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Riparian vegetation surveys for roughness estimation

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ABSTRACT

Vegetation growth along rivers may have effects on water resistance and velocity distribution. Roughness evaluation is crucial in constructing river stage-discharge curves, due to its great importance in river management and risk assessment. Usually, land managers mechanically remove vegetation to increase flow conveyance and reduce flooding risk, with negative effects on the riverine ecosystem and hydraulic risk downstream.

The study aims to implement a useful methodology for management planning along vegetated riparian zones through the development evaluation of both unmanaged and anthropically disturbed riparian ecosystems, using tree stands quantitative parameters required to estimate roughness caused by riparian vegetation.

For each watercourse, it was also possible to evaluate the equivalent roughness dependent on river morphology and the effective flow resistance over time.

The outputs of vegetation parameters analysis also may provide practical support in gentle maintenance interventions of Tuscan watercourses planning, to ensure positive effects both on water flow and on riverine ecosystem.

1. Introduction

1.1. Plants and water flow

Riparian vegetation interactions with rivers are complex. Vegetation plays a fundamental role in riverine ecosystems; indeed, its presence is affected by the hydrology of the catchment and the hydraulics of the river but, vice versa, riparian vegetation may influence both the hydrology and the hydraulics of a river, having several impacts on the functioning of the ecosystem (Gran and Paola, 2001; Bennett and Simon, 2004; O'Hare, 2015; Gurnell, 2014, Rowiński et al., 2018, Lama et al., 2021a). Plants along watercourses may provide habitats, improve slope stability, enhance water quality by reducing agricultural diffuse pollution, and also have aesthetic and recreational value (Pusey and Arthington, 2003; Merritt et al., 2010; Cole et al., 2020).

Moreover, vegetation growth along rivers may have effects on water resistance and velocity distribution, i.e. flow conveyance and water levels, as well as on turbulence intensity, erosion, and nutrient and sediment transport (Camporeale et al., 2013; Corenblit et al., 2014; Lama et al., 2020, 2021b; Valyrakis et al., 2021).

Despite it is known that vegetation locally reduces flow rate, increasing drag resistance, Coon (1995) noticed that bank vegetation generally has no measurable effect on the roughness coefficients of rivers wider than 30 m if less than 25 % of the wetted perimeter is vegetated, while for wide channels in which larger percentages of the wetted perimeter are vegetated, bank vegetation appears to have a small additive effect on roughness (Coon, 1995). Other studies underlined that whenever the river cross-section width-to-riverbed elevation ratio (W/D) is greater than 10, the effect of vegetation on the flow may not be significant, except on vegetated strips (Preti and Guarnieri, 2005; Nepf, 2012; Aberle and Järvelä, 2013; Luhar and Nepf, 2012).

However, it is still an issue describing quantitatively water flowing through the vegetation, because each plant species has its own unique biomechanical and architectural properties (Yagci et al., 2010). Namely, plants influence on water flow is complex due to the specific morphological and structural characteristics, density, height, and phenological phase of the vegetation (Chow, 1959; Wang et al., 2015; Vargas-Luna et al., 2015). For instance, some riparian woody species can survive floods, among them Salicaceae and Betulaceae, thanks to their morphological adaptation that allows them to sustain and reproduce their population within naturally disturbed riparian ecosystems (Glenz et al., 2006; Gurnell, 2014; Sutili et al., 2012; Pasquino et al., 2018). Indeed, the riparian ecosystem, under natural conditions of evolution, heads towards formations such as *Salix alba* and *Populus alba* galleries (Angelini et al., 2016). Nevertheless, anthropogenic pressures and disturbances, including especially the vegetation management carried out

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by local land managers have advanced the spread of invasive alien species, above all *Robinia pseudoacacia* and *Ailanthus altissima* (Motta et al., 2009; Erdélyi et al., 2021).

1.2. Riparian vegetation and roughness calculation

The evaluation of flow resistance and, therefore, of roughness is a crucial factor in creating river stage-discharge curves, due to its great importance in river management and risk assessment (Fathi-Maghadam and Kouwen, 1997; Darby, 1999). Manning's coefficient (n) still represents one of the most used resistance measures for open channel flows (Manning, 1891; Chen et al., 2009; Kim et al., 2012; Zhu et al., 2020).

Historically, evaluation of roughness was based on Manning's n tables or on a comparison of a site of interest with published photographs of similar channels for which n values have been already computed and used (Arcement and Schneider, 1987; Coon, 1995).

Furthermore, many studies have investigated the correlation between different types of vegetation and water flow, by proposing different roughness equations. Some of them have focused on stiff non-submerged vegetation, typically trees (Ming and Shen, 1973; Baptist et al., 2007; Kothyari et al., 2009; Stone et al., 2013), while others have introduced additional complexity by considering fully flexible and fully submerged vegetation, such as grass and macrophytes (Kouwen et al., 1981; Yen, 2024; Nepf, 2012; Li and Shen, 1973; Errico et al., 2018).

In addition to plant morphology, some studies have also considered the effect of leaves on total flow resistance (Vogel, 2020; Järvelä, 2002, 2004). Flow resistance of flexible vegetation does not depend only on flow properties, but mainly on leaf characteristics or, more generically, on foliage density and seasonality due to plant growth and annual cycle of vegetation (Sellin and van Beesten, 2004; Yang et al., 2007; Antonarakis et al., 2010; Antonarakis et al., 2009; Västilä and Järvelä, 2014; Västilä and Järvelä, 2014; Box et al., 2021). Consequently, during measurements for estimating tree stand density, the period of the year in which the floods could occur must also be considered (Kiss et al., 2019; Valyrakis et al., 2021).

1.3. Riverine vegetation management practices

As already mentioned, riparian vegetation plays a key role in the river ecosystem, interacting with the environment both from an ecosystemic and a hydraulic perspective. However, in the past, land managers often mechanically removed vegetation to increase flow conveyance and reduce flooding risk, totally or partially, to safeguard safety in urban areas by adopting civil engineering solutions, through traditional hydraulic structures and infrastructures (López and García, 2001; Vereecken et al., 2006; Old et al., 2014; Verschoren et al., 2017; Lama et al., 2021b). In the last decades, the management and conservation of riparian vegetation have acquired even more importance (Broadmeadow and Nisbet, 2004; Yagci et al., 2010).

Indeed, EU water policy shows as its first objective the need to prevent further deterioration, protect, and improve the status of aquatic and terrestrial ecosystems as well as wetlands directly dependent on aquatic ecosystems in terms of water needs (Directive 2000/60/CE).

Moreover, practitioners and experts in the field are increasingly recognizing that understanding vegetation's effects within a fluvial system is crucial from both a scientific and river management perspective (Forzieri et al., 2011; Dufour et al., 2012; Zhu and Tsubaki, 2022). Furthermore, the conservation and restoration of native riparian plants are frequently recommended by environmental agencies for river management and bank protection, by planting or adopting soil bioengineering techniques (Chiaradia et al., 2019; Preti et al., 2022).

From a vegetation management perspective, various strategies should also be applied depending on the spatial distribution of plants in the riparian zone, to reconcile flood risk mitigation and aquatic ecosystem preservation (Tabacchi, 2024). Many studies also pointed out that if vegetation is kept elastic closer to the main channel, it could easily bend as the water flow increases, reducing its volume and flow resistance (Wilson et al., 2003; Stone et al., 2013; Tymiński and Kałuża, 2024). Previous studies underlined how typical riparian species decrease their bending capacity significantly when their basal stems are wider than 4 cm, so that removal interventions may be conducted starting from that threshold value (Weitzer et al., 1998; Weitzer et al., 2000; Florineth, 2004). This threshold value should guarantee vegetation flexibility during flood events so that plants can cover and protect riverbanks and prevent or at least reduce erosion processes. Similarly, Pasquino et al. (2018) concluded that a basal diameter of 3 cm can be identified as a value above which stems behave as almost rigid elements for a reference flow velocity of 1 m s-1, with a significant impact on the flow resistance and the riverbank stability.

Another approach used to discriminate the degree of plants' flexibility is the so-called MEI analysis. This vegetational stiffness parameter assesses the combined effect of the product of M, E, and I, where: M indicates the number of plants per unit area, E is the material's elastic modulus, and I is the second moment of stem cross-sectional area. Thus, MEI is used as a single parameter that reflects the overall resistance to deformation of the streamlining because of a flow passing over it (Kouwen, 1988). Previous studies suggest that vegetation is flexible up to the MEI value of 200 N m^{-2} (Darby, 1999). In this study, the stiffness threshold is exceeded starting from the diameter of 3 cm. The elastic modulus used for the calculation is equal to 5.8 GPa and refers to young stems of Populus spp. (Bjurhager et al., 2008).

1.4. Research gap and aim of the study

Previous research showed that understanding riparian vegetation development in natural and anthropogenic environments plays a key role in combining the protection of the riparian environment and its management (Castellarin et al., 2011; Stella et al., 2013; Solari et al., 2014). Globally, only a few studies are based on real-scale field surveys, without creating a significant database of quantitative parameters useful for analyzing vegetation-water flow relationships (Guarnieri and Preti, 2005; Errico et al., 2018, 2019). As a matter of fact, most of the studies on this subject have been conducted in flume laboratories (van Velzen et al., 2003).

Therefore, this study aims to implement a useful methodology for management planning along vegetated riparian zones, assessing interventions without unnecessarily harvesting but preserving dynamic balanced riparian ecosystems and also reaching flood risk management.

To do this, it was necessary to analyse the development of both unmanaged and anthropically disturbed riparian ecosystems utilising tree stands quantitative parameters required to evaluate roughness caused by riparian vegetation.

Thereby, it has been found a possible relation between stand growth and riverbanks roughness through numerous (>50) vegetation surveys along several Tuscan watercourses, with diverse hydro-geomorphologic characteristics and vegetational composition, so that management techniques would be perfectioned and best suited to different conditions.

2. Materials and methods

2.1. Vegetation surveys

Plants along watercourses could be morphologically mainly divided into three types: herbaceous, shrubby, and woody. This distinction means different plants' behaviour when flood events occur, which affects the methodology for estimating the roughness coefficient. Bending and streamlining degree is conditioned both by the hydraulic characteristics of the flood and, intrinsically, by those of vegetation itself. On the one hand, grasses and shrubs bend as they are flexible, on the other hand, trees have a dual behaviour: in the juvenile phase they can bend as they are still elastic, then they increasingly become rigid and stiff

(Plomion et al., 2001; Rowe and Speck, 2005; Fournier et al., 2006; Read and Stokes, 2006; Jonsson et al., 2022).

Hence, to characterize riparian vegetation flow resistance, it was necessary to carry out several field surveys, that took place along seven water courses in Tuscany, central Italy (WGS 84, EPGS 4326: from 43.781 N, 11.057 E to 42.634 N, 11.458 E) with a site elevation range between 30 and 510 m a.s.l., while cross section widths vary from 10 to 124 m and bankfull water depth were calculated between 1.4 and 9.6 m (Fig. 1). The examinated watercourses were: Bisenzio river, Ombrone stream, Tiber river, Arbia stream, Merse river, Ombrone grossetano river and Albegna river.

Reaches were firstly photo-interpreted from satellite and orthophotos so that homogeneous vegetation cover allowed the identification of stretches, then a random-sampling field campaign took place, verifying the actual vegetation representativity of the sampled area.

Field surveys were conducted from 2019 to 2023 in longitudinal rectangle-shaped areas along the vegetated banks of the watercourses. Those areas could vary according to several factors, such as bank's morphology, vegetational composition and site's accessibility. However, the surveyed quantitative vegetation parameters are diameter and tree stand density, which were reported in related surface units (m^2).

Within randomly sampled test areas, breast height diameters (DBH) of the woody vegetation were measured with a tree calliper and recorded in 1 cm wide classes. On a sample basis, considering the frequency of diameters, tree age was also detected by using Pressler's increment borer.

Where measured mean breast height diameter was smaller than 4 cm, i.e., in young tree stands, the Leaf Area Index (LAI) has also been detected, which is a key parameter in determining the plant density effects on roughness (Järvelä, 2004).

LAI values were derived from satellite image processing and corrected with data collected in the field by indirect and non-destructive methods (fisheye digital camera or Plant Canopy Analyzer LI-COR instruments). The data for the growing season from 2019 to 2022 were analyzed for each test area, choosing the highest LAI value to simulate the hydraulically riskiest scenario.

The parameters thus obtained in each test area are:

- mean DBH (d_g) [cm]
- density (m) [m^{-2}]
- average diameter increment [cm]
- Leaf Area Index if d_g were below 4 cm.

Then the relationship between mean diameter and tree stand density has been compared with similar studies (Errico et al., 2018, 2019; van Velzen et al., 2003).

Mean diameter increment data provide quantitatively sample plant diametrical growth until the moment of the survey. Although the tree stand has multiple age classes, the sampling made by using Pressler's increment borer, defined the average diametric increment in such a way as to associate the stand with its growth rate.

Where d_g was less than 3 cm, that is in juvenile surveyed stands, the LAI has been derived from satellite image processed and corrected with data collected in the field by indirect and non-destructive methods (Chianucci et al., 2023). Data of the growing season from 2015 to 2023 were analyzed for each juvenile stand, then the highest logged LAI value was taken to consider the scenario with higher hydraulic risk.

Collected data follows a similar trend to previous studies referring to short rotation forestry (Deckmyn et al., 2004; Pellis, 2004; Laureysens et al., 2005; Tripathi et al., 2016). This analogy may be valid since, in the initial vegetative stages, the growth of the riparian stand can be assimilated to that of a short rotation forestry for LAI purposes.

2.2. Determination of roughness coefficient

As previously stated, tree vegetation exhibits elastic behaviour up to a basal diameter of approximately 4 cm (Florineth, 2004). In this study, tree basal diameter in selected sample areas was measured in order to assess its correlation with DBH. Namely, for trees with a basal diameter up to 4 cm, DBH was found to be approximately 1 cm smaller (with a mean difference of 0.5143 cm and a standard deviation of 0.5071 cm). Hence, woody vegetation still behaves elastically until breast diameter is less than 3 cm, so once this threshold is exceeded, it will behave as rigid elements. Therefore, mean breast diameter (d_g) is the quantitative parameter assumed to discriminate flexibility. In materials science, a woody stem should be considered as a flexible material with its elastic modulus but, for simplicity and applicability in roughness calculation vegetation is considered flexible or stiff. Hence, diameters have been

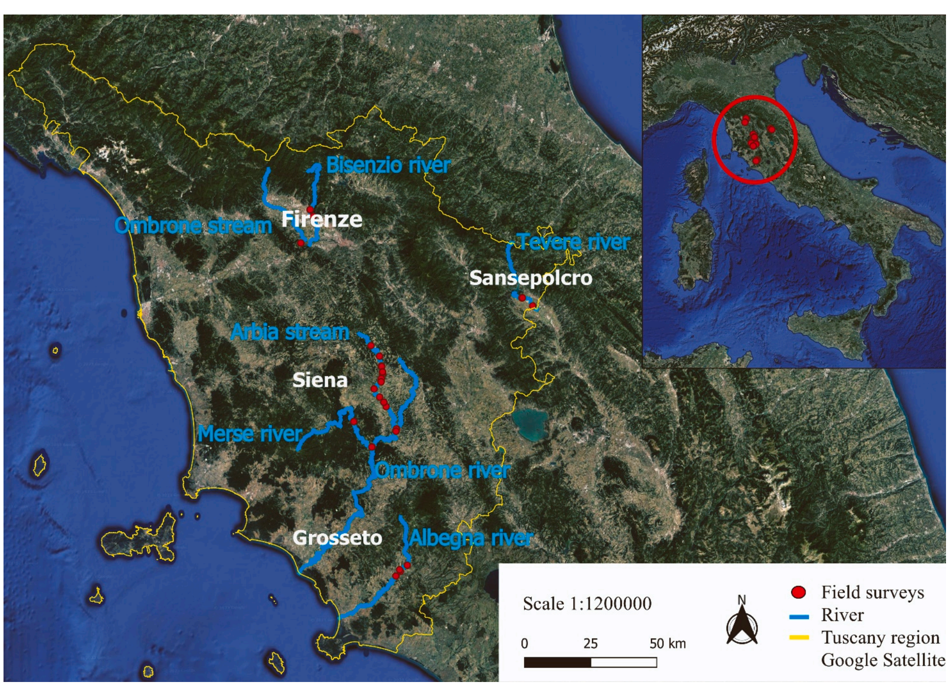

Fig. 1. Vegetation field surveys along seven water courses in Tuscany.

necessarily detected in the test areas, for the calculation of the vegetation roughness (nv). These considerations are fundamental for the choice of the formulation for the calculation of riparian vegetation roughness.

Actually, when the vegetation is greater or equal to the diameter at breast height of 4 cm, it would behave as a rigid element and the Eq. (1) has been used (Baptist et al., 2007):

$$n_v = \sqrt{\frac{m\,C_D D Y}{2}}\left(\frac{Y^{\frac{1}{6}}}{g^{\frac{1}{2}}}\right)\ [\mathrm{m}^{-1/3}\ \mathrm{s}] \tag{1}$$

Where:

m [np m^{-2}] is the density expressed as the number of plants (np) per unit area;

C_D is the average drag coefficient, assumed to be equal to 1.5 (van Velzen et al., 2003);

D [m] is the average breast diameter of the tree;

Y [m] is the water level;

g [m s^{-2}] is the gravitational acceleration.

For shrubby and flexible woody vegetation with an average breast diameter less than or equal to 3 cm, we considered Eq. (2), proposed by Järvelä (2002, 2004) and Aberle and Järvelä (2013):

$$n_v = \sqrt{\frac{C_{D\chi} LAI\left(\frac{U_m}{U_\chi}\right)^{\chi}}{2}}\left(\frac{Y^{\frac{1}{6}}}{g^{\frac{1}{2}}}\right)\ [\mathrm{m}^{-1/3}\ \mathrm{s}] \tag{2}$$

Where, in addition:

$C_{D\chi}$ is a species-specific drag coefficient, assumed for black poplar to be equal to 0.33 (Aberle and Järvelä, 2013);

LAI is the leaf area index;

U_m is the mean cross-sectional velocity;

Uχ [m s^{-1}] is the lowest velocity assumed to be equal to 0.10 and used in determining χ, a vegetation parameter unique for each species which for black poplar was assumed to be equal to −1.03 (Aberle and Järvelä, 2013).

To evaluate roughness with Eq. (2), it was also necessary to calculate the mean cross-sectional velocity U_m by using the Chezy equation, which has been used in uniform flow, constructing the cross-sectional discharge scale for each surveyed water courses with different water levels including bankfull (Fig. 2, Table 1).

Table 1
Trendline equations presented in Fig. 2.

Surveyed juvenile plots	Trendline equations	Coefficient of determination	*P* Value
Ombrone	y = 10532 × ^{0,302}	$R^2 = 0.99$	0.14
Merse	y = 11893 × ^{0,526}	$R^2 = 0.99$	<0.1
Bisenzio	y = 0,9034 × ^{0,5247}	$R^2 = 0.99$	<0.1
Ombone PT	y = 0,6976 × ^{0,4552}	$R^2 = 0,99$	<0.1
Albegna 3	y = 10136 × ^{0,2653}	$R^2 = 0,99$	<0.1
Albegna 5	y = 10038 × ^{0,3759}	$R^2 = 0,71$	<0.1

Besides, another methodology has been used for flexible submerged vegetation (Nepf, 2012; Luhar and Nepf, 2012):

$$n_v = \left[\sqrt{\frac{2}{C_*}}\left(1-\frac{K}{Y}\right)^{3/2} + \sqrt{\frac{2}{C_D a K}}\ \frac{K}{Y}\right]^{-1}\left(\frac{Y^{1/6}}{g^{1/2}}\right) \tag{3}$$

Where *a* is the frontal area per volume, *K* the height of flexed vegetation, *Y* water depth, C_D is drag coefficient, C_* is a coefficient describing the interfacial shear between vegetated and unvegetated flow regions and its range is between 0.05 and 0.13.

3. Results

The surveyed and analyzed parameters are the number of plants per surface unit (*m*) and the mean diameter (d_g). The field surveys showed a correlation between diameter and tree stand density: as the first increases, density decreases (Fig. 3, Table 2). Surveyed data are integrated with other studies (Errico et al. (2018, 2019) and van Velzen et al. (2003)) to fill gaps and compare correlations in the range of diametric overlap.

Surveyed data were secondly divided by mean diameter (d_g) both to distinguish flexible from stiff vegetation, but also by dissimilar characteristics and growth stages in different stands (Fig. 4, Table 3).

In the 1–3 cm diameter range, a smaller variability is shown. However, in the 4–10 cm diameter range greater dispersion of values is noted. In the 11–20 cm diameter range, the trend is almost constant (slope close to zero) and the dispersion of values is low. Since the parameter m*d affects the roughness jointly, it is even more important to

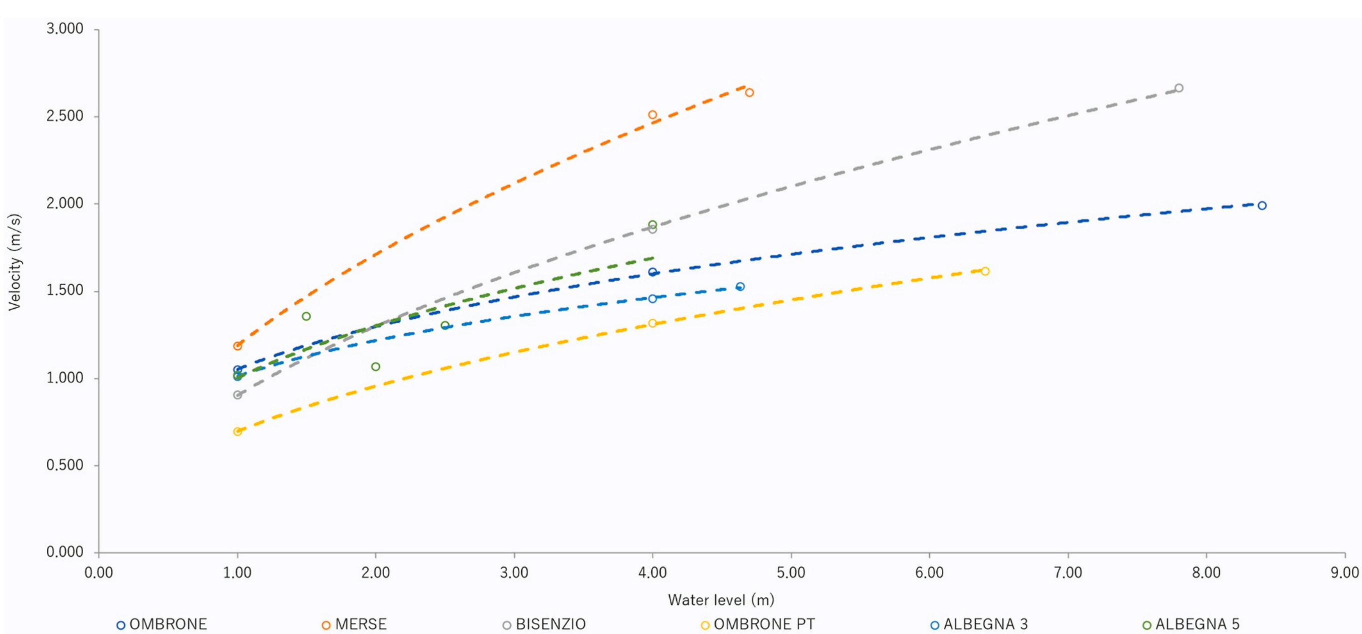

Fig. 2. Correlation between water level and mean cross-sectional velocity.

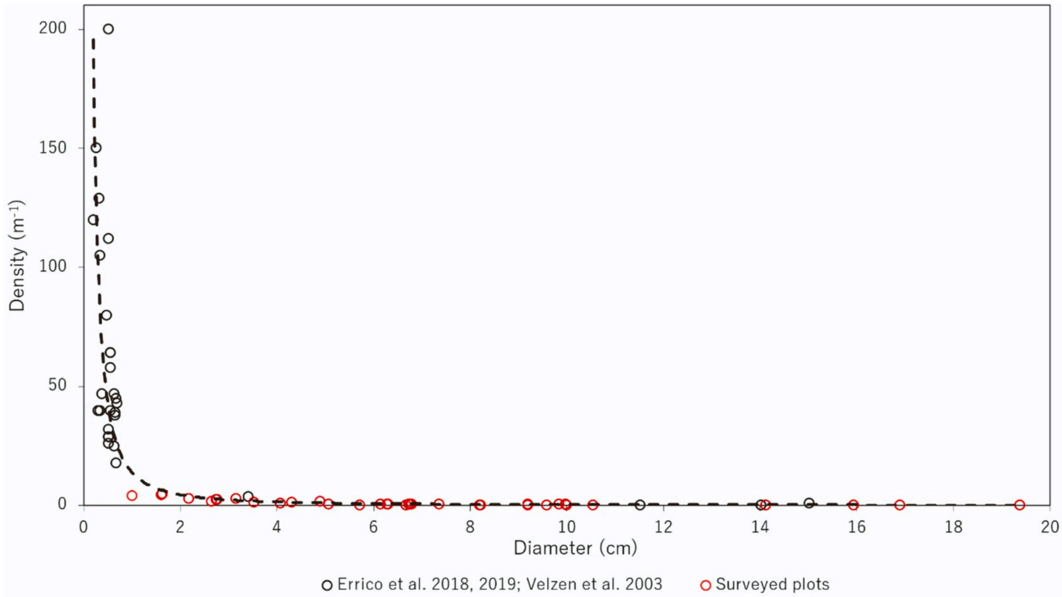

Fig. 3. Correlations between number of plants per unit area and average diameter. Black dotted line refers to Errico et al. (2018, 2019) and van Velzen et al. (2003).

Table 2
Trendline equations presented in Fig. 3.

Source	Trendline equation	Coefficient of determination	P value
Errico et al., 2018, 2019; van Velzen et al., 2003	$y = 13.843x^{-1.653}$	$R^2 = 0.58$	<0.1
Surveyed plots	$y = 6.74484x^{-1.344}$	$R^2 = 0.78$	<<0.01

highlight the dispersion of m*d as a function of mean diameter than the simple correlation m = f(d) (Fig. 5).

To visualize the dispersion and statistical distribution of diameters, boxplots were processed for each vegetation surveyed plot (Fig. 6). The box is bounded by the first and third quartiles, 25th percentile and 75th percentile and divided within it by the median. Whiskers mark the minimum and maximum values.

Results in Fig. 6 show a high variability among surveyed stands. To confirm this, coefficients of variation were calculated (Fig. 7).

The surveyed vegetation properties have been applied to roughness formulae which require only one diameter or LAI that describes the tree stand. For this reason, it has been considered the mean diameter of the surveyed plots.

The other variable parameter within the roughness formula is water depth. To evaluate roughness, we assumed 3 m of water depth in order both to standardize results for different streams and to ensure the submergence of the areas considered (Fig. 8, Table 4).

Table 3
Trendline equations presented in Fig. 4.

Diameter range	Trendline equation	Coefficient of determination	P value
1–3	$y = 4.9683\ x^{-0.672}$	$R^2 = 0.55$	<0.1
4–10	$y = 4.7603\ x^{-1.195}$	$R^2 = 0.51$	<0.01
11–20	$y = 0.0289\ x^{-0.7264}$	$R^2 = 0.73$	<0.1

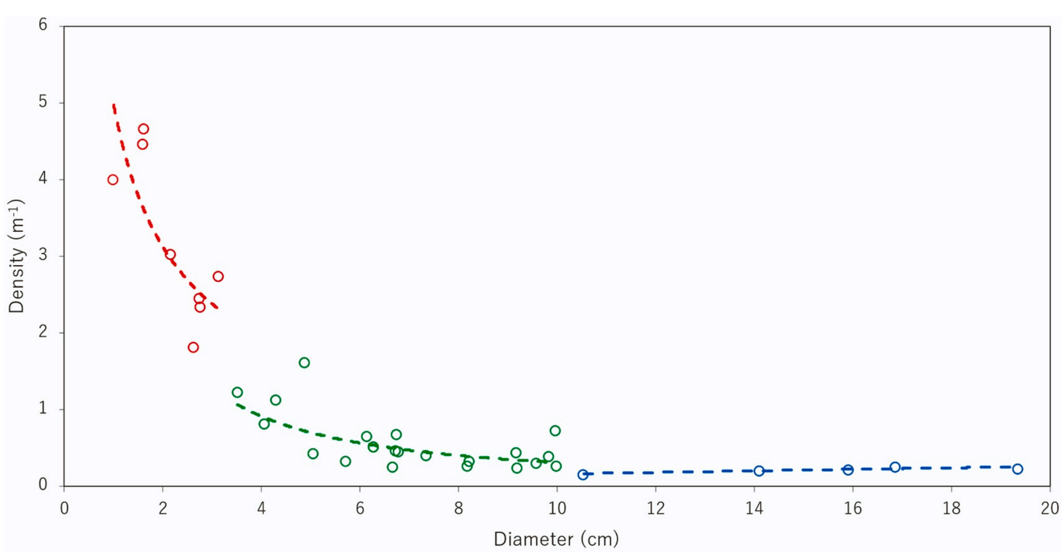

Fig. 4. Correlations between the number of plants per unit area and average diameter, for surveyed plots, divided by stand evolutionary range.

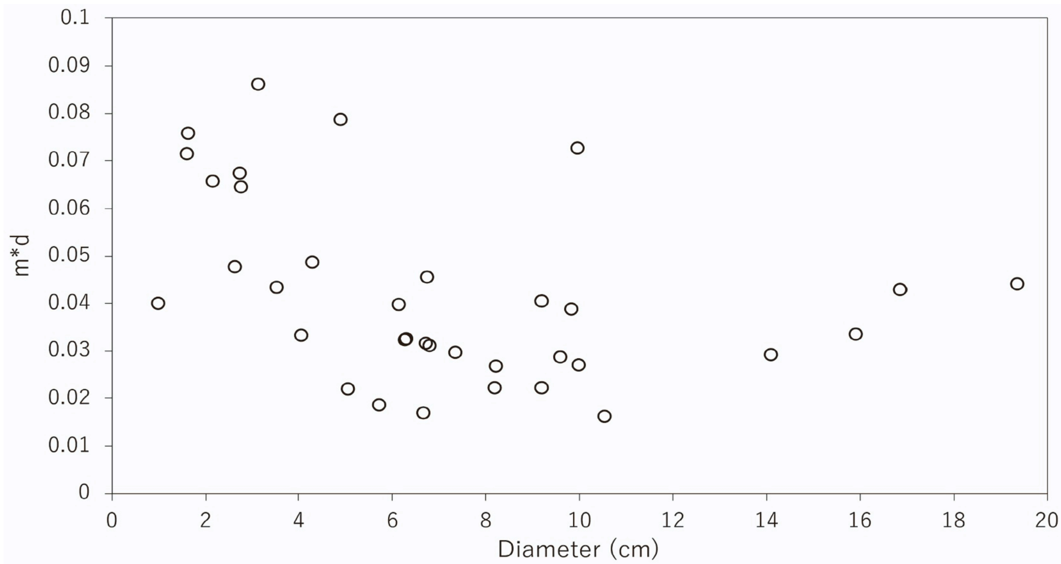

Fig. 5. Relation between diameter and m*d.

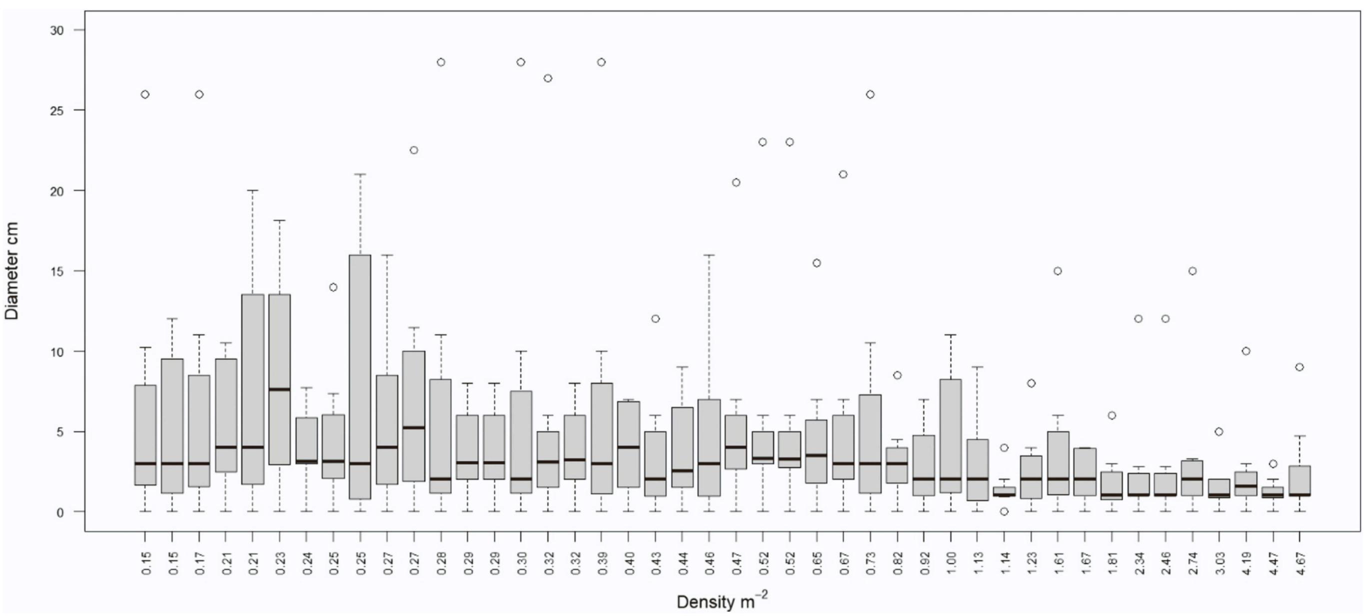

Fig. 6. Statistical analysis with boxplot of mean diameter in surveyed areas.

4. Discussion

Analyzed riparian stands have an average diameter ranging from 1 to 20 cm. The populations assume different behaviours and structures against hydraulic discharge.

Surveyed stands showed an average diametric increment of about 1 cm year^{-1}, a trend in line with previous studies (Ross and Ross, 1998; Ross and Mõttus, 2000; Laureysens et al., 2005; Bjurhager et al., 2008). Adopting this simplified diameter-increment correlation allowed the construction of the average growth curve of Tuscan riparian forests. This can refer exclusively to the riparian forests analyzed and for juvenile growth stages or in any case ranging between 0 and 15 years, considering also that management interventions do not usually exceed these age values.

In Fig. 3 it is possible to see how the values found in this study agree with the trend proposed by the bibliography (Errico et al., 2018, 2019; van Velzen et al., 2003). For surveyed riparian strips, as the average diameter increases, stand density decreases.

Fig. 4 shows in detail data from surveyed plots, in which the variability in the first range (1–3 cm) is due to a more even-aged stand having a regular structure. Young stands with smaller mean diameters show a higher value of tree density. Then, the density decreases as plants with high diameters were surveyed, but they were few, sparse and distributed in such a way that does not affect water flows.

The greater values dispersion in the second range can be explained by a tree stand that, after the juvenile stages of establishment, tends to a non-regular structure with plants of different ages. Also in Fig. 6, it is visible that results follow a natural evolutionary dynamic, namely stems go through self-thinning processes during population development (Westoby, 1984; Mrad et al., 2020). Additionally, riparian environments are objects of multiple stressors, both natural and anthropogenic (Stella and Bendix, 2019). The plots were disturbed by factors such as, primarily, flooding and thinning, but also by wildlife activities. However, when the stand's average diameter exceeds 10 cm, it tends to regularize

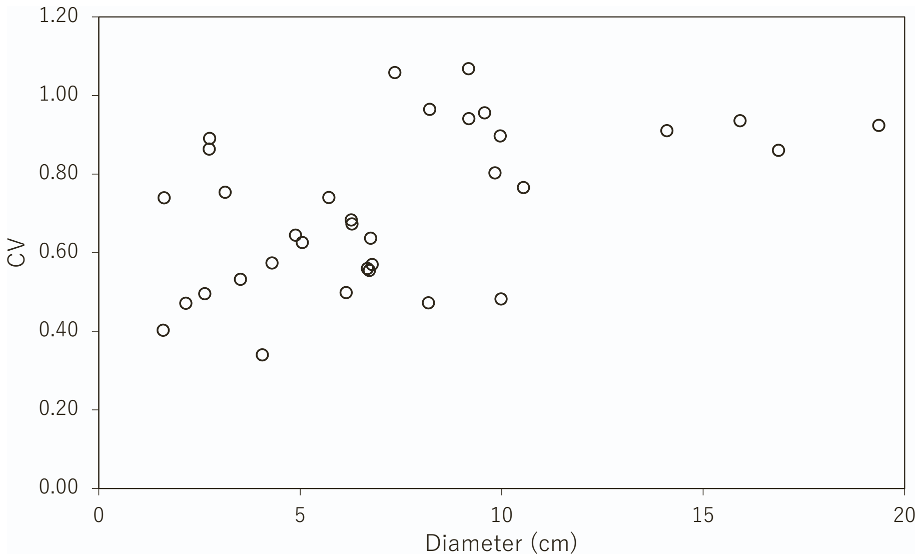

Fig. 7. Trend of the coefficient of variability by diameter.

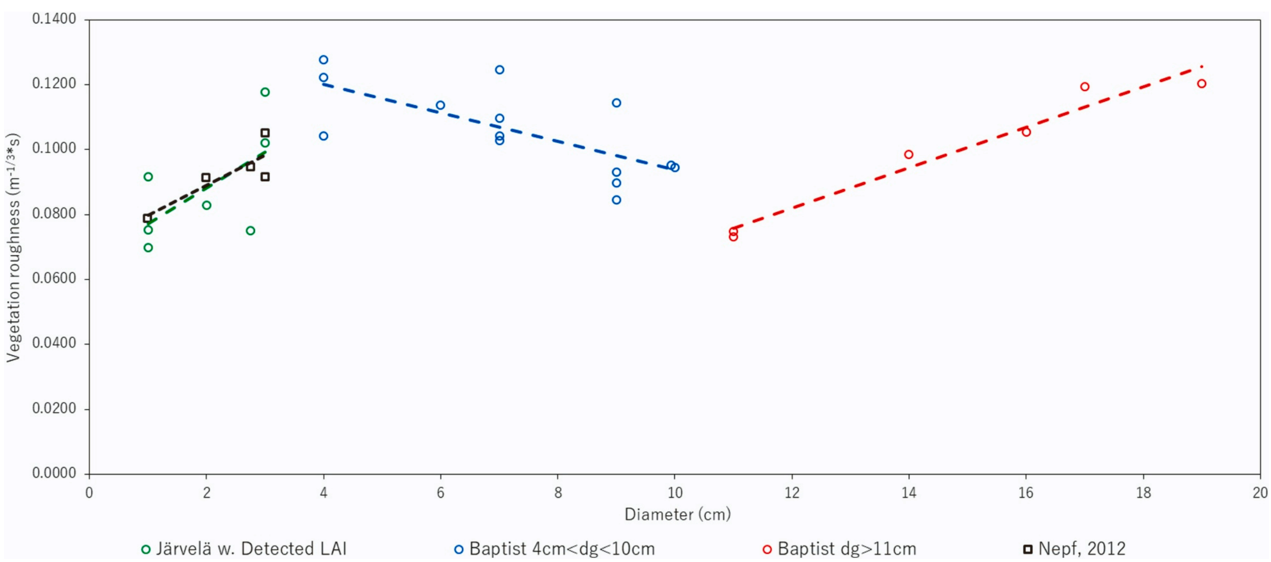

Fig. 8. Correlation trends between diameter and roughness.

Table 4
Trendline equations presented in Fig. 8.

Diameter range [cm]	Trendline equation	Coefficient of determination	P value
1–3 (Järvelä)	y = 0.0111× + 0.0661	$R^2 = 0.38$	0.14
1–3 (Nepf)	y = 0.093× + 0.0704	$R^2 = 0.72$	0.39
4–10 (Baptist)	y = −0.0044× + 0.1378	$R^2 = 0.49$	<<0.01
11–20 (Baptist)	y = 0.0062× + 0.0072	$R^2 = 0.96$	<<0.01

again, as confirmed by the trend in Figs. 4 and 7, where seems not to be present noticeable disturbances. Moreover, tree stand density multiplied by mean diameter (m*d) decreases up to the diameter of 10 cm and then starts to increase (Fig. 5). This suggests that up to the diameter of 10 cm, the stand density decreases and conditions the m*d value. In stands with an average diameter greater than 10 cm (within our field of variation 0–20 cm), as seen, density remains constant while the diameter increases. Thus, in this case, it is the diameter that mostly affects the m*d multiplication. Consequently, this affects Eq. (1) and thus the trend of roughness.

Regarding boxplots (Fig. 6), the trend seems to be a general flattening of the diameters as density increases, also because the samples were chosen randomly. Namely, the unevenness is confirmed by the coefficient of variability, which has high values (>0.5) for several test areas, indicating stands with high diametric variability (Fig. 7).

Furthermore, for high values of breast height diameter (d_g), the variability is greater because the stand is more mature and developed, becoming uneven-aged. This is emphasized along reaches that pass through low anthropized areas as it was found during the sampling campaign. The greatest variability is observed in the range of 4–10 cm mean diameter, confirming what was affirmed in the correlation m vs d_g. When the stand has average diameters greater than 10 cm, the variability is high but constant.

In addition, two statistical tests were performed on the sample: the Shapiro-Wilk test (normality test) and the Skewness measure (symmetry test). In the first case, it emerges that all values are 'not normal'. As far as the symmetry test is concerned, the values obtained are all non-zero. The index of all samples is greater than zero, which means that the distribution is "non-symmetrical" and is also right-skewed (positive). This was also expected because the arithmetic mean of the samples is always greater than the median and the mode. Hence, the right asymmetry shows that most of the values refer to smaller diameters as well as young tree stands with greater flexibility.

Analyzing obtained values and based on calculated correlations, 5 sample areas were considered non-significant to evaluate roughness, not appearing in Fig. 8. The values of m*d multiplication and roughness are in two cases very high in comparison to the trendline and in 3 cases very low. The lower representativeness is due to areas where, before the surveys, tree vegetation had been harvested or where the morphology of the riverbed had been excessively artificially modified, that is embedded and bounded riverbed. However, these outliers can be highlighted in Fig. 5.

Furthermore, in Fig. 8 roughness for young stands where d_g was below the flexibility threshold, was also calculated by using Eq. (3), considering the parameters $C^* = 0.1$, $CD = 1.5$ and $Y = 3$ m, according to literature (van Velzen et al., 2003; Nepf, 2012; Luhar and Nepf, 2012). Then, a has been obtained from the product of m and d_g collected in this study. Concerning the K parameter, it has been estimated for different diameters: $K = 0.3$ m for $d_g = 1$ cm, $K = 0.6$ m for $d_g = 2$ cm and $K = 0.9$ for $d_g = 3$ cm.

Lastly, results for d_g up to 3 cm have been calculated by using Eqs. (2) and (3). In this range, the roughness value increase is brought on by an ever-increasing density of plants per area, which increases water flow resistance. The trend lines have a coefficient of determination variable between 0.38 (Eq. (2)) and 0.72 (Eq. (3)). In the second range, between 4 and 10 cm, the roughness coefficient decreases probably due to the natural stand competition, but also external disturbances such as flooding and thinning. As a result, the number of plants per unit area declines while the average diameter of the tree stand increases. In this case, the trend line has a determination coefficient of 0.49, while the trend line over 10 cm depicts a gradually rising roughness coefficient as the average stand diameter increases, with a determination coefficient equal to 0.96.

Hence, two reversals of the roughness trend are detected: one in proximity of 3 cm diameter, that is limit of stem flexibility, where the roughness coefficient starts to decrease, and one in proximity of 10 cm, where the roughness turns to increase again.

It would be useful to evaluate the maximum tolerable plant size from a hydraulic perspective so that it would be identified a diameter threshold value above which vegetation management should be carried out. However, from a management point of view, e.g. Sutili et al. (2012) affirmed that young plants with small diameters are likely to be more flexible, and better suitable for riverbank stabilization. Other studies showed that near the main channel, it would be appropriate to release a strip of flexible vegetation ($d < 3$ cm) to provide greater protection from the erosive effect of the current and not weigh down the bank, while too rigid plant elements can cause turbulence and erosive phenomena (Weitzer et al., 1998; Weitzer et al., 2000; Florineth, 2004). This interval corresponds to young seedlings grown under frequent stage fluctuations, with high shear stress but flow rates with tolerable risk (Vesipa et al., 2017). In contrast, on bank strips and riparian zones far from flowing water, where vegetation is influenced by larger floods, it would be appropriate to keep the average diameter in a range to have lower roughness. By the way, due to the river ecosystem dynamic, it is essential to monitor riparian vegetation development and natural succession to evaluate its effects on water flow (Naiman et al., 2005; Wheater and Evans, 2009; Huylenbroeck et al., 2020).

Therefore, for management purposes, Fig. 9 shows three possible evolutionary scenarios of the riparian stand, due to three different types of intervention planned when the stand has a d_g of 10 cm. This moment corresponds, as shown in the figures above, to a minimum roughness value.

The green trend line represents the evolution of the stand after a clear-cut. Vegetation starts to regrow following the same green trend, reaching a maximum roughness value of 0.13 $m^{-1/3}$ s in a short time.

The other trends show two possible evolutionary scenarios as a result of gentle selective thinning of vegetation in the 10th year. After 5 years from this intervention, monitoring is carried out by analyzing the new vegetation parameters (m and d_g if the m*d value is greater than 0.025, intervention would be required and thus the scenario would be referable to the grey line; if not, no thinning would be carried out and a new monitoring (and likely intervention) would be expected after another 5 years (the blue trend). The grey trend line follows a growth rate equal to

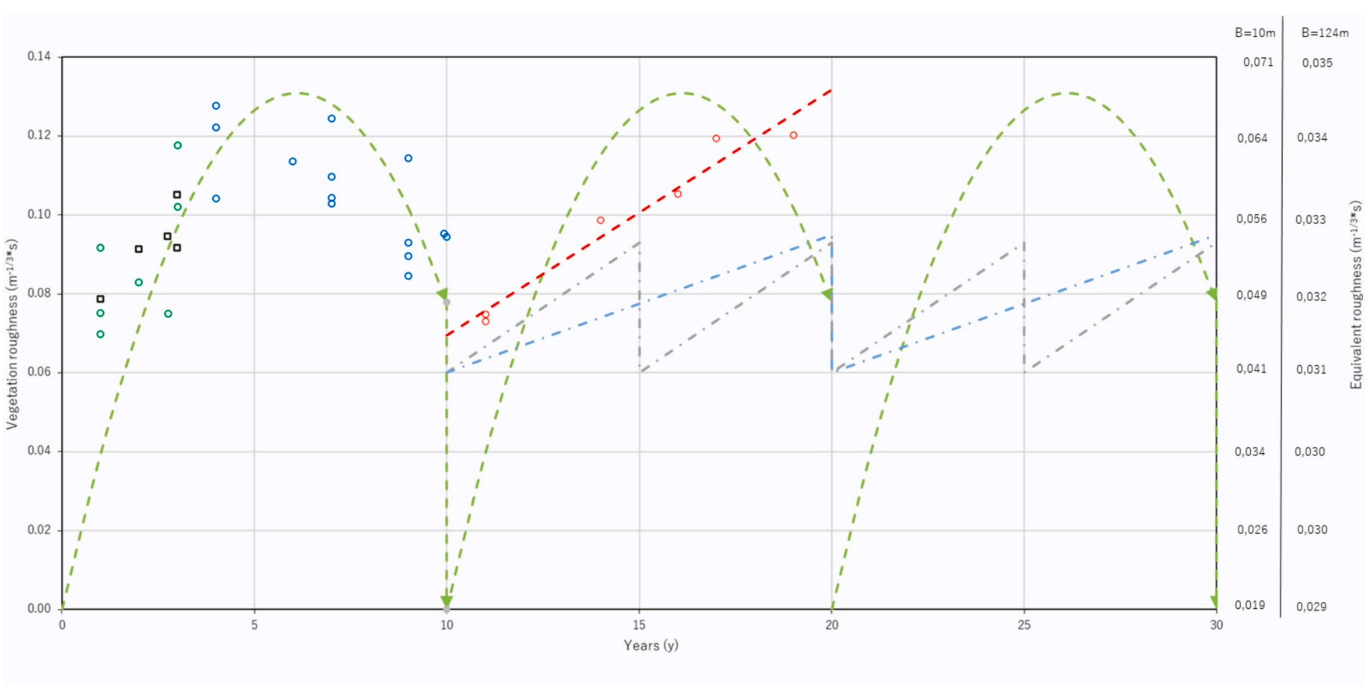

Fig. 9. Simulated thinning scenarios.

the red line and thus same angular coefficient. The blue line has the same angular coefficient as the linear regression with y-intercept at 0.06 $m^{-1/3}s$ and referring to diameter values up to 10 cm.

The scenarios associated with the last two management proposals aim to maintain the bank roughness coefficient in the range of 0.06–0.09 $m^{-1/3}$ s.

By considering the same vegetation roughness values, the secondary axis explains the equivalent roughness of watercourses with different riverbed widths, varying between 10 m and 124 m, namely the limit values of those rivers in which riparian vegetation has been surveyed.

The effects obtained with a clear-cut lead to a higher roughness value, that is a worsening of the hydraulic risk, also causing environmental consequences (Keenan and Hamish Kimmins, 1993; Domer et al., 2019; Angiolini et al., 2023). Results also show the importance of cross-section width in equivalent roughness evaluation, i.e., as width increases, the weight of vegetation grown on the riverbanks decreases, demonstrating the low utility of vegetation removal along wide riverbeds.

Surely, each river reach is related to different hydraulic risk factors, which means different riparian vegetation management. However, in specific conditions, clear-cutting can be a drastic choice, not only from an ecological but also an economic point of view. Therefore, it would be ideal to address management according to the desired roughness coefficient for that specific stretch by analyzing the m*d value.

5. Conclusions

Riparian vegetation interacts with watercourses and there is an increasing need to make strategic management decisions also considering climate change issues. This study may support the gentle maintenance of Tuscan watercourses. However, the watercourses need constant monitoring to better calibrate the various parameters analyzed and to better hypothesise vegetation scenarios.

Results showed that stems and branches' flexibility decreases over time and plants behave even more as rigid elements, but at 10–12 years roughness coefficient gradually increases. Therefore, it could be envisaged a longer curing period, to operate on a target diameter to maintain the tree stand with an average diameter of approximately 10 cm, also considering that each intervention must be contextualised to the existing risk in the area, rather than acting frequently by clear-cutting which should be avoided in any case.

It must be underlined that parameters necessary for roughness evaluation could also be obtained by using new technologies, such as UAV, that allow managers to significantly reduce the timing of field surveys, acting also on management economic sustainability (Forzieri et al., 2009; Forzieri et al., 2011). However, these new methods are still not properly being tested in riparian environments, which means further studies and investigations should also be implemented.

Surveys carried out in this study showed that the diameter-density correlation is appropriate to estimate the hydraulic roughness of riparian vegetated strips. Maintenance activities conducted by land managers should be reduced or even avoided when riparian vegetation does not quantitatively affect flow discharge. The evaluation of bank roughness, vegetation management and thus hydraulic risk mitigation activities should also be assessed considering the specific characteristics of the watercourse such as morphology and the surrounding area.

In conclusion, monitoring is a fundamental step in maintenance activities planning. A periodic check of the qualitative and quantitative characteristics of the stand, with a minimum frequency of at least five years, is necessary for the evaluation of roughness to ensure both appropriate water flow and a satisfying ecological status.

CRediT authorship contribution statement

A. Signorile: writing, literature review, data collection and analysis, review and editing. **R. Saracino:** data collection and analysis, writing, review. **M. Rillo Migliorini Giovannini:** literature review, writing, data collection and analysis, editing. **A. Dani:** data collection and analysis, review. **F. Preti:** conceptualization, funding, data collection and analysis, coordination, supervision, review.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Federico Preti reports financial support was provided by Consorzio di Bonifica 6 Toscana Sud. Federico Preti reports a relationship with Consorzio di bonifica 6 Toscana Sud that includes: funding grants.

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Data availability

Data will be made available on request.

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