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ANALYSIS OF RIPARIAN VEGETATION BASED ON AIRBORNE LIDAR DATA

Thesis of Dissertation

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Szeged, 2023

1. Introduction, aims

Hydrological and geomorphological processes in the floodplains have been fundamentally altered due to river regulation and flood protection works. The lateral and vertical sedimentation in the Tisza floodplain has intensified, the vegetation cover has changed, invasive plants have spread, and the vegetation density and floodplain roughness have increased (Fiala and Kiss 2005, Sándor 2011, Amissah et al. 2018, Nagy et al. 2018ab; Kiss et al. 2019a; Vass et al. 2019). As a result of these processes the cross-sectional area of the channel and the floodplain has also decreased (Kiss et al. 2019b). Therefore, at the end of the 20th century, the hydro-morphological parameters of the river already indicated a loss of equilibrium, which was confirmed by the floods of 1998-2006 and the extremes of the following flood-free decade (Kiss 2014)

Recognizing the changes in the floodplain and the riverbed, the hydrologists and river managers have also started to work on the problem. The basis for preserving the successful flood protection is the Government Decree on the "Channel and floodplain Management Plan" (2014), which is based on Act LVII of 1995 on Water Management. In addition, the Management Plan provide a framework to change the floodplain conditions to achieve more favorable flood conveyance conditions. Several examples are already exist on the implementation of floodplain management in practice in Hungary (Sági 2015, Vizi 2021). However, the further development of the plans is needed, and to achive this more detailed and accurate data should be collected, and to explore the relationships is essential for the effective and sustainable floodplain and channel management for the wide range of stakeholders.

The forme, point-based researches (e.g. Oroszi 2009; Sándor 2011; Nagy et al. 2018b; Kiss et al. 2019a; Vass et al. 2019) suggest that the riparian vegetation in the Tisza's hydrological system has been significantly modified since the near-natural conditions of the 19th century, resulting in significant degradation in vegetation roughness. As a result, the riparian vegetation is increasingly contributes to rising peak water levels. Therefore, I hypothesize that the riparian vegetation fundamentally influences flood levels by reducing overbank flow velocity and declining the flood conveyance of the floodplains. However, only point-based observations on vegetation density exist and on the reduction of the water convey capacity of the floodplain (Oroszi 2009; Sándor 2011; Nagy et al. 2018b; Kiss et al. 2019a), but practically no data exists on its spatial (vertical and horizontal) changes.

However, in my opinion, one possible way to reduce flood risk and restore fluvial equilibrium is to manage riparian vegetation roughness. By appropriately management of the crucial riparian vegetation types (e.g., fallows, planted forests, invasive thickets), the flood conveyance capacity of floodplains could be improved, and the overbank sedimentation could be controlled. Thus the decline of the total floodplain cross-sectional area could be reduced, thus the flood conveyance could be ensured.

Problems related to riparian vegetation, i.e., land-use change, the explosive spread of invasive species, and a substantial increase in vegetation roughness, are typical for the entire length of the Tisza in Hungary (Vass et al. 2019; Gábris and Somhegyi 2003; Nagy et al. 2018a, Kiss et al. 2019ab). My general aim are (1) to determine the density of riparian vegetation by combining methods that could be applied to a larger area instead of the previously applied point-based data; (2) to use the data to model the overbank flow conditions in the floodplain; and (3) to make recommendations for appropriate floodplain management.

In my Ph.D. thesis, I set the following detailed aims:

Determination of the riparian vegetation types

-What statistical parameters can be used to identify the main vegetation types (i.e. riparian willow forest, mature poplar plantation, young poplar plantation, native poplar stands, Amorpha thicket, and open surface) in the floodplain based on the LiDAR point cloud?

-What is the precision with which the vegetation types can be distinguished? What are the weaknesses and strengths of the classification algorithm?

-What is the spatial distribution of the identifed vegetation types? Where are the Amorpha thickets and where do they form dense stands?

Determination of the density of riparian vegetation patches

-How dense is the vegetation at different flood heights?

-What is the typical vegetation density of the identified vegetation types?

-How does the vegetation density of the floodplain vary spatially?

Determination of the relationship between the vegetation density, flow velocity, and water levels in the floodplain

-How do flow velocity and levels vary under different floodplain management scenarios?

-Where are the flood conveyance corridors in the floodplain? How does the flow velocity vary in the flood conveyance zones under different floodplain management scenarios?

-How does the vegetation influence overbank flow velocity and flow conditions along meanders with different morphometric parameters?

2. Research methods

The vegetation types were classified using a decision tree-based classification algorithm. The vegetation density of the vegetation categories was determined by analyzing the reflectance ratios using the NRD method. The effect of vegetation density on flow conditions (water level and flow velocity) was modelled along meanders of different morphology using HEC-RAS 2D hydrodynamic software. The model was calibrated for the 2006 flood was validated for the 2000 flood based on water levels. Water velocities were validated based on overbank flow velocity measurements at different points of the floodplain during the 2006 flood (Sándor 2011).

2.1. Identification of the vegetation types in the floodplain

To perform the analyses on the point-cloud of a LiDAR survey (2015), I used Fusion 3.8 and ArcMap 10.6.1 software, and the classification algorithm – decision tree – was written in Python using the scikit-learn (0.22.1) library (Pedreagosa et al. 2011). Based on the decision tree, I determined the vegetation type of each pixel in the whole study area and validated the results with field measurements. As a first step in the study area delineation, I defined the vegetation types to be identified: open surface, Amorpha thicket, young poplar plantations, mature poplar plantations, riparian willow forest, and riparian poplar forest. The preliminary definition of the categories was based on previous field visits and the Forestry Web Map of Hungary. Based on field visits and available orthophotos, I assigned homogeneous vegetation study plots of 15x15 m pixel size, 40-50 plots per class. In the next step, I calculated the descriptive statistical parameters of the point cloud representing the vegetation at 15x15 m resolution (cells) using the GridMetrics tool of the Fusion program. In the next step, I parameterized the decision tree algorithm. The decision tree I used determined the values separating the classes based on the Gini index. The parameters of the decision tree were set automatically using the GridsearchCV module, taking into account (1) the maximum depth of the decision tree; (2) the minimum number of elements in the decision tree leaves; and (3) the minimum number of elements that determine the further subdivision of the decision tree leaves. I used the following parameters to perform the classification: canopy relief ratio, the standard deviation of height values, height value corresponding to 95% height, slope of the distribution curve of height points, and height value corresponding to the 99% height. To verify the algorithm's accuracy, I used a cross-validation technique widely used in solving machine-learning problems (Bengio and Grandvalet 2004). The accuracy of the decision tree developed for the learning domain based on the ten-fold cross-validation is 92%. I verified the classification accuracy by field measurements in the winter of 2019 when I took aerial photographs of 72 points with a DJI Phantom III Pro drone. Based on the field validation, the classification accuracy was 83%.

2.2. Determination of the riparian vegetation density

To determine the vegetation density, the LiDAR reflectance ratio was calculated at 15x15 m resolution per meter in different height zones (e.g., 1-2 m, 2-3 m), which represent the gradual flooding up to 5 m. For the calculations, I used the DensityMetrics function of Fusion software. The input data were the elevation model and the point cloud. The reflectance ratios of the different elevation zones were the basis for the density calculation following the NRD method (Seielstad and Queen, 2003). Accordingly, the number of points reflecting from the vegetation zone under study was divided by the total number of points reflecting from and below the vegetation zone. The calculations were performed in every meter, but in my study, I only analyzed in detail the zone between 1 and 5 meters above the surface, as the effect of vegetation density on flow velocity is critical in this elevation zone in the event of a flooding event in the study areas.

I further analyzed vegetation density in the previously identified vegetation classes. For each class, I calculated the median NRD density value (Dv_{50}) per meter (height zones), as this parameter is less sensitive than the average to outliers due to mixed pixels and classification errors. I also calculated the median of the upper (Dv_{10}) and lower decile (Dv_{90}) values per vegetation category to illustrate the extremes within them.

A distribution analysis of the density data was also performed to determine the vegetation density categories. The histogram is single-peaked and highly skewed (towards values less than 0.1). Such highly skewed and single-peaked distributions are best classified into categories using class boundaries following the geometric distribution (Francisci 2021; Li and Shan 2022). Based on the distribution curves and field experience in Mindszent and Algyő, I finally created five vegetation density categories: no undergrowth, sparse, medium, dense, and very dense.

2.3 Relationship between vegetation density, flow velocity, and water levels

For the hydrodynamic modeling of various vegetation density conditions, I used the HEC-RAS 2D model, calibrated for the 2006 flood wave and validated with the 2000 flood wave for water levels, and validated water velocities for the 2006 flood wave based on measurements by Sándor (2011). The modeling aimed to analyse the effect of vegetation density on water levels and velocity. The model was built by incorporating geometry data (topography, roughness), specifying hydrological boundary conditions (water level and discharge), and performing calibration runs and validation. The model geometry was based on a topography model that included elevation data of the floodplain and the channel. Correct input of the geometry data and Manning's roughness coefficients is crucial for the study's accuracy, as it characterizes the water conveyance capacity of the floodplain and the channel. The values of roughness can vary widely and depend to a large extent on different environmental factors, such as the channel material, the channel surface, in-channel vegetation, the channel contour, and the quantity and quality of sediments. The vegetation of the floodplain is also a significant factor, and structures (bridges, embankments) also affect roughness (Chow 1959).

During the modelling altogether four model variants were created to show the effect of vegetation density on flow conditions. The base scenario (S_current) corresponds to the current state of the riparian vegetation and thus includes spatially assigned roughness values based on LiDAR data and roughness values determined from literature data. In the S_maintained scenario, I modeled what would happen if the current dense to very dense understory vegetation patches (mainly overgrown with invasive species) were maintained by eliminating the invasive understory vegetation. Within the least desirable scenario (S_invasive), the situation would worsen compared to today due to further expansion of invasive species, abandonment of agricultural fields, and unmanaged forests. Thus, very dense undergrowth would replace the patches with dense, medium and sparse undergrowth. Within the model variant with the lowest roughness (S_meadow), the entire floodplain is covered by low grassland. This scenario represents a significantly different riparian state, which is close to the pre-regulation conditions: both study areas were either covered by marshes or wet meadows, according to First Military Map.

The modeling covered the period from 5 April to 5 May 2006, when the floodplain was fully inundated. In addition, the highest water level was almost at the top of the levees (water cover averaged 5-6 m), making this period the most ideal for studying the impact of riparian vegetation on flood conveyance. The upper boundary condition was discharge, and the lower boundary condition was set as water level. As the flow conditions were the most relevant model output data from the point of the research objectives, I used the SW Momentum algorithm with the full solution formula, which is capable of modeling more complex flow conditions with increased computational power.

During calibration, the 2D flow models for the 2006 flood were calibrated using hydrographic data and the spatial distribution of undergrowth. The calibration of the models was based on the water level recordings on the levees at the peak of the 2006 flood. The longitudinal profiles show that the model adequately represents the developed water levels, with the largest deviations in the upstream part of the modeled area (Mindszent -9 cm, Algyő -7 cm). Therefore, only the central part of the modeled areas (Mindszent: 214-211 rkm; Algyő: 184- 181 rkm) was analyzed in detail, where the accuracy was within ±5 cm.

The calibrated model was validated using the hydrological data at the peak of the 2000 flood. For the validation, the model data calibrated by KÖTIVIZIG for the 2000 flood event were used as boundary conditions, as well as the land cover data produced for the period. The vegetation data were estimated from a 10 cm resolution orthophoto taken in 2000 and provided by ATIVIZIG. The values of the control fit (2000 flood water level record values and the 2000 flood modeled water level) at flood peak did not give a good match, as the discrepancies exceeded 20 cm in several places. Possible reasons for this are (1) the difference in average water depths during the floods under study and (2) the increase in vegetation density between 2000 and 2006. Taking this into account, the Manning's roughness coefficient values determined for the forested areas were uniformly reduced in the validation. The measured and calculated water levels along the entire length of the river sections under study showed a very good agreement, with differences of less than 10 cm.

Based on the measurements of Sándor (2011), I was able to validate the model not only for water level but also for flow velocities, using a total of 23 measurement points. The measurements were made at Mindszent, on the eastern floodplain section by Andrea Sándor and Tímea Kiss on 30 April 2006, at a water level of 1018 cm, eight days after the peak of the flood wave. Comparing the data of the field measurements to the modelled ones, the average difference between the modeled and measured velocities was only 0.1 m/s, which, considering the accuracy of the instrument, is acceptable. The largest discrepancy was 0.3 m/s when the modeled velocity was 0.42 m/s instead of 0.12 m/s. There were also six measurement points (i.e., more than a quarter of the measurements) where the discrepancies were within ±0.01 m/s.

3. Results

1. The vegetation types of dense riparian vegetation can be determined with high accuracy based on LiDAR surveys and using machine learning methods. The decision tree algorithm used can be used to classify forests (on Lower Tisza: riparian willow, riparian poplar, matrure poplar plantations, and young poplar plantations) and can well distinguish open surface and Amorpha thickets.

In a very dense vegetation, there is a theoretical risk that the dense canopy may make the lower levels barely visible on the LiDAR point-cloud, which may result in inaccurate classification. Nevertheless, the accuracy of my classification (83%) is in line with the literature, as similar results have been obtained in areas of dense riparian shrubs. For example, in floodplain forests, Saarinen et al. (2013) achieved 72.6% accuracy when classifying mobile laser scanner data, while Michez et al. (2016) obtained 79.5-84.1% accuracy when analysizing drone-derived point clouds, and in shrubland, Madsen et al. (2020) achieved 86.9-95.2% classification accuracy when classifying aerial LiDAR data.

In the Mindszent study area, forests cover 74.1% of the floodplain, and here the most common vegetation category (32%) is mature poplar plantations. In contrast, the proportion of forests in the Algyő study area is 81.4%, dominated by riparian willow forests (38.2%). Thus, the area of forests is in agreement with previous measurements in Lower Tisza (Kiss et al. 2019b; Nagy 2020), but the method I used also allows to identify the type of the forest. The results are useful for modelling, planning, and nture conservation, as the metod provided an accurate high-resolution image of the riparian vegetation in raster or vector form.

2. Based on the LiDAR point-cloud it is possible to determine the NRD (Normalized Relative point Density) values of the identified vegetation categories within the inundated height zones, and the vegetation density could be accurately determined at a given date, even in such a dense vegetation as the riparian vegetation in the Tisza's floodplain.

Most forests in the study areas (in Mindszent: 48%; in Algyő: 62%) belong to the medium or higher density categories. Within this, one-third of the study areas (in Mindszent: 28%; in Algyő: 37%) have dense or very dense undergrowth. The spatial analysis shows that the dense vegetation patches are along the banks, especially in abandoned forests or fallow lands. Our field observations confirmed that the increased understorey density is mainly due to the invasion of *Amorpha fruticosa* and other invasive plants, which almost entirely displaced the native shrub layer. Although Sándor (2006) and Delai et al. (2018) came to a similar conclusion based on their analysis of a few points, my study confirmed that the spread of floodplain species is causing a significant increase in understorey density all across the study areas, and I also demonstrated that this is not spatially uniform.

The applied method allows the precise delineation of vegetation patches that impede flood flow, which, in areas as large as the floodplain, can help to plan vegetation management and to monitor it by the authorities.

3. Based on the created vegetation density maps, the spatial extent of vegetation roughness within the Manning roughness coefficient can be accurately and up-to-date determined for each flooded height zone.

According to my results, in the 1-2 m height zone, the voxels of the Amorpha thickets have the highest density value (NRD_{50}: 0.051). In the same height zone, the understory of the riparian willow forests is almost half as dense (NRD_{50}: 0.029). In contrast, the median density value in this zone of the mature poplar plantations (NRD_{50}: 0.024) is a further 17% lower than the value measured in the riparian willow forests and 53% lower than in the Amorpha thickets. The median density in riparian poplars ($NRD50$: 0.021) is 28% lower than in riparian willow forests, and 59% lower than in Amorpha thickets. The lowest vegetation density value was measured for young poplar plantations with intermittently maintained undergrowth (NRD_{50}:0.007).

The variation in density of the different vegetation categories in the different altitudinal zones could be explained by their characteristic association and branch structure. Due to the lack of natural regeneration of the forests and the displacement of native shrubs, the shrub layer is now dominated by Amorphas. Its typical height is ca. 3 m, although older specimens can reach higher. In Amorpha thickets and patches of forests invaded by Amorpha, especially at their edges where there is sufficient light, the vegetation is very dense at the flood level of 1-3 m. Above this height zone, the canopy of riparian willow forests and native poplar patches in the 3-5 m height zone makes the zone dense. Due to the sparse branches of the poplar plantations and the clearance of the undergrowth of young stands, these patches have the lowest vegetation density at each height zone.

The primary hydrological function of low-gradient, low-lying floodplains is to support flood conveyance. In this context, I have calculated the return period of overbank floods that may inundate the analyzed height zones (1-5 m). The dense vegetation patches occupy the largest area (39%) of the analyzed floodplain in the 1-2 m elevation zone in Algyő, and thus, together with the very dense vegetation class (12%), they cover half (51%) of the study area. This height zone could be flooded every two years or so, slowing down the 550-650 cm high flood waves. The data also show that these relatively frequent, but low floods may be slowed down quite effectively by the dense undergrowth. Due to the proximity of the study areas, the vegetation roughness conditions of the two areas are similar, besides, there is no any hydrological influencing factor that would lead to different results.

I concluded, that the orthophoto-based methods do not provide an accurate assessment of vegetation density, as they show the top of the canopy and not the understorey density, while field measurements can only provide point data in small and accessible areas. However, with the method I have presented, it is possible to analyse the actual vegetation density over a large area.

4. Based on the modeling of different vegetation densities in the floodplain, the more dense the riparian vegetation is, the more it increases the peak water levels (Mindszent +24 cm, Algyő +18 cm), decreases the area average water velocities in the floodplain (from 0.41 m/s to 0.17 m/s), and increases the average water velocities in the channel (from 0.59 m/s to 0.98 m/s).

The modeling suggests that along a cross-section in the middle of the study area in Mindszent (213.4 rkm), if the understory vegetation in the forests were maintained (Sz_maintained), at peak of the flood level the difference between the S_current and Sz_maintained scenarios would reach 10 cm, i.e., forest maintenance would decrease the peak flood levels by 10 cm in the study area. The impact of dense forests with dense undergrowth on water levels is illustrated by the hydrograph of the

S_invasive scenario, which resulted in 7 cm higher water levels at peak compared to the S_current scenario. In an ideal case, when pastures or meadows would cover the floodplain in Mindszent, there would be a 17 cm decrease in water levels at peak compared to the S_current scenario. Comparing the changes in water level at Algyő (182.6 rkm) with the changes at Mindszent, it becames clear, that the hydrographs of the flood wave are almost identical in the two study areas due to the low slope of the Tisza and because the same factors influence the processes in both areas. In the S_maintained scenario, the water levels are 6 cm lower than in the S_current scenario. At the same time, in the Algyő study area, a further increase in the density of forest undergrowth (S_invasive) would increase the water levels by 6 cm. In the S_meadow model variant, the water levels would be 12 cm lower than in the current situation.

If the dense and very dense understorey vegetation in the Algyo study area were maintained (S_maintained), during the peak of te flood the average overbank flow velocity would increase to 0.28 m/s, i.e., the average velocity in the floodplain would increase by 16%, thus the flood conveyance could be improved. The worst flood conveyance conditions would be in case of dense undergrowth in the forests and oerall spread of invasive species (S_invasive). During the peak of the flood, there is a 30% decrease in overbank flow velocity between the S_invasive (0.17 m/s) and S_present (0.24 m/s) scenarios. If the studied floodplain was entirely covered by meadows or open surfaces (S_meadow), the mean overbank flow velocity at the peak of the floood would increase to 0.41 m/s, being higher than the baseline (S_current) by 68%.

The in-channel flow velocity is closely related to the overbank flow velocity, as the scenarios reflect decreases flow velocity in the channel if the flow velocity increases in the floodplain. In the S_maintained scenario, the average flow velocity in the channel at the peak was 7% lower (0.8 m/s) than in the baseline scenario (0.86 m/s). In contrast, as the density of undergrowth increases (S_invasive), the average velocity in the channel increases from 0.86 m/s to 0.98 m/s at the peak of the flood, which is 14% higher than in the S_current scenario. In the scenario of S_meadow, the entire width of the floodplain can effectively convey the oberbank flood, thus the mean in-channel flow velocity (0.59 m/s) at the time peak of the flood is lower by 32% than in scenario S_current (0.86 m/s).

5. A loop curve describes the relationship between the in-channel and overbank flow velocities, and the relationship between them changes at the peak of the flood wave.

As the density of vegetation in the floodplain increases, the loop curve shifts towards the axis of in-channel velocities (anti clockwise direction); thus the in-channel flow velocities increase simultaneously to the increase in vegetation density.

In the rising limb of the floodn (first part of the curve), velocities in the channel hardly change, while overbank flow velocity intensely increases, as the floodwave spreads in the floodplain. After the inundation spreaded onto the floodplain, the increase in channel flow velocity becomes more intensive in the function of vegetation roughness. At the peak of the flood the curve inverts, and during the falling limb of the floodwave the velocities decreas both in the floodplain and in the channel. During the most intensive decrease of the flood, most of the water starts to move in the channel, where velocities start to increase, while they slowly continue to decrease in the floodplain.

6. The overbank flood follows characteristic flow paths depending on vegetation density. The lower the vegetation density of the riparian zone, the wider the path of the intensively moving water and the higher the flow velocity towards the distal parts of the floodplain.

The water flow on the floodplain is influenced mainly by crevasses and scroll bars that support the flood conveyance, but the higher forms (e.g., natural levees, artificial barriers) block or divert water movement. In the current scenario (S_current) in the Mindszent study area, the flow velocity in the estern floodpain with dense understory vegetation on the river bank allows only 0.1-0.2 m/s overbank flow velocity even during the peak, and the high vegetation roughness forces the water to flow by the foot of the artificial levee. In a sparse poplar plantation, especially in its low-lying areas (formerly plowed pits), the flow velocity reaches 0.5-0.6 m/s. Thus, the channel in the middle of the floodplain and the tree lines can effectively influence overbank flow direction and velocity in this situation. The typical flow velocity in the channel is 1-1.1 m/s. The water enters the floodplain via several crevasses, and one of them leads the water into an agricultural field with low roughness, therefore here high flow velocities (0.4-0.5 m/s) evolve. In contrast, in areas with dense and very dense undergrowth, the velocity of the water flow slows down to 0.1-0.2 m/s.

In the Algyő study area the flow velocities differ only by 5-10% compared to the Mindszent area, due to the different bank geometry and vegetation. The distribution of flow velocities is more uniform along the straight section of the Tisza, and due to the downstream location of the Algyő site the retreat of the water started later. The comparison of the sites shows, that vegetation is the most crucial factor influencing overbank flow velocity, though it is also influenced by topography (e.g. crevasses, clay-pits, deep-lying areas) and floodplain width.

For future planning, it is advise to create and maintain conveyance belts, where the overbank flow is not blocked by any obstacles (including vegetation) and by managing the vegetation along these belts water flow is promoted. This could also positively impact the riverbed processes by reducing the in-channel velocity and the resulted incision.

7. Dense vegetation on the floodplain is undesirable from a flood protection point of view, because it increases the peak water levels and influences the overbank flow velocities in an undesirable direction.

The analyzed scenarios (S_maintained, S_invasive) show that the further spread of invasive riparian species and the resulted increase in vegetation roughness would further increase flood levels (Mindszent +7 cm, Algyő +6 cm), while the maintenance of vegetation would reduce them (Mindszent –10 cm, Algyő –6 cm). However, the fact that the water level would rise "only" by 7 cm due to unmanaged undergrowth shows that the floodplain is already dominated by dense shrub vegetation, consists of mainly invasive species. If short grass meadows and pastures were to cover the floodplain in the study areas, a flood wave similar to the record high flood of 2006 would result in a water level decrease by 17 cm at Mindszent and 12 cm lower level at Algyő. This flood peak reduction is significant since in some places the 2006 flood reached the top of the artificial levee.

The dense vegetation on the floodplain and especially along the banks, creates overbank flow zones with high water velocities at the foot of theartificial levees (0.5-0.6 m/s) and in the channel (1-1.2 m/s). This is disadvantageous from the point of flood protection, as the high flow by the levee can support its breaching (Altinakar et al. 2008). In the floodplain, the slow overbank flow results in accelerated accumulation (Sándor and Kiss 2008; Nagy et al. 2018b; Kiss et al. 2019b), and this further increases flood levels (Kiss et al. 2019a). In the channel, high water velocities increase incision, which makes it more difficult to withdraw water during low flows, and reduces the groundwater levels especially during droughts (Lóczy et al. 2016).

8. The management of riparian vegetation (e.g., removing invasive species, and creating lower vegetation roughness conveyance belts) can reduce peak flows effectively only if longer river sections (more than 10 km) are managed.

Based on the results of my modeling on the Maros, Middle and Lower Tisza (Nagy et al. 2018b, Kiss et al. 2019), the impact of the management on flood water levels depends on the size of the managed floodplain area and the slope conditions of the reach. In the Lower Tisza, vegetation maintenance over a 10 km long floodplain section could decrease the flood levels by 22 cm in the upstream end of the maintained area. In contrast, the Maros has higher slope, thus the flood level decrease is more effective (–34 cm) in the upstream section of the managed area. However, it must be noted that the peak reduction decreases towards downstream. Thus, at the downstream end of the managed section, only 2 cm of low water level decrease could be achived along the Maros. But in case of the Lower Tisza, and impundement effect was detected at the downstream end, thus here water level became 5 cm higher than before maintenance, as the very dense vegetion downstream of the managed section impedes flow.

Thus, if only patches are maintained on the floodplain, no significant impact on water conveyance could be predicted, and therefore floodplain management needs to be planned comprehensively over large areas. The LiDAR and machine-learning-based classification methods can be effectively used to generate these plans, which in combination with 2D hydrodynamic modeling, can provide accurate information on the effects of interventions and the extent of impacts.

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