



Modeling arboreal vegetation-induced friction and its influence on river flooding using a two-dimensional model

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Abstract

Extensive research on vegetation flow resistance at the laboratory scale has yielded numerous formulations for determining vegetation friction coefficients. However, implementing and validating these equations at the river scale is often complex due to the lack of data on vegetation features and flow characteristics during floods, resulting in a limited number of field application studies. In this research, we use the Telemac-2D hydrodynamic model in a new case study to evaluate the performance of five vegetation friction formulations applied to arboreal vegetation. Employing vegetation data acquired through field surveys and LiDAR, along with flow data collected during one of the highest peak floods recorded on the Piave River, we built a two-dimensional (2D) river model. This model considers existing arboreal vegetation and terrain conditions to compare observed water surface elevations (WSE) during the flood with those simulated using vegetation friction equations. Our findings reveal that all tested equations perform similarly in all simulations. While these equations overestimated WSE throughout most of the flood, they accurately predicted levels at the highest peak and its proximity. Additionally, we explore several vegetation scenarios, varying density and percentage of area covered by arboreal vegetation, to assess their effect on water levels and flood risk.

Keywords Arboreal vegetation · Flood simulation · Hydrodynamic modeling · Piave River · Vegetation friction

1 Introduction

Floods are one of the most common natural disasters worldwide, inflicting long-term environmental effects such as erosion and sedimentation [1], significant damage to people and infrastructure, and great economic losses. According to the technical report published by the Joint Research Center (JRC), floods across Europe and the UK have resulted in annual damages of 7.8 billion euros, with more than 170000 people at risk of river flooding [2]. Italy, a country historically susceptible to flooding, has reported 75 fatalities, 32 injuries, and nearly 50500 evacuations in the last five years (from 2018 to June 2023) due to

flooding [3]. Climate change has worsened the situation, rendering floods more frequent and severe in recent years [4–6].

Several factors influence water levels during a flood event, including (i) precipitation, (ii) river size, shape, and flow rate, (iii) topography of the flood-affected area, (iv) soil type, (v) the presence of structures in and along the river, (vi) anthropogenic activities such as land use changes and urbanization, and (vii) vegetation.

Vegetation in and around rivers can modify the shape and size of a stream channel, altering the flow patterns and velocities, resulting in geomorphologic changes [7]. Additionally, it can stabilize river banks, mitigating erosion and limiting the runoff into rivers, thereby decreasing flood impacts [8]. However, floodplain vegetation can increase flow resistance, reducing flow velocities and river conveyance capacity [9]. This phenomenon can induce higher water levels, posing an increased risk of flooding. Therefore, an accurate estimation of vegetation-induced flow resistance, particularly friction coefficients, is crucial in flood analysis.

During water-vegetation interaction, vegetation introduces hydrodynamic resistance influenced by various factors such as flow characteristics, drag coefficients, and morphological and mechanical properties of vegetation. Existing literature suggests assessing this resistance based on the flow conditions (emergent or submerged) and vegetation type (rigid or flexible) [10]. Unlike rigid vegetation, which remains erect and maintains its shape and position, flexible vegetation can adopt different configurations depending on flow dynamics.

Under emergent flow conditions, friction coefficients increase with greater water depth and vegetation density. Experimental research has revealed that within vegetation areas, the vertical velocity profile deviates from the typical logarithmic distribution, and the average flow velocity is lower compared to areas without vegetation [11]. For rigid emergent vegetation, resembling trees without foliage, the velocity profile tends to be uniform across most of the intermediate depth, forming a "J" shaped distribution [12]. However, for flexible emergent vegetation, such as plants with flexible foliage, the velocity profile varies in foliage and stem parts, with velocity decreasing within the foliage and increasing within the stem [13].

Submerged vegetation flow is often analyzed using a two-layer model, which divides the flow into non-vegetated and vegetated layers. However, to better describe vegetation turbulence features, some studies recommend a three-layer model [14, 15]. Laboratory studies indicate that fluctuating velocities within and above vegetation cause an inflection point in mean velocity profiles near the top of vegetation [16]. While the logarithmic velocity profile remains applicable in the non-vegetated layer [17], the vegetated layer presents greater complexity due to momentum exchange often dominated by the Kelvin-Helmholtz instabilities between layers [18]. In the case of rigid vegetation, velocity distribution within the vegetated layer remains relatively constant throughout the intermediate depth, similar to the emergent case, with a velocity spike near the bed and an increase near the top boundary [15, 19]. In contrast, flexible vegetation exhibits an "S" shaped velocity profile [20]. Generally, submerged vegetation friction coefficients tend to decrease with greater water depth. At high water depths and velocities, flexible submerged vegetation bends, reducing the effective area obstructing the flow and thus flow resistance [21].

Given the diverse range of vegetation types and flow conditions present in riverine ecosystems, hydrodynamic modeling has become a valuable tool for analyzing flood events in natural environments and assessing vegetation friction coefficients.

A general practice for determining vegetation friction coefficients using hydrodynamic models is through a calibration process from observed field data. This process assigns

friction values based on literature [22, 23] and then adjusts them to minimize the difference between model predictions and observations, such as water levels or inundation areas [21]. However, this method is limited because flood data is often unavailable, and the predictions are less reliable for flows over the maximum flow calibrated [24]. An alternative method incorporates vegetation friction formulations into hydrodynamic models, enabling friction coefficient calculations based on water depths and vegetation characteristics.

Mason et al. [25] conducted one of the first studies on integrating vegetation friction formulas into hydrodynamic models. Using Telemac-2D and vegetation height acquired by LiDAR, they calculated friction factors at each node of the model mesh by applying Kouwen and Unny equation [26] for grasses and Fathi-Maghadam and Kouwen formula [27] for trees and bushes. For the flood event they tested, the simulated flood extent agreed with the observed flood extent in almost the entire modeled domain.

Straatsma and Baptist [28] developed a method to parameterize floodplain friction by combining multispectral and airborne laser scanning (ALS) data of the floodplains of the Waal River in the Netherlands. ALS data facilitates the analysis of vegetation height and density for forest and herbaceous areas. The method proposed by the authors was evaluated from water levels calculated using the equation of Baptist et al. [29] in the Delft 3D hydrodynamic model. The model produced accurate predictions of water levels and discharge measurements.

Abu-Aly et al. [30] used Katul et al. [31] equation to develop a two-dimensional hydrodynamic model that analyzed the effects of spatially distributed vegetation friction. Employing LiDAR data, they determined floodplain vegetation height along a river corridor and performed simulations with and without vegetation. The results indicated that vegetation increased the mean water depth by up to 25% and decreased the flow velocities by up to 30% at the maximum modeled discharge.

Folke et al. [32] examined Baptist et al. [29], Järvelä [33] and Lindner [34] vegetation formulations in Telemac-2D using a hydraulic model of the Rhine river, finding that these formulations accurately predicted measured water levels. Similarly, Chaulagain et al. [35] evaluated Baptist et al. [29] and Järvelä [33] equations in an SRH-2D model of the San Joaquin River, comparing measured water levels predictions obtained through two methods for acquiring vegetation parameters: field-based and LiDAR. While all models performed well overall, the Baptist-field model was the most accurate.

In a recent study, Wang and Zhang [24] investigated the integration of vegetation friction formulas into one-dimensional models. They incorporated eleven equations into a Hec-Ras model to examine the San Joaquin River reach. According to their findings, Whittaker et al. [36] equation provided the best predictions for friction coefficients and river stages. Furthermore, they concluded that methodologies based on the rigid cylinder analogy - in which vegetation geometry is simplified as rigid cylinders - produce accurate river stage predictions and are suitable for calculating friction coefficients in 1D models for areas dominated by trees and shrubs under emergent conditions.

The last decade has brought significant progress in integrating vegetation equations into hydrodynamic models. However, much of this research has been focused on laboratory-scale investigations [37–39]. Large-scale studies are comparatively few due to difficulties in gathering vegetation field data. Besides, crucial data such as flow depths and discharges are often unavailable during major flood events. As a result, most river-scale applications have been conducted under steady-state conditions, with very few considering flood events [40]. This work intends to bridge this gap by evaluating the performance of five vegetation friction formulas under an unsteady-state flow regime, simulating a river flood event. Furthermore, it seeks to broaden the current river-scale literature through a new case study.

By employing the Telemac-2D hydrodynamic model and incorporating arboreal vegetation data and flow data from the Piave River, this research outlines the workflow for simulating vegetation friction in 2D river-scale models. Moreover, it explores different vegetation scenarios to provide insights into effective vegetation management strategies.

This work is structured as follows: Sect. 2.1 provides an overview of the hydrodynamic model and the vegetation friction formulations employed in this study. The characteristics of the study area, the vegetation, and the examined flood are detailed in Sects. 2.2 to 2.4. Section 3.1 presents the parameters used for setting up the model, while Sect. 3.2 illustrates the results of the numerical simulations. Additional findings related to vegetation friction coefficients and simulations involving various vegetation scenarios are discussed in Sects. 3.3 and 3.4, respectively. The study concludes in Sect. 4.

2 Methodology

2.1 Hydrodynamic model

This study employed the two-dimensional hydrodynamic model Telemac-2D, developed by the Research and Development Department of Electricité de France (EDF), to simulate free-surface flow under both steady and unsteady conditions. Telemac-2D solves the Saint-Venant equations, a set of partial differential equations derived by integrating the Navier–Stokes equations over the vertical axis [41]. These equations represent the conservation of mass and momentum in two dimensions and are expressed as follows:

Continuity equation:

$$\frac{\partial h}{\partial t} + \mathbf{u} \nabla(h) + h \operatorname{div}(\mathbf{u}) = S_h, \quad (1)$$

Momentum equations:

$$\frac{\partial u}{\partial t} + \mathbf{u} \nabla(u) = -g \frac{\partial Z}{\partial x} + S_x + \frac{1}{h} \operatorname{div}(h v_t \nabla u), \quad (2)$$

$$\frac{\partial v}{\partial t} + \mathbf{u} \nabla(v) = -g \frac{\partial Z}{\partial y} + S_y + \frac{1}{h} \operatorname{div}(h v_t \nabla v), \quad (3)$$

where h represents the water depth, u and v denote the horizontal velocity components along x and y axes respectively, g is the gravity acceleration, v_t represents the momentum diffusion coefficient, Z stands for the free surface elevation, t denotes time, x and y are the horizontal space coordinates, S_h is the source or sink of fluid, and S_x and S_y denote source or sink terms in the dynamic equations.

Telemac-2D applies either finite-element or finite-volume methods to solve equations 1 to 3. Previous research has shown that while the finite-element method yields similar results to the finite-volume method, it requires less computational time [42]. Hence, we opted for the finite-element approach in this investigation.

The software includes several friction laws, such as Chèzy, Strickler, Manning, and Nikuradse, primarily for bottom friction. However, to accurately model vegetation effects, additional methodologies are necessary. Version V8pr2 provides eight equations for computing vegetation friction coefficients. This study implemented the approaches proposed by Lindner [34], Van Velzen et al. [43], Baptist et al. [29], Huthoff et al. [44], and Luhar and

Nepf [45]. These approaches do not account for vegetation flexibility and can be applied to both emergent and submerged vegetation, except for Lindner, which is specific to emergent conditions.

2.1.1 Vegetation friction formulations

2.1.1.1 Lindner (1982) Lindner [34] defined the vegetation friction factor f as follows:

$$f = \frac{4Dh}{a_x a_y} C_D, \quad (4)$$

where D is the diameter of the plant, h is flow depth, $a_{x,y}$ are the longitudinal and lateral distances between the plants, and C_D is the drag coefficient.

2.1.1.2 Van Velzen et al. (2003) Van Velzen et al. [43] assessed vegetation flow resistance by examining velocities in both vegetated and surface layers, using the vertical velocity profile model introduced by Klopstra et al. [46].

$$V = \frac{h_v}{h} V_v + \frac{h - h_v}{h} V_s, \quad (5)$$

where V is the average flow velocity over the entire flow depth, h_v is vegetation height, V_v and V_s are depth-averaged velocities in the vegetated and surface layers, respectively.

$$V_v = \frac{2l}{h_v} \left(\sqrt{Ke^{h_v/l} + u_s^2} - \sqrt{K + u_s^2} \right) + \frac{u_s l}{h_v} \ln \left[\frac{\left(\sqrt{Ke^{h_v/l} + u_s^2} - u_s \right) \left(\sqrt{K + u_s^2} + u_s \right)}{\left(\sqrt{Ke^{h_v/l} + u_s^2} + u_s \right) \left(\sqrt{K + u_s^2} - u_s \right)} \right], \quad (6)$$

$$V_s = \frac{u_*}{\kappa(h - h_v)} \left[(h - (h_v - h_s)) \ln \left(\frac{h - (h_v - h_s)}{z_0} \right) - h_s \ln \left(\frac{h_s}{z_0} \right) - h + h_v \right] \quad (7)$$

The variable u_s corresponds to flow velocity through vegetation for emergent conditions, whereas the variables K and l are defined below:

$$u_s = \sqrt{\frac{2gJ}{C_D m D}}, \quad (8)$$

$$K = \frac{gJ(h - h_v)l}{\alpha \cosh \left(\frac{h_v}{l} \right)}, \quad (9)$$

$$l = \sqrt{\frac{\alpha}{C_D m D}} \quad (10)$$

with J equal to the total energy slope, g is the gravity acceleration, m is the number of plants per surface area and $\alpha = 0.0227h_v^{0.7}$.

The roughness height of the surface layer, z_0 , and the height of the virtual bed of the surface layer, h_s , are calculated as:

$$z_0 = h_s e^{-M}, \quad (11)$$

$$h_s = \frac{1 + \sqrt{1 + 4L^2 \kappa^2 (h - h_v)/gJ}}{2L^2 \kappa^2 / gJ} \quad (12)$$

where L and M are:

$$L = \frac{k \cosh(h_v/l)}{l \sqrt{2K \sinh(h_v/l) + u_s^2}}, \quad (13)$$

$$M = \frac{\kappa \sqrt{2K \sinh(h_v/l + u_s^2)}}{u_*} \quad (14)$$

and $\kappa = 0.41$ is the Von Kármán constant, while u_* is the shear velocity of the surface layer:

$$u_* = \sqrt{gJ(h - (h_v - h_s))} \quad (15)$$

Once the velocity that characterizes the flow is known (V), it is possible to obtain the vegetation friction coefficient through the Manning or Chézy equations.

2.1.1.3 Baptist et al. (2007) Baptist et al. [29] employed a genetic programming algorithm on synthetic data generated with a 1D model solving a simplified version of the Navier–Stokes equations to develop an expression for the vegetation friction coefficient applicable to submerged and emergent conditions.

$$C = \sqrt{\frac{1}{1/C_b^2 + (C_D m D h_v)/(2g)}} + \frac{\sqrt{g}}{\kappa} \ln \left(\frac{h}{h_v} \right), \quad (16)$$

where C_b is the Chézy coefficient for bare soil.

2.1.1.4 Huthoff et al. (2007) Based on the two-layer theory, Huthoff et al. [44] proposed that the velocity in the vegetation layer is intricately linked to the velocities of the non-vegetated layer. Thus, they defined an equation for the velocity of both layers that considers the bulk properties of the flow and the Kolmogorov theory's definition of turbulent scales.

$$V = \sqrt{\frac{2gJ}{C_D m D}} \left[\sqrt{\frac{h_v}{h}} + \frac{h - h_v}{h} \left(\frac{h - h_v}{s} \right)^{\frac{2}{3} \left(1 - \left(\frac{h}{h_v} \right)^{-5} \right)} \right], \quad (17)$$

here $s = 1/\sqrt{m} - D$ is average distance between plants.

2.1.1.5 Luhar and Nepf (2012) The model developed by Luhar and Nepf [45] asserts that the hydraulic resistance induced by vegetation at the reach scale mainly depends on the blockage factor B_x . This factor is defined as the fraction of the channel cross-section obstructed by vegetation.

$$B_x = \frac{wh_v}{hB}, \quad (18)$$

where, w is vegetation width and B channel width. The relationship between B_x and the Manning coefficient is described by the following equations:

$$n \left(\frac{\sqrt{g}}{Kh^{1/6}} \right) = \left(\frac{C_D ah}{2} \right)^{1/2} \quad B_x = 1, \quad (19)$$

$$n \left(\frac{\sqrt{g}}{Kh^{1/6}} \right) = \left(\frac{C_*}{2} \right)^{1/2} (1 - B_x)^{-3/2} \quad B_x < 1, \quad (20)$$

where $K = 1 \text{ m}^{1/3} \text{ s}^{-1}$ is a constant that corrects the dimensions of the equation, a is the frontal area per unit volume, and $C_* = 0.05 - 0.13$.

In the case of submerged vegetation, the expression becomes:

$$n \left(\frac{\sqrt{g}}{Kh^{1/6}} \right) = \left[\left(\frac{2}{C_*} \right)^{1/2} \left(1 - \frac{h_v}{h} \right)^{3/2} + \left(\frac{2}{C_D ah} \right)^{1/2} \frac{h_v}{h} \right]^{-1} \quad (21)$$

2.2 Study area description

The Piave River, located in the Veneto region of Italy, extends for 220 km and drains a catchment area of 4130 km² before flowing into the Adriatic Sea. This study focuses on a 30 km reach in the lower basin, traversing the municipalities of Ponte di Piave, San Donà di Piave, and Eraclea (Fig. 1). The study area covers approximately 13.65 km² with the river width ranging from 60 and 100 m. The selection of this reach was motivated by its diverse vegetation composition, including arboreal species, shrubs, vineyards, and crops, as well as the availability of water depth data at three hydrometric stations installed by the Regional Agency for Environmental Prevention and Protection of Veneto (ARPAV) on the bridges of Ponte di Piave, San Donà di Piave, and Eraclea [47].

2.3 Vegetation data and friction zones

The Department of Land, Environment, Agriculture, and Forestry TESAF at the University of Padova provided the vegetation data used in this study. The data was collected through field surveys and LiDAR techniques, and it was used to generate two digital raster maps containing information on densities and average tree diameters. Both maps had a resolution of 20 m x 20 m.

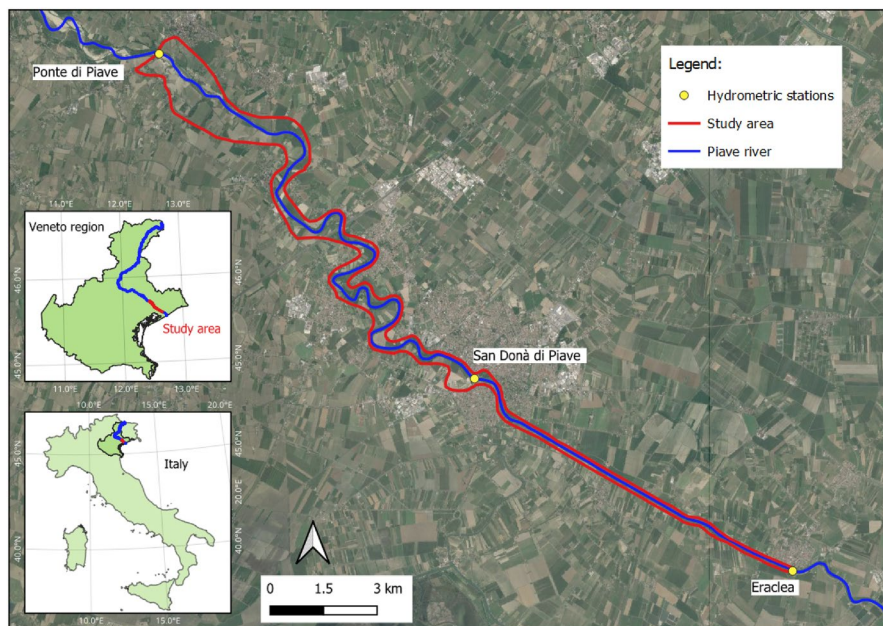


Fig. 1 Location of the study area along the Piave River. Hydrometric stations are denoted by yellow circles, and the model boundary area is highlighted in red

Table 1 Vegetation parameters of the friction zones

ID	Diameters [cm]	Density [tree/Ha]	s [m]
VC	1-5	1000	—
T8	6-15	1200	2.9
T1		1400	2.7
T7		1600	2.5
T6		2000	2.2
T5		3000	1.8
T10	16-25	1200	2.9
T2		1400	2.7
T9		1800	2.4
T3	26-35	1400	2.7
T4	36-60	1400	2.7

s: distance between plants, VC: vineyards and crops, T1 - T10: Tree vegetation

To implement the two-dimensional model, the vegetation data was categorized into 11 distinct friction zones within the study domain. Table 1 reports the diameters, densities, and distances among plants (s) in each category. A constant friction coefficient of $n = 0.035 \text{ s/m}^{1/3}$ was assigned for vineyards and crop fields (VC) based on existing literature [22]. Figure 2 depicts the distribution of friction zones across the study area.

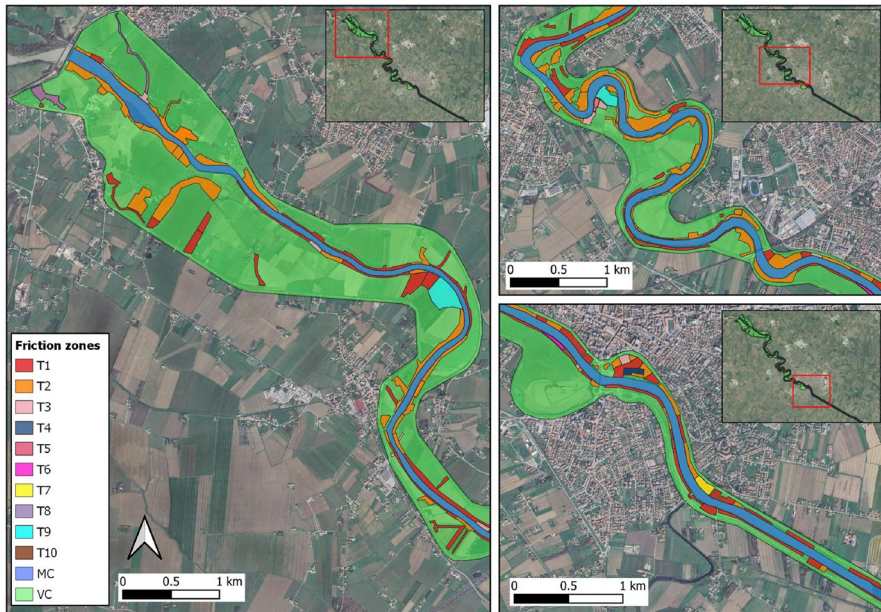


Fig. 2 Distribution of friction zones in the study area. "MC" denotes the main channel, "VC" represents vineyards and crops, while "T1" to "T10" categorizes tree vegetation according to their diameter and density

2.4 Flood event

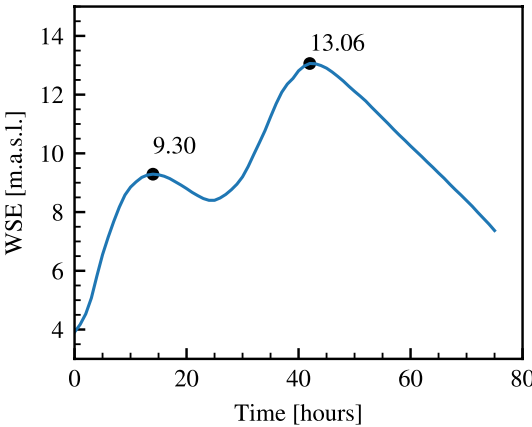
The flood under investigation occurred between October 29th and 31st, 2018 (Fig. 3). It was characterized by intense precipitations and strong winds, resulting in one of the highest peak flows ever recorded [48]. Water levels in the floodplains reached up to 6 m, causing loss of life and substantial damage to forests and infrastructure.

During the event, the hydrometric station at Ponte di Piave (see Fig. 1) registered two peaks, measuring 9.3 and 13 m.a.s.l, corresponding to discharges of 1200 m³/s and 2064 m³/s, respectively, according to ARPAV flow rating curve [49]. Figure 4 shows the water surface elevations (WSE) recorded by the Ponte di Piave hydrometric station.



Fig. 3 Photographs of the flood at Ponte di Piave municipality. The pictures show water levels reached in the floodplain areas and main channel (Source: <https://www.vigilfuoco.tv/veneto/venezia/venezia/sorvolo-elicottero>)

Fig. 4 Water surface elevations at the Ponte di Piave hydrometric station during the flood. The figure shows two peaks: 9.30 m.a.s.l. at 14 h and 13.06 m.a.s.l. at 42 h after the beginning of the event (Source: https://www.arpa.veneto.it/dati-ambientali/dati-indiretta/meteo-idro-nivo/variabili_idro?codsest=300001769 & focus=LIVIDRO)



3 Application of the hydrodynamic model

3.1 Model setup

3.1.1 Computational mesh

The model mesh for the study area was generated from a digital terrain model (DTM) with a resolution of 2 m x 2 m using the software BlueKenue [50]. A grid independence study was carried out to identify the mesh characteristics yielding similar simulation results in less computational time. We tested four grid sizes and compared water depths at a control point. Table 2 illustrates the mesh characteristics, the water depth variations relative to the initial test, and the corresponding simulation times. According to these findings, the selected mesh was an unstructured triangular grid consisting of 106778 elements and 54490 nodes (test 3), with a resolution of 10 m in the river main channel and 25 m in the floodplains (Fig 5). To guarantee model convergence and stability, we implemented a variable time step ensuring a Courant number below 1.

3.1.2 Boundary conditions

Boundary conditions were established based on data collected from the hydrometric stations and the flow rating curve. Accordingly, the flow hydrograph at Ponte di Piave and

Table 2 Grid independence test

Test	Mesh element sizes [m]		Nodes	Elements	Water depth variation [%]	Simulation time [min]
	Channel	Floodplains				
1	5	15	83350	162715	–	571
2	10	10	139609	273297	0.3	956
3	10	25	54490	106778	0.6	372
4	10	30	49256	96558	2.4	337

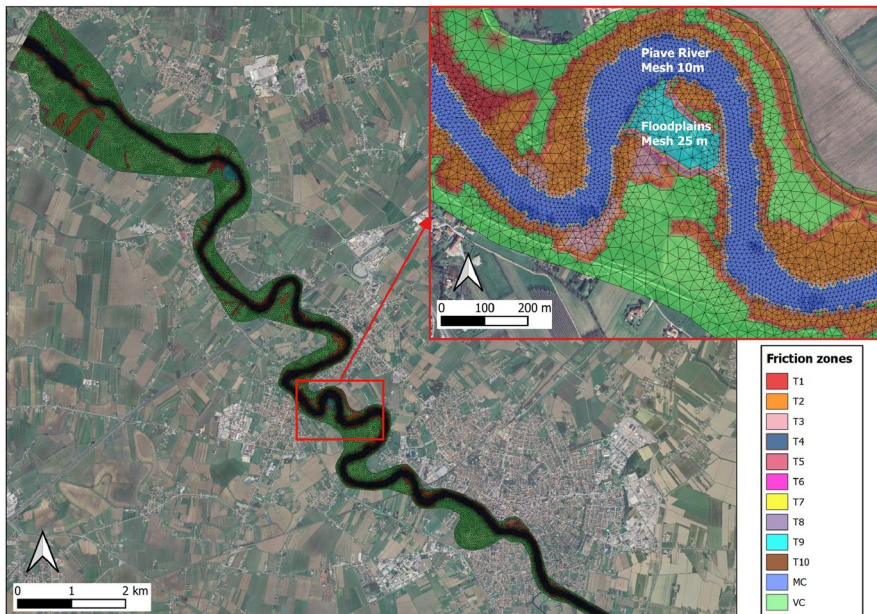


Fig. 5 Mesh of the study area composed of 106778 elements and 54490 nodes. The mesh resolution was 10 m for the river main channel and 25 m for the floodplains

WSE at Eraclea were employed as the upstream and downstream boundary conditions, respectively (Fig. 6a and b).

3.1.3 Friction considerations

Friction formulations were applied for arboreal vegetation using the data detailed in Table 1 and subdividing the mesh according to the friction zones illustrated in Fig. 2.

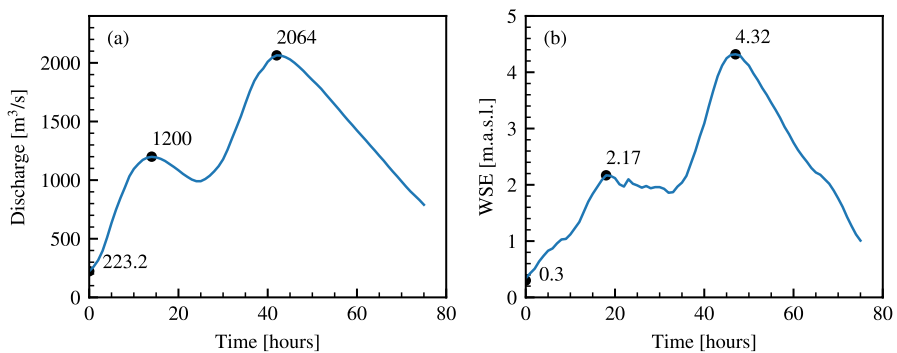


Fig. 6 Boundary conditions: **(a)** Flow hydrograph at Ponte di Piave station displaying the two flood peaks. The first peak recorded a discharge of 1200 m³/s, while the second peak increased to 2064 m³/s. **(b)** Water surface elevations measured at Eraclea station. The highest levels reached 2.17 m.a.s.l. at 18 h and 4.32 m.a.s.l. at 47 h

Given the prevalent arboreal species in the area, a tree height of 10 m was adopted. Since water depths in the floodplains reached up to 6 m, most of the arboreal vegetation was emergent, with the water mainly interacting with the trunk (see Fig. 3). A vegetation drag coefficient equal to 1 was used, consistent with similar studies [32, 40], which suggest that this value minimizes errors in modeling natural vegetation. A constant friction coefficient of $n = 0.035 \text{ s/m}^{1/3}$ was assigned to the crop fields.

During floods, the flow resistance within the main channel experiences variations. The increased flow velocities mobilize larger sediments, alter erosion and deposition patterns, and facilitate the transport of debris such as tree trunks or branches. Additionally, high flows create or modify bedforms like dunes and ripples on the river bed. As a result, the friction coefficient of the main channel becomes dynamic, varying with water depth. To reduce uncertainty, we calibrated this coefficient for high-flow conditions.

Initially, the friction coefficient for the main channel was set at $n = 0.0295 \text{ s/m}^{1/3}$. This value was derived through calibration of a Telemac-2D model under low-flow conditions, using water level and discharge data acquired during a flow measurement campaign [51] conducted with the River Surveyor M9, an ADCP instrument developed by SonTek. Then, varying the friction coefficient within $\pm 10\%$ and $\pm 20\%$ of its initial value, simulations were performed to replicate the highest flood peak. The WSE values obtained from these simulations were compared with the measured value at the San Donà hydrometric station. Among all simulations, the friction coefficient of $n = 0.0325 \text{ s/m}^{1/3}$, representing 10%, resulted in the least mean absolute percentage error (MAPE) of 0.9%. Thus, it was selected as the friction coefficient for the main channel in the flood analysis.

3.1.4 Initial conditions

A steady-state simulation established the required time steps for achieving model convergence. Discharge and water surface elevation (WSE) convergence were assessed at the model boundaries. For this simulation, the initial flow hydrograph value at Ponte di Piave, $223.2 \text{ m}^3/\text{s}$, was set as the upstream boundary condition, while the initial water level at Eraclea, 0.3 m.a.s.l. , served as the downstream condition (Fig. 6). The model stability for both variables was attained after 40000-time steps (Fig. 7). The computational time for this simulation was 45 min, utilizing an Intel(R) Core(TM) i7-4790 CPU @ 3.60GHz. The

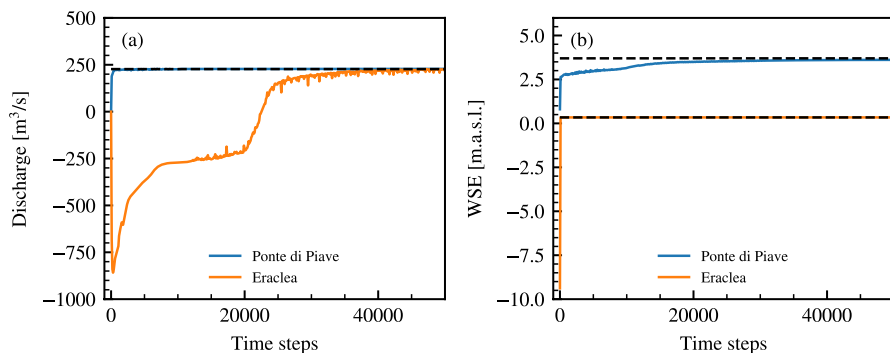


Fig. 7 Model convergence: (a) Discharge set to $223.2 \text{ m}^3/\text{s}$ at both boundaries. (b) Water surface elevation stabilize at 3.8 m.a.s.l. at Ponte di Piave and 0.33 m.a.s.l. at Eraclea

steady-state simulation results were used as the initial condition for the unsteady simulation, providing a converging baseline.

3.2 Model performance

Simulations were carried out under unsteady-state conditions using five vegetation friction formulas. Figure 8 compares the differences in water levels along the river reach during the second flood peak for all formulas. The water level differences were calculated relative to the results obtained using the Baptist et al. formula. All vegetation friction models exhibited similar performance, with differences in the order of centimeters (maximum 6 cm for Huthoff at the San Donà di Piave station). This finding aligns with the observations made by Folke et al. [32] in their study on the Rhine River. The results could be attributed to the relatively small area covered with arboreal vegetation within the study domain. Specifically, only approximately 20% (2.8 km²) of the total simulated area (13.65 km²) is occupied by arboreal vegetation. The remaining 80% were vineyards and crops modeled with a constant friction coefficient.

The performance of the vegetation friction models was assessed using the water surface elevation (WSE) data collected during the flood at the intermediate hydrometric station, San Donà di Piave. This station was selected because of its distance from the boundary conditions. Figure 9a compares the measured WSE values at the San Donà di Piave section with the simulated results from the vegetation friction equations.

The simulations generally overestimated water levels throughout the flood, except for the highest peak, which is accurately simulated. At this point, the observed data registered 7.59 m.a.s.l., while the simulated values ranged between 7.61 and 7.66 m.a.s.l. (relative errors of 0.2% - 0.9%). However, during the first peak, the water levels were overestimated by approximately 1 m, resulting in a relative error of 26%. Additionally, all models exhibited a time lag of around 3.5 hours compared to the measured values.

The observed discrepancies between the results of the models and the measured data can be attributable to several factors. Firstly, the model does not currently consider the additional flow resistance induced by bushes or shrubs, which represent undergrowth vegetation. This vegetation has a higher impact during low and intermediate flow conditions, which could explain the higher disparities found during the first flood peak. When

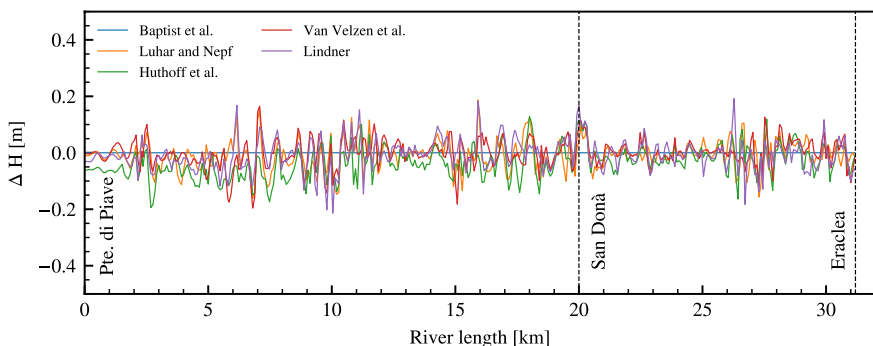


Fig. 8 Differences in water level between the Baptist formula and the other vegetation friction formulas at the second peak along the river reach

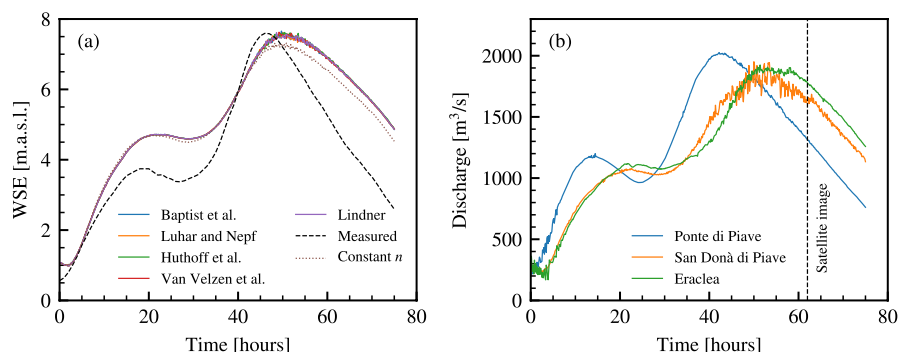


Fig. 9 **a** Water surface elevation simulated by the vegetation friction models and the observed values at San Donà di Piave during the flood. **b** Simulated flow hydrographs obtained using the formula of Baptist et al. The curve at Ponte di Piave represents the upstream boundary condition for the model. The dashed vertical line marks the time at which the satellite image was captured

submerged, such vegetation can create turbulence and instabilities associated with the transition from emergent to submerged states, which, added to the variation of velocities between the vegetated and non-vegetated layers, influences flow resistance.

Another aspect concerns the underlying physics of the vegetation friction models implemented in this study. The approaches employed treat vegetation as rigid elements, disregarding the effects of deformation and flexibility. When the force exerted by the current exceeds the flexural rigidity of the stem, plants tend to bend, modifying both geometry and cross-section, thereby affecting flow velocity, drag force, and the resulting friction coefficient. This phenomenon might be relevant for specific crop species, undergrowth vegetation, and small-diameter trees, particularly at high flow velocities. Accounting for such effects could potentially improve the results of this study. Hence, given the significant heterogeneity in natural environments, formulations incorporating the flexibility of different plant species should be included to cover a wide range of species in the analysis.

In the absence of field data, a conventional practice for modeling vegetation effects is to adopt a constant value from the literature. However, this practice can introduce errors because friction coefficients depend on vegetation characteristics and water depth. To illustrate this limitation in our study, Fig. 9a depicts the WSE predicted by a simulation using a constant friction value of $0.08 \text{ s/m}^{1/3}$ [22], corresponding to bushes and trees.

Similar to the vegetation friction models, the constant n simulation overestimated the WSE by 26% at the first peak. But, at the second peak, it was underestimated by 30 cm (a relative error of 4%). The results using the constant n were quite similar to those using the vegetation models, except close to the highest peak and afterward, where the differences were more pronounced. This similarity can be explained by the small area covered by arboreal vegetation within the modeled domain. However, it is likely that in scenarios with a higher proportion of arboreal vegetation, the discrepancies between the constant Manning approach and the vegetation equations would be more evident.

Considering the similar performance observed with all vegetation friction equations examined in this study, the maps and figures presented in the rest of this paper utilize the results obtained from the equation of Baptist et al [29].

Figure 9b displays the simulated flow discharge at the three hydrometric stations. The two flood peaks are visible at the San Donà and Eraclea stations. The rectilinear shape of

the river in this segment allows for an almost simultaneous propagation of the flood wave at these two stations. The time difference between the arrival of the peak flow from the upstream to the downstream station was approximately 7 h for the first peak and 9 h for the second peak.

In general, the simulated flow hydrographs agree well with the observed data in terms of both discharge and flood wave propagation. At the peak of the first flood wave, the simulated discharge was 1200 m³/s at Ponte di Piave and 1078 and 1118 m³/s at San Donà and Eraclea, respectively. For the second peak, the simulated discharge was 2064 m³/s at Ponte di Piave and 1950 and 1925 m³/s at San Donà and Eraclea. The lower discharge values obtained at San Donà and Eraclea suggest an attenuation of the flood wave due to the retention capacity of the floodplains.

Validating hydrodynamic models for river floods is a complex task, as gauging stations mainly collect water level data within the main channel, while floodplain areas often lack instrumentation. Thus, direct comparisons between simulated and observed water levels across entire cross-sections and flood extents are difficult. We employed a visual validation to determine the model's capability to replicate the flood extent. The flooded area in a Sentinel satellite image captured on October 31st at 10:11:40 UTC (Fig. 10) was compared to the flooded area simulated at the same time (Fig. 9b). The results of this comparison are shown in Fig. 11.

The numerical simulation results indicate extensive inundation of the floodplains at the specified time. At some locations, water depths reached up to 6 m, while areas furthest from the main channel, particularly near Ponte di Piave and the downstream rectilinear reach, had water depths of less than 0.5 m. Overall, the flood extension depicted in the satellite image (shown by the orange polygon in Fig. 11) aligns well with the numerical model output.

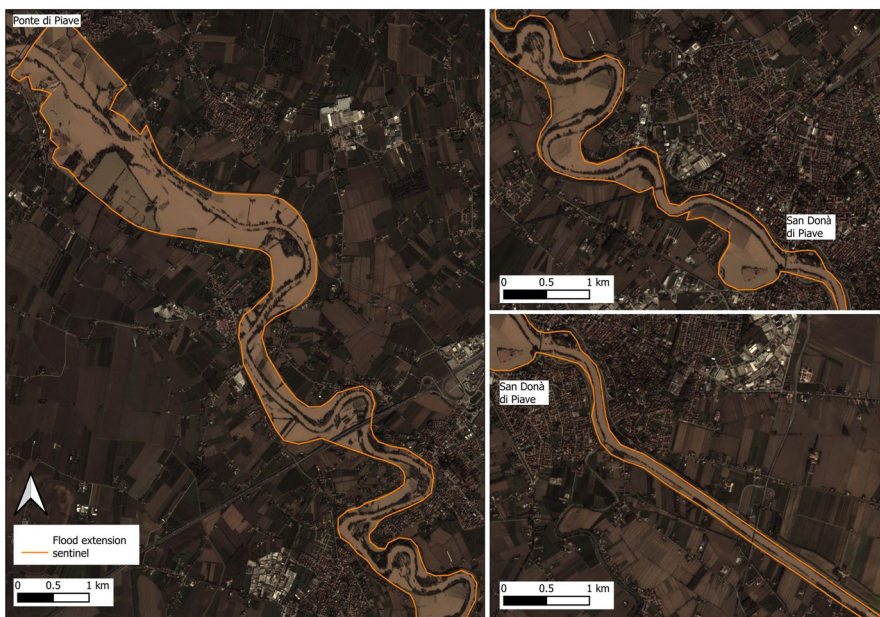


Fig. 10 Sentinel-2 L2A image depicting the extent of flooding on October 31st at 10:11:40 UTC (62 h of the numerical model)



Fig. 11 Flood extent and water depths simulated at the time of the satellite image. The orange polygon outlines the flood extension observed in the satellite image

Figure 12 presents the simulated scalar velocities during the second peak of the flood. The highest velocities, reaching up to 2 m/s occur within the main channel. In the floodplains, velocities vary depending on land cover. Velocities in arboreal vegetation areas ranged from 0.05 to 0.6 m/s, while cultivated areas reached up to 1.2 m/s. The figure shows that velocities are lower (below 0.4 m/s) in the initial part of the domain, where floodplains are wider. In contrast, the meandering section of the river exhibits higher velocities of up to 1.4 m/s.

3.3 Vegetation friction coefficients

Vegetation friction coefficients depend on the vegetation characteristics and flow conditions [10], implying that the friction coefficient for a specific plant will vary over time during a flood event. For instance, in the case of arboreal vegetation, the Manning values tend to increase with the flow depth. Considering this, we generated vegetation friction maps at different times of the studied flood.

Figure 13 illustrates the predicted friction coefficients using the Baptist equation at three stages of the flood: the beginning of the event, the first peak, and the second peak.

The maps indicate that the Manning coefficient remained constant and equaled $0.0325 \text{ s/m}^{1/3}$ at the start of the flood, as all the water remained within the main channel. However, fourteen hours later, the first peak occurred, and the water began to overflow into the

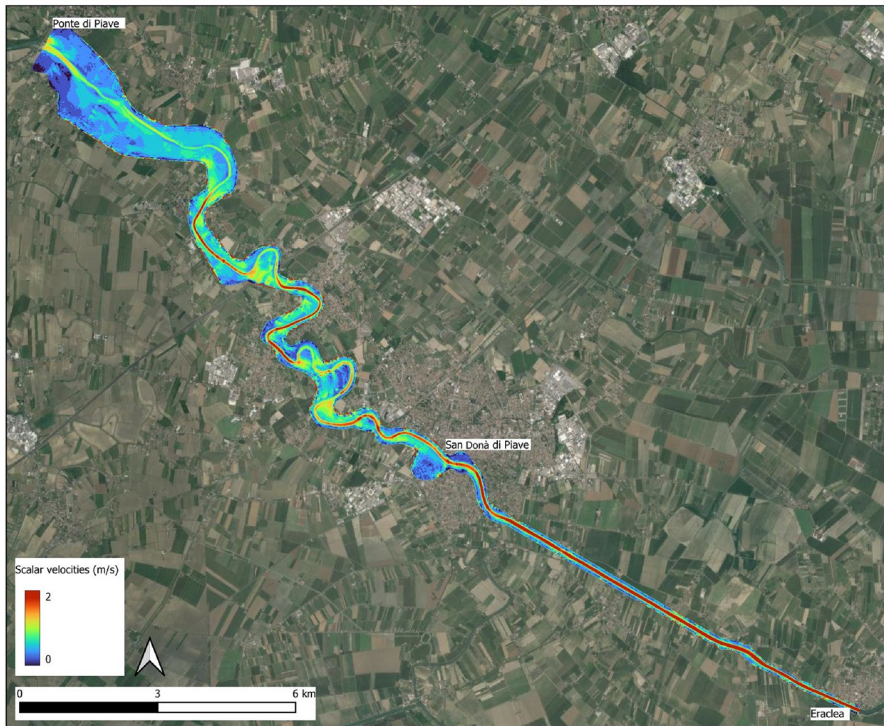


Fig. 12 Scalar velocities simulated at the second peak of the flood event

floodplains. Since vegetation creates flow resistance, friction values start to vary based on the type and density of vegetation and the flow depth. In areas closest to the main channel, where arboreal vegetation predominates, n values ranged from 0.040 to 0.067 $\text{s/m}^{1/3}$. Approximately 28 h later, the second peak arrived, completely inundating the floodplain areas. In this case, the friction coefficients increased due to high water depths, with Manning values fluctuating between 0.050 and 0.20 $\text{s/m}^{1/3}$. As expected, areas with denser vegetation exhibited higher Manning coefficients.

Table 3 presents the Manning coefficients simulated for each arboreal vegetation zone during the first and second peaks. The results reveal a general trend of increased Manning coefficients during the second peak compared to the first for higher diameters and densities. Generally, larger diameters, higher densities, and deeper water levels contribute to higher flow resistance. Nevertheless, during the first peak, the Manning coefficients show a minimal variation for the same densities and different diameters. This is explained by the spatial distribution of vegetation and the flow conditions in those areas.

3.4 Simulations with various vegetation scenarios

Additional simulations were performed to examine how the variations in densities and areas covered by arboreal vegetation affect water levels within the study area. Table 4 details the densities and percentage of areas employed in seven scenarios along with the actual field conditions. Scenarios 1 to 3 explored the effects of changing density while

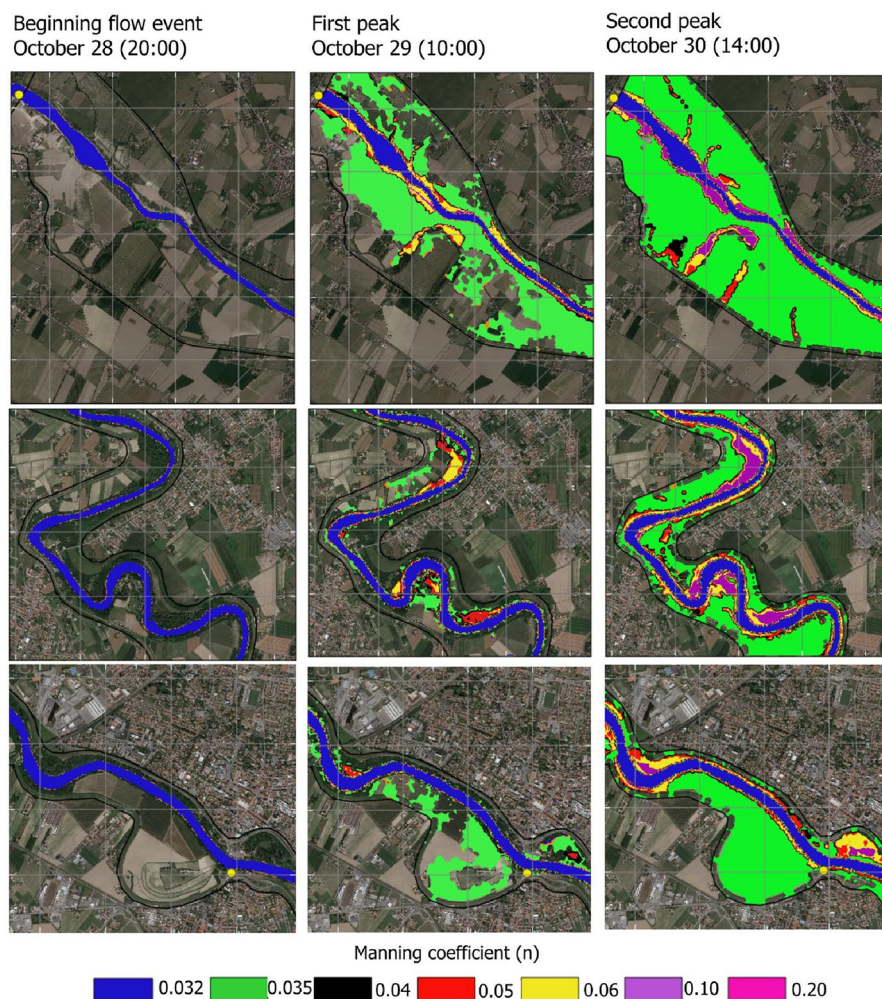


Fig. 13 Predicted Manning coefficients based on the Baptist friction approach at three different stages of the flood: the beginning of the event, the first peak, and the second peak

maintaining a constant 20% arboreal vegetation cover, corresponding to the real value. These scenarios investigated densities from 1000 to 3000 trees per hectare. Scenarios 4 to 7 examined the impact of increased area coverage. In these scenarios, the area covered by arboreal vegetation increased by 40 to 70%. To achieve these percentages, areas previously occupied by vineyards and crops were replaced with arboreal vegetation at a constant density of 2000 trees per hectare. This density was selected as the median density value within the study area (see Table 1).

Figure 14a displays the simulated water levels during the second peak for scenarios 1 to 3, compared to the actual scenario with existing vegetation density. The results pointed out the influence of vegetation density in the reach between Ponte di Piave and San Donà. This area has extensive floodplains and higher vegetation than the rectilinear river reach (from San Donà to Eraclea). As shown in the figure, reducing vegetation

Table 3 Manning coefficients simulated for different vegetation zones

ID	Diameters [cm]	Density [tree/Ha]	n [s/m ^{1/3}]	
			First peak	Second peak
T8	6-15	1200	0.04	0.05
T1		1400	0.05	0.05 - 0.1
T7		1600	0.05	0.067
T6		2000	No data ¹	0.1
T5		3000	No data ¹	0.067
T10	16-25	1200	0.04	0.067
T2		1400	0.05 - 0.067	0.05 - 0.2
T9		1800	0.05	0.1
T3	26-35	1400	0.04 - 0.067	0.067 - 0.1
T4	36-60	1400	0.05	0.1

¹This zone was not flooded during the first peak

Table 4 Vegetation variables of the simulated scenarios

Case	Density [tree/ha]	Area [%]
1	1000	20
2	2000	
3	3000	
4	Real & 2000	40
5		50
6		60
7		70
Actual	1125 ¹	20

¹ Weighted average density

density to 1000 trees per hectare (lower than the average) led to an average decrease in water levels of 10 cm within the Ponte di Piave and San Donà reach, with a maximum decrease of 30 cm. Scenarios 2 and 3, which simulated vegetation densities approximately twice and three times the average density, respectively, showed average water level increases of 10 and 20 cm in the same reach. However, localized increases of up to 30 and 45 cm were also observed. The impact of vegetation density on water levels was less pronounced in the rectilinear reach. In this case, average water level differences were -2, 2, and 7 cm for vegetation densities of 1000, 2000, and 3000 trees per hectare, respectively.

The comparison of water levels during the second peak of scenarios 4 to 7 is depicted in Fig. 14b. These simulations revealed that the most significant water level variations occurred within the first 12 km of the river, with higher values observed at Ponte di Piave. As the area covered by arboreal vegetation expanded from 40 to 70% (2 and 3.5 times greater than the actual area, respectively), water levels at this point increased linearly from 30 cm to 60 cm. The average rise in water level was moderate along the first 20 km of the river reach (from Ponte di Piave to San Donà). These increases were 6 cm for an increment of 40 and 50% of the arboreal vegetation area,

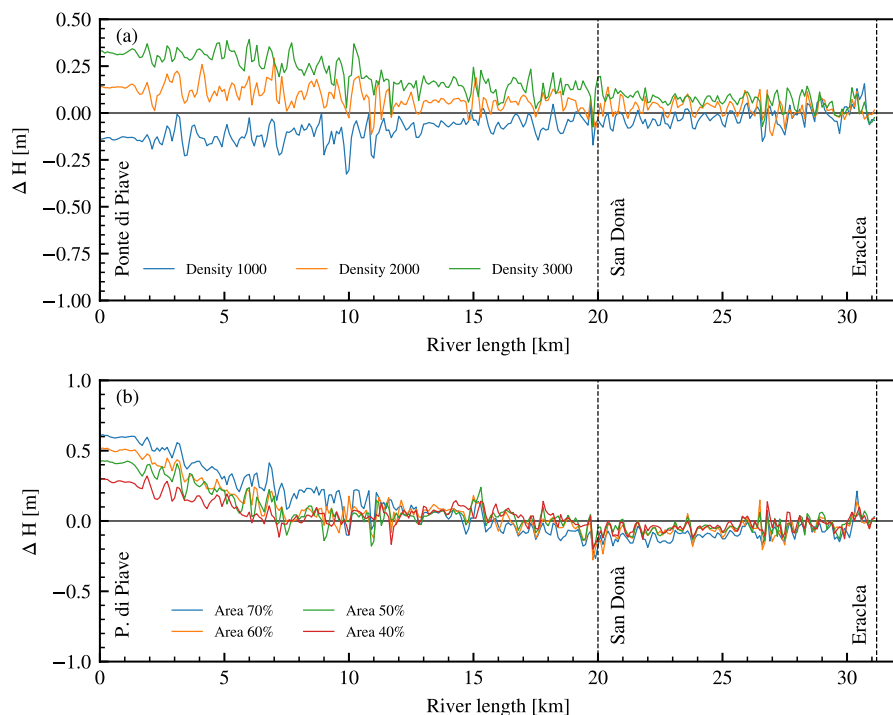


Fig. 14 Comparison of water levels among vegetation scenarios and the actual scenario during the second flood peak along the river reach: **a** Scenarios 1 to 3. **b** Scenarios 4 to 7

10 cm for 60%, and 15 cm for 70%. In the rectilinear reach, the water levels decreased in all scenarios, with average values ranging from -4 to -10 cm.

The additional simulations aimed to quantitatively assess how changes in arboreal vegetation, in terms of density and coverage, affect floodwater levels. The findings from this case study suggest that maintaining the small vegetated area (20%) while increasing densities has a more uniform effect on water levels along the entire river reach, as evidenced in scenarios 1 to 3. In contrast, expanding arboreal coverage has a more pronounced and localized effect on water levels, particularly influencing downstream areas. The outcomes of scenarios 4 to 7 indicate that an increase in arboreal vegetation leads to water accumulation at Ponte di Piave, resulting in reduced water levels downstream in San Donà and Eraclea.

These proposed scenarios can be valuable for planning vegetation management strategies. Conventional approaches often prioritize vegetation removal to mitigate flood risk. However, this analysis confirms a trade-off: while vegetation can elevate water levels locally, it also contributes to delaying and attenuating peak flows downstream, providing flood protection to urbanized areas. Therefore, the findings emphasize the importance of implementing management practices that balance risk mitigation and ecological considerations.

4 Conclusions

Numerical studies validating vegetation friction models on a river scale are scarce due to the lack of necessary flow and vegetation data. This study evaluated the performance of five vegetation friction formulas under unsteady-state flow within the Telemac-2D hydrodynamic model, applied along a reach of the Piave River. To accomplish this, we employed arboreal vegetation data gathered through field surveys and LiDAR, coupled with data from the October 2018 flood event.

The study did not reveal significant differences in water depths, velocities, or friction coefficients among the vegetation approaches examined. Therefore, it was inconclusive which formula performed best in this specific case. The predicted water levels in the validation section (San Donà di Piave) generally exceeded the measured values. However, the model accurately simulated the highest flood peak, with an error in water levels less than 1%, and an error propagation time of 3.5 h. Regarding flood extension, the numerical results exhibited an overall agreement with the satellite image observations. The Manning coefficients induced by the arboreal vegetation ranged from 0.040 to 0.067 $\text{s/m}^{1/3}$ during the first peak and increased from 0.05 to 0.20 $\text{s/m}^{1/3}$ at the second peak due to the increased water depth.

Incorporating undergrowth vegetation, such as bushes and trees, into the analysis would provide a more comprehensive understanding of flow resistance throughout a flood event, particularly during low and moderate flow conditions when their influence is more significant. Additionally, implementing vegetation friction models that consider the vegetation bending and swaying characteristics could improve simulation accuracy.

To investigate the effects of varying densities and coverage of arboreal vegetation on water levels during the examined flood, additional simulations were conducted. The reach between Ponte di Piave and San Donà exhibited the most significant fluctuations in water levels. For this case study, maintaining the covered area and increasing densities had a uniform effect on water levels along the entire river reach. On the other hand, expanding arboreal coverage resulted in more localized and pronounced variations, increasing substantially water levels upstream while reducing them downstream. Considering that conventional management strategies often prioritize vegetation removal, the proposed scenarios highlighted the importance of effective vegetation management practices emphasizing a balance between risk mitigation and environmental protection.

Given the advantages of remote sensing techniques for field data collection, it is strongly advised to pursue further applications to validate vegetation friction equations at the river scale using this data source. Furthermore, the accessibility and versatility of open-source software, such as Telemac, provide an opportunity to implement and analyze different vegetation friction approaches based on existing literature. This not only enhances the scalability of studies but also encourages collaborative research efforts, thus contributing to a better understanding of the complex interactions between vegetation and river hydrodynamics.

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Code availability Not applicable.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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Consent for publication Not applicable.

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References

1. Zelenáková M, Gaňová L, Purcz P, Horský M, Satrapa L, Blišťan P, Diaconu DC (2017) Mitigation of the adverse consequences of floods for human life, infrastructure, and the environment. *Natural Hazards Rev* 18(4):255. [https://doi.org/10.1061/\(ASCE\)NH.1527-6996.0000255](https://doi.org/10.1061/(ASCE)NH.1527-6996.0000255)
2. Dottori F, Mentaschi L, Bianchi A, Alfieri L, Feyen L (2020) Adapting to rising river flood risk in the eu under climate change. Joint Res Centre (JRC). <https://doi.org/10.2760/14505>
3. Bianchi C, Salvati P (2022): Rapporto periodico sul rischio posto alla popolazione italiana da frane e inondazioni. Istituto di Ricerca per la Protezione Idrogeologica (IRPI). Consiglio Nazionale delle Ricerche (CNR) . <https://polaris.irpi.cnr.it/wp-content/uploads/rapporto-semester-2023.pdf> (Accessed October 6, 2023)
4. Milly PCD, Wetherald RT, Dunne K, Delworth TL (2002) Increasing risk of great floods in a changing climate. *Nature* 415(6871):514–517
5. Wetherald RT, Manabe S (2002) Simulation of hydrologic changes associated with global warming. *J Geophys Res Atmosph* 107(D19):7–1715. <https://doi.org/10.1029/2001JD001195>
6. Bronstert A (2003) Floods and climate change: interactions and impacts. *Risk Anal* 23(3):545–557. <https://doi.org/10.1111/1539-6924.00335>
7. Rutherford I, Anderson B, Ladson A (2007) Managing the effects of riparian vegetation on flooding. *Principles for Riparian Lands Management*. Edited by S. Lovett, and P. Price. Land and Water Australia, Canberra, pp 63–84
8. Majone U (2007) La Sistemazione dei Versanti e dei Corsi D'acqua Montani. Nuova Editoriale Bios, Cosenza
9. Sellin R, Van Beesten D (2004) Conveyance of a managed vegetated two-stage river channel. *Proce Inst Civ Eng Water Manag* 157:21–33
10. D'Ippolito A, Calomino F, Alfonsi G, Lauria A (2021) Flow resistance in open channel due to vegetation at reach scale: a review. *Water* 13(2):116

11. Wu F-S (2008) Characteristics of flow resistance in open channels with non-submerged rigid vegetation. *J Hydrodyn Ser B* 20(2):239–245
12. Huai W-X, Wu Z-L, Qian Z-D, Geng C (2011) Large eddy simulation of open channel flows with non-submerged vegetation. *J Hydrodyn* 23(2):258–264
13. Li Y, Du W, Yu Z, Tang C, Wang Y, Anim DO, Ni L, Lau J, Chew SA, Acharya K (2015) Impact of flexible emergent vegetation on the flow turbulence and kinetic energy characteristics in a flume experiment. *J Hydro-Environ Res* 9(3):354–367
14. Li S, Shi H, Xiong Z, Huai W, Cheng N (2015) New formulation for the effective relative roughness height of open channel flows with submerged vegetation. *Adv Water Resour* 86:46–57
15. Huai W, Zeng Y, Xu Z, Yang Z (2009) Three-layer model for vertical velocity distribution in open channel flow with submerged rigid vegetation. *Adv Water Resour* 32(4):487–492
16. Caroppi G, Gualtieri P, Fontana N, Giugni M (2018) Vegetated channel flows: turbulence anisotropy at flow-rigid canopy interface. *Geosciences* 8(7):259
17. Cheng N-S (2015) Single-layer model for average flow velocity with submerged rigid cylinders. *J Hydraul Eng* 141(10):06015012
18. Yang F, Huai W-X, Zeng Y-H (2020) New dynamic two-layer model for predicting depth-averaged velocity in open channel flows with rigid submerged canopies of different densities. *Adv Water Resour* 138:103553
19. Liu D, Diplas P, Fairbanks J, Hodges C (2008) An experimental study of flow through rigid vegetation. *J Geophys Res Earth Surface* 113(F4):1024
20. Huai W-X, Zhang J, Katul GG, Cheng Y-G, Tang X, Wang W-J (2019) The structure of turbulent flow through submerged flexible vegetation. *J Hydrodyn* 31:274–292
21. Shields FD Jr, Coulton KG, Nepf H (2017) Representation of vegetation in two-dimensional hydrodynamic models. *J Hydraul Eng* 143(8):02517002
22. Chow VT (1959) *Open-Channel Hydraul*. McGraw-Hill Book Company, New York, p 1
23. Arcement G.J, Schneider V.R (1989) *Guide for selecting manning's roughness coefficients for natural channels and flood plains*
24. Wang J, Zhang Z (2019) Evaluating riparian vegetation roughness computation methods integrated within hec-ras. *J Hydraul Eng* 145(6):04019020. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001597](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001597)
25. Mason DC, Cobby DM, Horritt MS, Bates PD (2003) Floodplain friction parameterization in two-dimensional river flood models using vegetation heights derived from airborne scanning laser altimetry. *Hydrolog Process* 17(9):1711–1732
26. Kouwen N, Unny TE (1973) Flexible roughness in open channels. *J Hydraul Div* 99(5):713–728. <https://doi.org/10.1061/JYCEAJ.0003643>
27. Fathi-Maghadam M, Kouwen N (1997) Nonrigid, nonsubmerged, vegetative roughness on floodplains. *J Hydraul Eng* 123(1):51–57. [https://doi.org/10.1061/\(ASCE\)0733-9429\(1997\)123:1\(51\)](https://doi.org/10.1061/(ASCE)0733-9429(1997)123:1(51))
28. Straatsma MW, Baptist M (2008) Floodplain roughness parameterization using airborne laser scanning and spectral remote sensing. *Remote Sens Environ* 112(3):1062–1080
29. Baptist MJ, Babovic V, Uthurburu JR, Keijzer M, Uittenbogaard RE, Mynett A, Verwey A (2007) On inducing equations for vegetation resistance. *J Hydraul Res* 45(4):435–450. <https://doi.org/10.1080/00221686.2007.9521778>
30. Abu-Aly TR, Pasternack GB, Wyrick JR, Barker R, Massa D, Johnson T (2014) Effects of lidar-derived, spatially distributed vegetation roughness on two-dimensional hydraulics in a gravel-cobble river at flows of 0.2 to 20 times bankfull. *Geomorphology* 206:468–482. <https://doi.org/10.1016/j.geomorph.2013.10.017>
31. Katul G, Wiberg P, Albertson J, Hornberger G (2002) A mixing layer theory for flow resistance in shallow streams. *Water Resour Res* 38(11):32–110
32. Folke F, Kopmann R, Dalledonne G, Attieh M (2019) Comparison of different vegetation models using telemac-2d. In: XXVth TELEMAC-MASCARET User Conference, 15th to 17th October 2019, Toulouse
33. Järvelä J (2004) Determination of flow resistance caused by non-submerged woody vegetation. *Int J River Basin Manag* 2(1):61–70
34. Lindner K (1982) *Der Strömungswiderstand Von Pflanzenbeständen*. Mitteilungen (Technische Universität Braunschweig. Leichtweiss-Institut für Wasserbau). Leichtweiss-Inst. für Wasserbau d. Techn. Univ., Braunschweig
35. Chaulagain S, Stone M.C, Dombroski D, Gillihan T, Chen L, Zhang S (2022) An investigation into remote sensing techniques and field observations to model hydraulic roughness from riparian vegetation. *River Research and Applications*

36. Whittaker P, Wilson CA, Aberle J (2015) An improved cauchy number approach for predicting the drag and reconfiguration of flexible vegetation. *Adv Water Resour* 83:28–35
37. Folke F, Attieh M, Kopmann R (2019) In search of friction laws for vegetated flow within 2d large-scale applications. In: E-proceedings of the 38th IAHR World Congress, Panama City, Panama
38. Li J, Claude N, Tassi P, Cordier F, Crosato A, Rodrigues S (2020) Implementation of a novel approach accounting for the influence of vegetation on sediment transport in gaia. In: online proceedings of the papers submitted to the 2020 TELEMAT-MASCARET user conference October 2020, pp. 2–8
39. Dalledonne G, Kopmann R, Brudy-Zippelius T (2019) Uncertainty analysis of floodplain friction in hydrodynamic models. *Hydrol Earth Syst Sci Discuss* 10:3373–3385
40. Morri M, Soualmia A (2019) Modeling the impact of riparian vegetation on flow structure and bed sediment distribution in rivers. *Arch Hydro-Eng Environ Mechn* 66:3–4
41. Hervouet J-M (2007) *Hydrodynamics of free surface flows: modelling with the finite element method*. Wiley, Chichester, England
42. Pavlíček M, Bruland O (2019) Numerical modelling of flash flood event in steep river using telemac 2d and sisyphe. In: TELEMAT MASCARET user conference
43. Van Velzen E.H, Jesse P, Afvalwaterbehandeling R.R, Cornelissen P, Coops H (2003) *Stromingsweerstand Vegetatie in Uiterwaarden: Deel 1 Handboek. Versie 1-2003. RIZA rapport. Ministerie van Verkeer en Waterstaat, Directoraat-Generaal Rijkswaterstaat, RIZA Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling, Lelystad, Netherlands*
44. Huthoff F, Augustijn DCM, Hulscher SJMH (2007) Analytical solution of the depth-averaged flow velocity in case of submerged rigid cylindrical vegetation. *Water Resour Res* 43(6):5625. <https://doi.org/10.1029/2006WR005625>
45. Luhar M, Nepf HM (2013) From the blade scale to the reach scale: a characterization of aquatic vegetative drag. *Adv Water Resour* 51:305–316. <https://doi.org/10.1016/j.advwatres.2012.02.002>
46. Klopstra D, Barneveld H, Van Noortwijk J, Van Velzen E (1996) Analytical model for hydraulic roughness of submerged vegetation. In: proceedings of the congress-international association for hydraulic research, pp. 775–780 . Local Organizing Committee of the XXV Congress
47. ARPAV: Hydrometric station data. https://www.arpa.veneto.it/dati-ambientali/dati-in-diretta/meteo-idro-nivo/variabili_idro
48. ARPAV: Relazione evento 27/10/2018 - 01/11/2018. Regione del Veneto (2019)
49. ARPAV: Livelli e portate medie giornaliere del fiume Piave a Ponte di Piave periodo 2008-2017. Regione del Veneto (2018)
50. National Research Council Canada: BlueKenue. <https://nrc.canada.ca/en/research-development/products-services/software-applications/blue-kenuetm-software-tool-hydraulic-modellers>
51. Herrera Gómez V, Ravazzani G, Mancini M, Marchi N, Lingua E, Ferri M (2023) Monitoring discharge in vegetated floodplains: a case study of the Piave river. *Water* 15(19):3470

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