**Modelling riparian vegetation management in Central Italy river**

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# ABSTRACT

Over the last centuries streams and rivers were managed with the main purpose of achieving drainage and flood control, with the reduction of hydraulic roughness and minimally obstruction of the flow, removing and impoverishing native riparian vegetation, causing flood peaks increase and flood wave travel time decrease.

This study focuses on the evaluation of the hydraulic effects caused by the application of different management techniques carried out in a vegetated river; the considered scenarios regard radical or severe cut and an alternative or selective cut, with the aim of simulating the interaction between flow hydrodynamics and riparian vegetation, in particular in terms of peak discharge and flood conveyance.

The proposed methodology is applied and tested along the Ombrone Pistoiese River in Tuscany.

Water flow resistance caused by rigid riparian vegetation along the reach were calculated on the base of measurements collected during two field campaigns, conducted in 2018 and 2022, before and after the severe management cut. The main morphometrical vegetation features (i.e., stem diameters and overstorey density) have been measured at different cross sections of the vegetated reach.

Hydraulic simulations in the 4.4 km modeled reach showed a wave celerity decrease up to 15%, due to the presence of surveyed riparian vegetation, potentially causing a delay of the flood up to 20 minutes.

Hence results suggest that there is considerable advantage in managing riparian vegetation with a less impacting technique, both to alleviate downstream flooding and also preserve riparian ecosystem.

We adopted three different formulations for each type of vegetation. For shrubby vegetation we used Jarvela's (2004) equation, that requires the Leaf Area Index (LAI) as input parameter. For herbaceous vegetation we adopted the formulation in the case of fully submerged herbaceous vegetation developed by Nepf (2012). Finally, for woody, rigid vegetation we considered the formulation developed by Baptist et al. (2007), which considers the rigid stems contribution calculating the roughness coefficient as a function of stem diameters, spatial density and water depth. Roughness coefficients obtained for cross-subsections were subsequently used to calculate the equivalent Manning’s value for each cross-section. Results showed that the higher intensity management techniques worsened the flood risk after few years after the cut, where low intensity or selective thinning would have had a lower impact.

**Keywords:** riparian vegetation management; one-dimensional hydraulic modelling; flow resistance; flood attenuation

# INTRODUCTION

Riparian zones are a vegetation interface between terrestrial and aquatic ecosystems along inland watercourses, lakes, reservoirs and other aquatic systems, that either affects and is affected by the presence of water (Fischer and Fischenich, 2000; Naiman et al., 2010). Vegetation in riparian zones plays several roles, as it controls channel morphology, maintains a favorable habitat for aquatic organisms and improves river water quality (Tabacchi et al., 1998; Perucca et al., 2007). Hence, riparian areas and their vegetation have been studied by multiple scientific and applied disciplines: hydrology, biology, geology, remote sensing, management and restoration (González et al., 2015). However, conceptual and methodological improvements are required to support sustainable management practices (Tabacchi et al., 2000), especially when focusing on the role of riparian vegetation on flood risk.

From a hydraulic perspective, previous studies demonstrated that increased roughness along a river reach attenuates the peak discharge at the catchment outlet and delays the arrival of the peak discharge, increasing flood wave travel times (Woltemade and Potter, 1994; Anderson et al., 2006; Ghavasieh et al., 2006; Thomas and Nisbet, 2007; Sholtes and Doyle, 2011; Dixon et al., 2019). Furthermore, Acreman et al. (2003) and Leyer et al. (2012) suggested floodplain rehabilitation and riparian-forest restoration as a valuable part of the flood management strategy of a catchment, reducing flood risk downstream. To better support the application of these concepts in the practical management of rivers, a detailed modelling of the role of vegetation on flood risk at the reach scale is essential.

In literature several analytical methods are available to determine roughness in vegetated riverbeds. Those methods make a distinction between fully, partially or non-submerged vegetation, and between flexible or rigid vegetation (Petryk and Bosmajian, 1975; Gwinn and Ree, 1980; Kouwen, 1992; Morgan and Rickson, 1995; Freeman et al., 2000; Järvelä, 2002, 2004; Baptist et al., 2007; Västilä, 2011; Nepf, 2012). Furthermore, to take into account the roughness variability along the wetted perimeter, several formulations have been proposed in literature to calculate the equivalent roughness, considering that each section can be divided in many regions with different values of Manning’s n (Djajadi, 2009).

Assessing vegetation flow resistance is fundamental for the evaluation of flood risk in vegetated rivers. Despite the relevance played by riparian vegetation-related roughness in the analysis of hydraulic processes, in hydraulic modeling roughness coefficients are often assigned by practitioners as a constant parameter based on reference tables taken from literature. In fact, riparian vegetation management is often poorly supported by an accurate evaluation of the effective influence of vegetation on flood risk, which by the way represents the main motivation of the management itself. Notwithstanding the lack of information regarding the role of vegetation in the flood dynamics of a river, maintenance practices along watercourses have historically involved severe management of riparian vegetation to achieve higher conveyance by the reduction of hydraulic roughness (Darby, 1999; Jakubínský et al., 2021).

The aim of this work is to introduce an alternative approach to riparian vegetation management, based on the preliminary evaluation of flood dynamics under different conditions of vegetation density. The present work pints at demonstrating that the most sustainable management approach needs to be based on the analysis of flow parameters under different vegetation scenarios rather than on the simplistic approach of maximizing river conveyance to reduce local flood risk.

The selected study case is the Ombrone Pistoiese River, where we analyzed the real-scale effects on the global flow resistance of different management practices carried out by the local land reclamation authorities along the 4-km long final reach of the river. More in detail, we performed a series of 1D ecohydraulic unsteady numerical simulations of the vegetated reach, repeated for different vegetation scenarios.

# THE CASE STUDY: OMBRONE PISTOIESE RIVER

The Ombrone Pistoiese River is one of the main right-side tributaries of the Arno River (Figure 1a), joining it after flowing across the populated Pistoia-Prato plain. It has a catchment area of 489 km2, a length of about 47 km and it constitutes the primary collector of the waters of the whole plain that extends from Pistoia to the Prato area, an important urbanized area located few kilometers West of Florence.

[FIGURE 1]

This plain, densely inhabited and rich in industrial settlements, plays a strategic role for the regional economy. Therefore, the impact of human settlements on the catchment is very relevant. Due to an historical urbanization pressure, the river has been straightened and embanked for a long reach of its length. The study area is located at the final 4.4 km reach of the river, from the Castelletti bridge to the confluence with the Arno River (Figure 1b).

In this area, the river flows through mainly agricultural and rural areas. Riparian vegetation that gradually is usually thinned, mowed, and totally removed with the sole purpose of maximizing the river conveyance operating with fast and heavy machinery (Figure 2). Precisely because of this simplistic management method, the riparian ecosystem has been deteriorated over time. The clear cut is carried out with an excavator with shredder head, that seriously compromises the tree stumps’ resprout, bringing to a poor vegetation recovery and heavy ecological consequences, mainly due to the colonization of invasive alien species in place of locals.

[FIGURE 2]

Currently, the autochthonous tree vegetation (mainly willows and poplars) is distributed discontinuously in small, dense groups along the riverbanks. As the vegetation resprouts from the few vital stumps and the plants born from seed are able to settle where the local conditions allow it. On the other hand, invasive heliophilous species such as black locust (*Robinia pseudoacacia* L*.)* and the tree of Heaven *(Ailanthus altissima* Mill*.),* are spread along the riverbank as more tolerant to the constant perturbation of the machinery activity. Herbaceous and shrubby vegetation cover the banks where tree vegetation is absent or less dense.

# MATERIALS AND METHODS

## Vegetation surveys

Concerning the analysis of riparian vegetation, two different surveys have been carried out along the river reach: the first in autumn 2018, few days before a clear cut, and the second in spring 2022, four years after it. Figure 3 shows the satellite images from 2018 to 2021, where it is possible to distinguish the time of the cut in early 2018 and the subsequent growth and evolution in time of vegetation (mainly herbs and shrubs) along the watercourse.

[FIGURE 3]

The first field survey was conducted along the entire study reach, starting from the bridge next to Castelletti’s Villa location (43°47'29.6"N 11°04'45.7"E) up to the bridge upstream to the final outlet in the Arno River (43°46'37.3"N 11°03'53.7"E). We surveyed 12 cross-sections, one every about 300 meters. The riparian vegetation surveyed along these cross-sections has been characterized in terms of species, size, and position on the riverbank. Each surveyed cross section was considered representative for the vegetation that was grown on its related 300 m-long stretch. The more abundant species were the black locust, the white poplar (*Populus alba* L.), the aspen (*P. tremula* L.) and the white willow (*Salix alba* L.).

Figure 4 shows an example of the riparian vegetation measurements carried out along the cross-section XS8, and the spatial distribution of surveyed riparian vegetation along the riverbanks.

[FIGURE 4]

To analyze the evolution of the tree vegetation after the destructive cut carried out in autumn 2018, riparian vegetation has been surveyed in two test areas in 2022. We considered the sampled plots as representative for the entire study reach.

As required by Baptist et al. (2007) and Nepf (2012) Manning’s *n* calculation method, the field-scale parameters measured at the twelve examined cross-sections were the vegetation density *m* (m−2), defined as the number of plants per unit riverbed area, and the average diameter *D* (m) of average basal area, measured at breast height.

Hence, the effect of the presence of different riparian vegetation has been estimated to determine an average Manning’s n coefficient for each cross-section.

The main results of the vegetation surveys carried out in 2018 are reported in Figure A1 (in Appendix), showing the tree species distribution in the cross-sections XS1, XS6, XS9, and XS11 (panels a), b), c), and d), respectively), with the four riparian vegetation species identified in detail.

In the last field surveys carried out in 2022 after the radical cut, local riparian vegetation was totally replaced by invasive species as black locust resprouts (see Figure A2 in Appendix).

Collected data during the 2018’s field survey along the 12 Cross sections and in the 2022’s plots are reported in Appendix (see Table A3).

## Vegetation modeling

The formulae adopted for the Manning coefficient calculation are the following:

(1), Baptist et al. (2007) for non submerged rigid vegetation

(2), Järvelä (2004) for fully submerged vegetation

(3), Järvelä (2004) for partially submerged vegetation

(4), Nepf (2012) for submerged bending vegetation

Where:

- m is the vegetation density [m-2] ;

- Cd is the vegetation drag coefficient; Cdχ is the specific species drag coefficient

- D is the average diameter of the plant [m];

- g is the gravitational acceleration [m s-2];

- Y is the flow depth [m];

- K is prone height of the plant;

- uχ is the velocity;

- a is the frontal area of the plant;

- H is the height of the plant;

- C\* is a dimensionless empiric coefficient variable from 0.005 to 0.13

Roughness coefficients were calculated for three different vegetation cover scenarios. The first, called Scenario 1 (S1), was related to the vegetation parameters obtained by the field survey performed in 2018, before the cut planned by local land managers. The second one, named Scenario 2 (S2), was based on the 2022 field survey carried out 4 years after the radical cut, assuming these data as representative of a possible vegetation recovery. Lastly, in Scenario 3 (S3) we considered the absence of vegetation cover immediately after the cut, corresponding to a constant Manning’s n of 0.035 m-1/3 s1 along the whole wetted perimeter for all cross-sections of the study reach. This roughness value was chosen to represent a gravel bed river, with completely herbaceous river banks and floodplain with high grass (Chow, 1959). As the latter is considered the target vegetation cover of the land manager intervention, we took it as the reference scenario, to which the other management methods were compared.

## 3.3 Hydraulic modeling

To analyze the differences between the different management scenarios we performed 1D numerical simulations using the HEC-RAS software. The model was composed by 100 cross-section profiles (numbered from 100 to 0) provided by the Northern Apennine District Authority.

The hydraulic modeling was conducted according to two different hypotheses. The first hypothesis assumed that all the discharge volume was contained in the cross-section, neglecting the lateral overflow. The second hypothesis took into account the effect of lateral overflow by means of the insertion of “lateral structures” in the Hec-Ras Geometry, which simulated the lateral flooding effects. In the second case, the peak of the flow discharge hydrograph was expected to decrease along the reach as a consequence of lateral flooding.

The upstream boundary condition was the discharge hydrograph extrapolated from the hydraulic model developed in 2012 by the Arno River Basin Authority, corresponding to a flood event with a rainfall duration of 12 hours and a return period of 30 years (Figure 5), while the downstream boundary condition was set as the normal depth, with an energy slope value of 0.006.

We chose the event with a return period of 30 year because this is the reference used by the local Basin Authority in the Plan for the Hydrogeological Asset to map the areas of hydraulic hazard from high to very high (Ministry of Environment, 1989; Presidency of Council of Ministers, 2005).

[FIGURE 5]

The water level for each scenario was determined adopting an iterative process, according to the following steps. The first step was an hydraulic simulation assuming a constant value 0.035 m-1/3 s1 for the Manning's coefficient in the whole cross section width along the reach. In the second step, the water level and velocity calculated from the previous step were used to calculate the related vegetation Manning’s n coefficients for each section, using equations (1), (2), (3) and (4). The so-determined water levels were used to run the previous equations again. Finally, the iterations were repeated until convergence, assumed as the difference from the previous step of 0.01 m in the water depth and 0.001 m -1/3 s1 in the Manning’s n coefficient.

# RESULTS

## 4.1 Roughness coefficients: Manning’s n calculation

Results of the hydraulic modeling showed convergence within the third iteration of the procedure for all the three simulated Scenarios. The average computed Manning’s n coefficients were: for Scenario 1, 0.076 m-1/3 s1 on the left bank, and 0.112 m-1/3 s1 on the right bank; for Scenario 2, 0.133 m-1/3 s1 on the left bank, and 0.163 m-1/3 s1 on the right bank; for Scenario 3, 0.035 m-1/3 s1 on both banks. As expected, Scenario 2 confirmed the higher values of the Manning’s n coefficient due to the high-density vegetation present in 2022, abundantly resprouted after the cut. The Manning’s coefficient values for each surveyed cross-section at each iteration are shown in Appendix (A4). These data are related to the first vegetation survey (2018), while in Table A5 we report results obtained by the processing of the second vegetation survey (2022).

## 4.2 Hydraulic modelling: 1D longitudinal profiles in different scenarios

In Figure 6a the water surface elevation profiles are plotted with the thalweg line for the entire study reach.

Along the reach, water depth in Scenario 1 changes between - 0.17 and + 0.18 from Scenario 2 and between -0.1 and +0.35 m from Scenario 3. Also flow velocity rates showed remarkable changes along the reach (Figure 6b). In the Scenario 3, values ranged from 6.04 to 1.52 m/s, while for vegetated scenarios the velocity range decreased to 5.39-1.35 m/s for Scenario 1 and to 5.15-1.27 m/s for Scenario 2, with a reduction respectively of about 11% and 15% for the maximum values, while 12% and 20% for the minimum values.

[FIGURE 6]

Consistently with the results described above, Figure 7 shows the differences of water depths for cross-section n. 89, representative of the simulated river reach where flooding can potentially involve the road and subsequently local settlements. Due to the dense resprouting vegetation after the cut, Scenario 2 shows a higher water level than Scenario 1, overflowing the levee system and flooding a wider area.

[FIGURE 7]

Figure 8 shows the water surface elevations at the cross section n. 16, located approximately 400 m upstream of the outlet without considering the lateral flooding effects, assuming that no volume losses occur. The vegetated Scenarios 1 and 2 show an increase of the estimated elevation of 0.14 and 0.19 meters, so between 3.3% and 4.5% respectively. These increases are related to the higher flow resistance caused by vegetation cover.

[FIGURE 8]

Figure 9 shows the differences in water level between the vegetated scenarios and the scenario after the cut, considering geometries with and without lateral flooding effects. Coherently with the other results, Scenario 2 involves higher water levels especially in the first and middle reach with a maximum value of 0.45 m (0.9 m without lateral flooding effects), while in the last cross-sections water level differences are up to 0.1 m (0.34 m without lateral flooding), due to the more flooded phenomena in the upstream reach. On the other hand, Scenario 1 shows a maximum water level difference value in the upstream area of 0.35 m (0.66 m without lateral flooding), while in the last cross sections is up to 0.08 m (0.24 m without lateral flooding).

[FIGURE 9]

Results show that in the study reach vegetation coverage causes significantly higher flow resistance. In fact, for both vegetated Scenario 1 and 2, flow velocity is slower than the one without vegetation (Scenario 3). That causes a higher water surface elevation and, therefore, a greater effect of lateral flooding. Focusing on flood wave propagation, the flood peak delay was calculated in 10 min for Scenario 1 and 20 min for Scenario 2, both considering or not lateral flooding effect.

[FIGURE 10]

# DISCUSSION

Results show that in the 4.4 km modeled reach the increased channel roughness rises the water level up to 3% (9% without considering lateral flooding effects), with a decrease in wave celerity up to 15%, causing higher flooding of the surrounding areas. Both computations with and without lateral flooding showed a flood peak delay from 10 (Scenario 1) to 20 minutes (Scenario 2). Peak discharge delay was less remarkable (continuous lines in Figure 10) compared to other similar studies on floodplain restoration. The observed low effect in flood lamination could be explained by the morphological features and hydraulic characteristics of the modeled reach, especially by the compacted shape of cross sections. The influence of vegetation resistance on water flow would probably be more relevant if evaluated on a longer study reach. Also, the shape of the cross sections could affect these results, if similar analysis were conducted on wider, less compacted, not-embanked and wider rivers.

However, outcomes are in line with previous studies in which authors simulated rivers and floodplains restoration, taking into account the riparian vegetation effects on flood wave attenuation. For instance, Acreman et al. (2003) measured a peak discharge decrease by a maximum of 16% and a delay of 17 hours in a simulated scenario with hypothetic channel and floodplain restoration. Turner-Gillispie et al. (2003) measured an approximated decrease of 3% in peak discharge for an increase in floodplain roughness in a 10 km reach model. Liu et al. (2004) simulated the restoration through increased channel hydraulic resistance and sinuosity in a 408 km2 catchment, finding a 14% reduction in peak discharge on average and a flood peak delay of 2 hours. In their work, Ghavasieh et al. (2006) showed that vegetated strips could reduce peak discharge up to 3.8% and wave celerity up to 9.3% over a hypothetical 20 km reach. Anderson et al. (2006) simulated different scenarios based on canopy height over a hypothetical 50 km reach, from no floodplain vegetation cover up to 3.0 m canopy heights and pointed out that vegetation could reduce peak discharge and mean celerity by a maximum of 12% and 70% respectively. Moreover, Sholtes (2009) reached a 2.5% decrease to peak discharge in a hypothetical ~1 km restored reach, while Ahilan et al. (2018) indicated up to 28% flood peak reduction in a floodplain restoration simulated along a 42 km creek.

Despite the flood peak reduction due to lamination, in Scenario 2 the vegetation dense regrowth leaded to higher water level compared to Scenario 1, meaning that four years after the clear cut vegetation density is even worse than before the cut, therefore the goal of increasing the conveyance was only momentary. As a consequence, in the simulated reach even though the flood wave is slowed down by vegetation, the higher roughness implies higher water elevations, potentially causing local more severe flooding affecting the surrounding agricultural lands, roads and urban settlements. Moreover, vegetation surveys performed 4 years after the clear cut showed that this type of vegetation management in zones already influenced by anthropogenic disturbances, can facilitate the spread and development of highly-dense invasive alien vegetation after few years, leading to an ecological worsening of local environment.

Hence, results showed that vegetation could have three different effects on flow discharge, even if lowered by simulated reach morphological characteristics: flood stage increase in the upstream cross-sections and headwater streams, due to the local higher vegetation roughness and flow resistance; flood peak reduction with widening downstream hydrograph; flow discharge reduction in downstream conveyance, due to the slowered flood passage and increased flood travel time (Archer, 1989; Wolff and Burges, 1994; Rutherford et al., 2007; Ahilan et al., 2016).

Nevertheless, further studies should take into account a wider spatial extent of vegetation effects in hydraulic simulation, considering the watershed scale, i.e. taking into account the contributions from all tributaries in the main channel flood wave propagation and flood mitigation effects for extreme rainfall events under different management scenarios, but also focus on the economic and ecological impact of this type of riparian vegetation management.

# CONCLUSIONS

Anthropogenic landscape modification and its consequent impact on rivers (e.g. straightening and diking of natural streams) is mainly aimed at increasing channel conveyance (Rowinski et al., 2018). However, these hydromorphological changes can reduce the natural flood attenuation bringing flood hydrographs to propagate faster downstream, increasing flood hazard in more urbanized areas (Wright R.L., 1998).

Riparian vegetation and floodplain forests naturally provide the service of slowing the flood. In highly anthropized regions, this ecosystem service has been lost in time by the systematic removal of the vegetation, with the aim of transferring discharge downstream. As a matter of fact, the seamless urbanization connected to anthropogenetic modification of watercourses have contributed both to a habitat degradation and to an increase in flooding severity affecting the lower stretches.

This study, based on the modelling of surveys carried out in the field, presents the hydraulic effects of three different vegetation management strategies along Ombrone Pistoiese River.

Results pointed out the importance of aware riparian vegetation management in flow wave attenuation and consequently in flood risk reduction.

As a matter of fact, outcomes have shown how the current management technique have brought to a simple momentary water conveyance increment. Indeed, the rapid regrowth of shredded vegetation after few years increased flow resistance and floods stages, with a worse situation in terms of local flood risk, that is consequences on public health and safety, as showed in Figure 7, in which is visible the paved road flooding in Scenario 2.

However, the effect of increasing flood level could overall restore more natural conditions, making watercourses able to flow over floodplains and has a positive influence in reducing the risk of flooding downstream, where the flood stage will be lower.

The findings of the hydraulic simulations carried out in this study could help land managers in rethinking vegetation control measures, namely avoiding any destructive cut or managing riparian vegetation with less impacting techniques, so called “gentle maintenance”, as well as planning river restoration anywhere possible. That could lead to the support of a more sustainable management of riverine ecosystems, maybe also planning vegetation management at a watershed scale.

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# DATASET AVAILABILITY STATEMENT

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

# FIGURE LEGENDS

**Figure 1**. Ombrone pistoiese river catchment (a) and focus on the simulated reach (b)

**Figure 2.** White poplar’s stump totally shredded after the radical cut in 2018.

**Figure 3.** Satellite images (Google Earth) over time: a) June 2018; b) August 2019; c) October 2020; d) June 2021

**Figure 4.** Type cross section. Extents are expressed in meters

**Figure 5.** Input flow discharge hydrograph.

**Figure 6.** Water surface profile (a) and flow velocities (b) for each scenario.

**Figure 7.** Water levels at the cross-section 89.

**Figure 8.** Water surface elevation at the Cross Section 16. Its location along the river is visible in Figure 1b

**Figure 9.** Water surface elevation differences along the simulated river reach between the total vegetation removal (S3) and the 2018’s surveyed vegetation scenario before the radical cut (S1), and the potential vegetation resprout 4 years after the cut (S2), considering both geometries with and without lateral flooding effects.

**Figure 10.** Discharge hydrographs at the Cross Section 16. The effect of lateral overflow is achieved by means of “lateral structures” which simulate the lateral flooding effects.