1046/j.1523-1739.1996.10020598.x

Pyšek, P., Prach, K. 1993. Plant invasions and the role of riparian habitats: a comparison of four species alien to Central Europe. *Journal of Biogeography* 20, 413–420. DOI: 10.2307/2845589

Pyšek, P., Prach, K. 1994. How important are rivers for supporting plant invasion? *Ecology and Management of Invasive Riverside Plants* 19, 19–26.

Rakonczai, J., Kozák, P. 2009. Az Alsó-Tisza-vidék és a Tisza (The Lower-Tisza region and the Tisza). *Földrajzi Közlemények* 133(4), 385–395.

Rátky, I., Rátky, É. 2009. Lehetőségek a Tisza vízszállító-képességének javítására (Improvement possibilities of the water carrying capacity of the Tisza River). *Hidrológiai Közlöny* 89(1), 35–44.

Ree, W.O., Crow, F. 1977. Friction factors for vegetated waterways of small slope. Technical Report Publication S-151, US Department of Agriculture, Agricultural Research Service.

Samuels, P.G., Bramley, M.E., Evans, E.P. 2002. A new conveyance estimation system Proceedings 37th Defra Flood & Coastal Management Conference, University of Keele.

Sándor, A., Kiss, T. 2008. A területhasználat változás hatása az üledék-felhalmozódásra, közép-tiszai vizsgálatok alapján (The effect of land use change on sediment deposition, case study at Middle-Tisza). IV. Magyar Földrajzi Konferencia (CD kiadvány), 1–6.

Sándor, A., Kiss, T. 2007. A 2006. tavaszi árvíz okozta feltöltődés mértéke és az azt befolyásoló tényezők vizsgálata a Közép-Tiszán, Szolnoknál (Assessment of deposition rate of spring flood and its affecting factors on the Middle-Tisza, Szolnok). *Hidrológiai Közlöny* 87(4), 19–24.

Schnitzler, A., Hale, B. W., Alsum, E. M. 2007. Examining native and exotic species diversityin European riparian forests. *Biological Conservation* 138, 146–156. DOI: 10.1016/j.biocon.2007.04.010

Simonkai, L. 1893. Aradmegye és Arad város növényvilága (Vegetation of Arad county and Arad city). In: Jancsó, B. (ed.) Aradvármegye és Arad szabad királyi város monographiája I., Arad, 426 p.

Szigetvári, Cs., Tóth, T. 2012. Cserjés gyalogakác (Amorpha shrubs). In: Csiszár, Á. (ed.) Inváziós növényfajok Magyarországon, Nyugat-magyarországi Egyetem Kiadó, 121–126.

Takuya, U., Keiichi, K., Kohji, M. 2014. Experimental and numerical study on hydrodynamics of riparian vegetation. *Journal of Hydrodynamics* 26(5), 796–806. DOI: 10.1016/s1001-6058(14)60088-3

Vargas-Luna, A., Crosato, A., Uijttewaal, W.S.J. 2015. Effects of vegetation on flow and sediment transport: comparative analyses and validation of predicting models. *Earth Surf. Process. Landforms* 40, 157–176. DOI: 10.1002/esp.3633

Wang, C., Zheng, S., Wang, P., Hou, J. 2015. Interactions between vegetation, water flow and sediment transport: A review. *Journal of Hydrodynamics* 27(1), 24–37. DOI: 10.1016/s1001-6058(15)60453-x

Warmink, J.J. 2007. Vegetation Density Measurements using Parallel Photography and Terrestrial Laser Scanning. Master thesis, Utrecht University, Utrecht, The Netherlands, 83 p.