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Influence of Riparian Vegetation on River Morphodynamics: A Numerical Modeling Framework

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Abstract

Riparian vegetation plays an important role in the morphological evolution of rivers; here, an alternative numerical methodology for modeling river morphodynamics influenced by vegetation is presented. The approach integrates a vegetation growth and flow-resistance submodule coupled with the TELEMAC–MASCARET system. Vegetation is represented at the patch scale, and its hydraulic effect is incorporated through an additional drag force in the momentum equation, while stem obstruction is accounted for using the porosity formulation in TELEMAC-2D. Vegetation dynamics consider water depth variability, interspecific competition, and nutrient availability. The model is applied to a braided river reach in southeastern Mexico. The results indicate that riparian vegetation promotes more organized flow paths, enhances bar development, and plays a significant role in modulating bar stability. These findings highlight the importance of explicitly representing flow–sediment–vegetation feedback in river hydro-morphological modeling.

Keywords: river morphodynamics; riparian vegetation; numerical modeling; TELEMAC

1. Introduction

Riparian vegetation is pervasive in rivers worldwide, and its presence not only alters the hydraulic characteristics of flow but also modulates deposition and erosion processes; furthermore, vegetation adds resistance and acts as a barrier to flow in proportion to its size. For instance, plant growth holds up bars and islands through deposition, a positive feedback condition for more vegetation development [1,2]. Additionally, vegetation can modulate the development of meanders by reducing riverbank erosion and modifying secondary flow. In this way, riparian vegetation also impacts river morphodynamics, reorganizing the channel and riverplain characteristics [2–4].

A number of studies have focused on including vegetation in morpho-hydraulic models as static elements parameterized by equivalent bed roughness, drag, or friction [5–13]; however, the use of friction coefficients only reflects the flow resistance of vegetation on the riverbed [14] but does not represent the effects of emergent canopy [15] since in such cases the flow through canopy is not fully turbulent, which is a necessary criterion for applying the Manning equation [16].

Furthermore, the drag approach typically considers the influence of the canopy at the local scale (isolated elements), with a higher computational cost, or at the patch scale using stem density, which can overestimate flow resistance. For example, De Doncker et al. [17] estimated the temporal variation in Manning coefficients for two vegetated rivers. They



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found a value of $n = 0.04 \text{ s m}^{-1/3}$ without vegetation and a value of $n = 0.4 \text{ s m}^{-1/3}$ when plants were present.

The experimental results reported by Ben Meftah et al. [18] showed a patch effect through a regular array of rigid and emergent cylinders. Their study suggests that transversal flow velocity in the interface between the non-vegetated and the canopy area can be estimated by a log-law; nevertheless, the experimental setup did not consider flow-induced plant deformations. Furthermore, works such as those of Luhar & Nepf and Nepf [19,20] had focused on linking the flow-vegetation interaction from individual scale to patch and river reach scales.

These works point out the importance of considering the non-uniform spatial distribution of the canopy and the reconfiguration effect in the characterization of flow resistance. Therefore, the use of simple rough parameterizations, such as stiff cylinders with constant drag or friction coefficients, can lead to biased estimations.

Alternative methods have been developed to deal with the impact of different stages of the vegetation life cycle on flow (e.g., [21–29]). Typically, these models are either based on rigid and isolated elements or are parameterized based on vegetation biomass to account for the impact at the patch scale. Nonetheless, approaches that use single elements and neglect the patch effect of plants, or the difficulty of representing bed roughness based on biomass, may limit the scope of their application.

For instance, the model presented by Nicholas et al. [22,23] considers two categories of grid cells for numerical modeling: active riverbed (permanently inundated) and floodplain (sometimes or never inundated). Riverbed cells are converted into floodplain cells, with higher roughness (due to vegetation growth), when the maximum water depth over a specified time exceeds a given threshold. Perucca et al. [24] adopted three models of biomass distribution for modulating riverbank erodibility: one based on water table fluctuations, another considering the extinguishing effect of vegetation due to floods, and a third one that combines both effects with the sedimentation effect. However, the model is based on a linear solution for meander migration [30], which assumes a constant channel width.

Similarly, Toda et al. [29] introduced a model considering an initial biomass and a diffusion equation for modeling vegetation growth; the destruction of vegetation is considered through a threshold of shear strength corresponding to flushing (scour depth). However, the diffusion equation needs several parameters to represent vegetation expansion or reduction.

On the other hand, the RIPVEG model [25–28] not only considers vegetation cover on the floodplain but also incorporates root reinforcement for riverbanks; additionally, the model employs a logistic sigmoid equation that considers physical traits such as age and lifespan to simulate the growth and mortality of plants. The RIPVEG model approach does not require biomass data, which usually is not available due to the variety of species and uncertainties in its estimation, but its main disadvantage is that it only represents one species of vegetation in each node of the computational mesh.

Although advancements in numerical modeling of river morphodynamics influenced by riparian vegetation have been progressive in recent years, improvements are still required to more accurately represent the complex physical processes associated with riverine vegetation and its interaction with the flow.

This paper presents an alternative approach to address the interaction between riparian vegetation, flow and riverbed morphology. The model developed here, called ATYS, integrates the model DRIPVEM [31,32] for plant development with the TELEMAC-2D and SISYPHE modules for the flow and riverbed morphology of the TELEMAC-MASCARET modeling system, with the aim of explicitly accounting for both the life cycle and distribu-

tion of vegetation, as well as the dynamical response of plants caused by changes in water depth and nutrients availability.

In addition, the model considers the effect on the flow of vegetation driven by the reconfiguration of stems to calculate drag force [33] and bulk drag coefficients [34]. Here, two simulation scenarios were defined, one without vegetation and another with vegetation, aiming to contrast both the variation in flow and bed evolution patterns. The results on planform morphological evolution are contrasted with the historical development of bars in a river located in the southeast of Mexico.

2. Materials and Methods

The Saint-Venant equations are a set of conservation laws forming a hyperbolic system that describes the flow in shallow water conditions. TELEMAC-2D (v8p3) solves the Saint-Venant equations in their non-conservative form [35]:

$$\frac{\partial h}{\partial t} + \vec{U} \cdot \nabla(h) + h \nabla \cdot (\vec{U}) = S_h \quad (1)$$

$$\frac{\partial u}{\partial t} + \vec{U} \cdot \nabla(u) = -g \frac{\partial H}{\partial x} + S_x + \frac{1}{h} \nabla \cdot [h \cdot v_t \cdot \nabla(u)] \quad (2)$$

$$\frac{\partial v}{\partial t} + \vec{U} \cdot \nabla(v) = -g \frac{\partial H}{\partial y} + S_y + \frac{1}{h} \nabla \cdot [h \cdot v_t \cdot \nabla(v)] \quad (3)$$

where h is flow depth (m); $\vec{U} = (u, v)$ is the vector of the depth-averaged flow velocity with components u and v in the x - and y -directions (m), respectively; g is the gravitational acceleration (m s^{-2}); v_t is the eddy viscosity ($\text{m}^2 \text{s}^{-1}$); H is the water surface elevation (m); t is the time (s); and S_h , S_x and S_y are the source or sink terms in the conservation of mass (m s^{-1}) and momentum equations (m s^{-2}).

The module SISYPHE (v8p3) simulates riverbed adjustments using the Exner equation with a sediment transport equation (e.g., Meyer-Peter and Müller) to calculate bed evolution:

$$\frac{\partial Z_b}{\partial t} = -\frac{1}{(1-\lambda)} \nabla \cdot \vec{Q}_b \quad (4)$$

where λ is the porosity of the bed material, Z_b is the bed elevation (m), and $\vec{Q}_b = (Q_{bx}, Q_{by})$ is the vector of volumetric sediment transport rate per unit width without pores, with components Q_{bx} and Q_{by} in the x - and y -directions ($\text{m}^2 \text{s}^{-1}$), respectively.

2.1. Vegetation Dynamics

The vegetation development model is based on the work of Asaeda & Rashid and Asaeda et al. [31,32]. Here, three submodules were adopted: TREE, HERB and NUTRIENTS. The TREE submodule estimates the spatial distribution, growth, and density of trees and their physiological traits based on allometric relationships (power functions), which depend on tree age. The HERB submodule calculates the biomass of herbaceous plants, also using allometric relationships. The NUTRIENT submodule simulates the concentration of nitrogen in sediments. The description of the equations of the previous processes can be found in Asaeda & Rashid and Asaeda et al. [31,32]. Additionally, the vegetation model considers the wet and dry seasons.

During the wet season, recruitment (seedling survival) of plants takes place, while during the dry season, the decomposition process of dead plant tissues occurs, which releases nitrogen into the substrate. Moreover, remaining vegetation uptakes the accumulated nitrogen in soil (both from decomposition and atmospheric fallout) to support growth in the following season.

Additionally, a reduction in vegetation density is considered through a self-thinning function that models the loss of plants due to competition for nutrients and by using a flushing function to account for the reduction in density due to hydraulic erosion.

The interspecific competition is evaluated by adding restricted factors to limit the growth of arbor and herbaceous plants [31,32]. In the case of tree development, the recruitment (TRECRU) is modeled using the following equation:

$$TRECRU = \left(\frac{0.25}{0.25 + d_{50}^2} \right) \left(\frac{350}{350 + HB} \right) TRDEN_0 \quad (5)$$

where d_{50} is the mean grain size diameter (mm), HB is the herb biomass (g m^{-2}), and $TRDEN_0$ is the initial density of trees (m^{-2}). If there is more than one sediment particle size, the size with the highest concentration in the riverbed is considered in Equation (5).

Additionally, the competition between trees is taken into account through a self-thinning function (see Equation (6)), where tree density decreases with age owing to competition among individuals [31,32].

$$THIN = TRAGE^{-2} \quad (6)$$

where $THIN$ is the self-thinning coefficient, and $TRAGE$ is the tree age (years). It multiplies the previous tree density to calculate the current loss of tree density.

Regarding herbs, this kind of plant adapts to existing conditions and has nitrogen restrictions [36]. Thus, the maximum herb biomass, f_N (Equation (7)), is a function of TN [31,32], where TN (g kg^{-1}) is the total nitrogen concentration in the substrate.

$$f_N = \frac{TN^2}{0.16 + TN^{2.5}} \quad (7)$$

The restricted herb biomass, f_s [31,32], limited by the presence of trees (which provide shade), is given by

$$f_s = \left[1 - 0.6 \left(\frac{Lb}{Cr} \right) \right]^{0.6} \quad (8)$$

where Lb is the leaf biomass (g m^{-2}) of trees, and Cr is the area of the tree crown (m^2), considering that the canopy is a perfect circle.

For the sake of simplicity, the influence of the sediment grain size in herb biomass was neglected; thus, the computation of maximum herbaceous biomass HB (g m^{-2}) considers the combined effect of TN and shade as follows:

$$HB = HB_{max} f_N f_s \quad (9)$$

where HB_{max} is the maximum herb biomass (g m^{-2}) without restrictions.

Nutrient availability is not a limiting factor that restricts the growth of arbor vegetation; trees can grow even if the substrate is not rich in nutrients. The main limiting factors for tree development are the flow conditions [32]. On the other hand, the development of herbs highly depends on nutrients in the soil [31], particularly nitrogen.

Some studies (e.g., [37,38]) suggest that plant development in coastal sand dunes is controlled by nitrogen availability rather than the amount of phosphorus. Furthermore, floodplain soils are relatively rich in phosphorus [31,37]. In riverine environments, such as new sediment bars, vegetative succession mostly depends on the enrichment of nitrogen by pioneering plant species as the new sediment deposits are deficient in nitrogen [39]. That is the main reason for using nitrogen as the limiting factor for plant growth.

2.2. Flow Resistance

Riparian vegetation is commonly modeled considering the stem (from small herb to larger trees) as a vertical cylinder, a suitable parameterization in rivers where flow velocity is low enough not to induce deformations in the stem. In order to consider the stem bending and predict the regime transition, Sharpe et al. [33] formulated a new drag coefficient, $C_{d\chi}$:

$$C_{d\chi} = C_d \phi_y^\chi \quad (10)$$

where C_d is the drag coefficient for a cylinder with diameter D (m), χ is an exponent that limits the regime in which vegetation is rigid, and ϕ_y is a dimensionless parameter.

$$\phi_y = \begin{cases} 1 & \text{if } \phi_y \leq 1 \\ C_y^{1/2} & \text{if } \phi_y > 1 \end{cases} \quad (11)$$

$$C_y = \frac{\rho C_d Z_{veg} U^2 H_{veg}}{2EI_{veg}} \quad (12)$$

where C_y is the Cauchy number, ρ is the water density (kg m^{-3}), U is the magnitude of velocity (m s^{-1}), H_{veg} is the total height of the tree stem (m), EI_{veg} is a reference rigidity (N m^2), and Z_{veg} is the projected first moment of the tree area (m^3):

$$Z_{veg} = \int_0^{H_{veg}} h dA_{veg} \quad (13)$$

where dA_{veg} is the change in the tree frontal area measured from the tree base.

Instead of simulating individual elements due to high computational costs, the vegetation patch approach was adopted here. The drag coefficient of an array of cylinders can be different when the combined effect of individual elements is considered; furthermore, the bulk drag coefficient can decrease as the density in the patch increases [40], or it can increase if a sheltering effect is produced [34]. In their work, Busari and Li [34] proposed a regression equation for drag coefficients fitted from experimental data obtained in a laboratory flume with arrays of semi-rigid cable tile blades partially submerged:

$$\overline{C_d} = C_d [f(\zeta_y)] [g(\zeta_x)] \quad (14)$$

$$f(\zeta_y) = 1 - \beta e^{-K(\zeta_y/b_{veg})} Re^{-\gamma} Fr^{-\vartheta_1} \quad (15)$$

$$g(\zeta_x) = 1 + \alpha e^{-M(\zeta_x/b_{veg})} Re^{-\delta} Fr^{-\vartheta_2} \quad (16)$$

where $\overline{C_d}$ is the bulk drag coefficient for herbs, while C_d is the same parameter utilized in Equation (10). The parameters ζ_x and ζ_y are the center-to-center distance between stems in the x - and y -directions (m), b_{veg} is the width of the stem (m), and Re and Fr are the Reynolds and Froude numbers, respectively.

The remaining parameters were obtained by a multiple regression model [34], and their values are

$$\begin{aligned} \beta &= 2.4831, \alpha = 2830, K = 0.1256, M = 0.1223, \\ \gamma &= 0.1490, \delta = 0.9288, \vartheta_1 = 0.0150, \vartheta_2 = 0.0350 \end{aligned} \quad (17)$$

2.3. Numerical Modeling

Figure 1a illustrates the modeling sequence and highlights the key processes of ATYS. First, TELEMAC-2D solves the flow hydrodynamics (the water depth, h , and the depth-averaged velocity vector, $\vec{U}$), where the drag produced by vegetation is incorporated. Second, SISYPHE calculates the sediment transport rate, $\vec{Q}_b$, and updates the bed elevation,

Z_b . Finally, ATYS calculates the drag coefficients (the maximum value between trees and herbs) and estimates the area occupied by vegetation stems, φ (see Figure 1a), to model the obstruction. Figure 1b illustrates a schematic representation of annual vegetation dynamics, where wet and dry seasons are considered. During the rainy (wet) season, recruitment occurs, while plant density decreases due to competition (self-thinning) and hydraulic erosion. During the dry season, recruitment ceases, and nitrogen released from decomposing plant biomass becomes available to surviving vegetation, together with a constant atmospheric nitrogen supply. Seasonal processes are implicitly represented in the model; thus, Figure 1b provides a simplified depiction of vegetation–flow interactions.

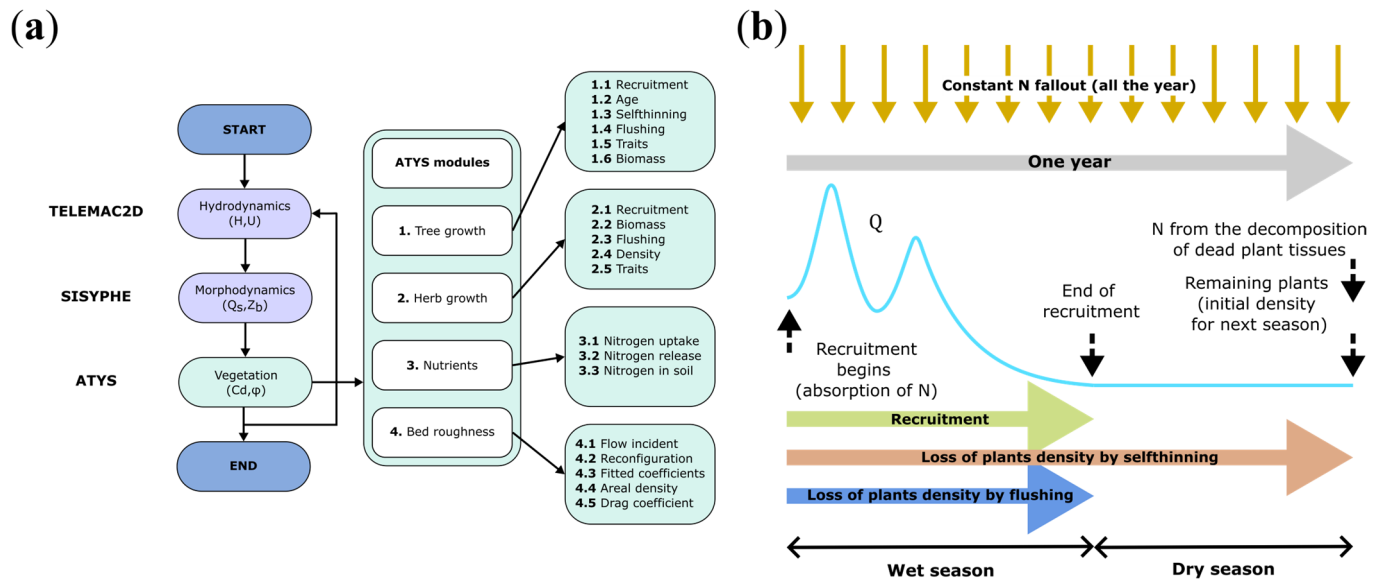


Figure 1. Schematic structure of the integration of the ATYS model in the TELEMAC system: (a) flow chart of calculation sequence; (b) vegetation growth model (based on DRIPVEM).

To simplify the proposed model, a set of considerations was made. For instance, the hydrodynamical variables, bed evolution and vegetation development, are solved separately due to their different time scales. Furthermore, the drag forces in Equation (18) were incorporated into the momentum equation as sink terms generated by the interaction of the flow with the vegetation (S_x and S_y in Equations (2) and (3))

$$S_x = -\frac{1}{2} \text{MAX}(C_d^*, \overline{C_d} \delta) u^2; S_y = -\frac{1}{2} \text{MAX}(C_d^*, \overline{C_d} \delta) v^2 \quad (18)$$

where the $\text{MAX}()$ function returns the largest drag coefficient between herbs and trees; $C_d^* = C_{d\chi} n D / A$; δ is a constant for dimensional homogeneity (m^{-1}); and n / A is the areal density of vegetation, with number of stems, n , per area, A (m^2), occupied by plants.

Obstructions caused by vegetation stems were taken into account using the porosity approach in the TELEMAC-2D code [41]. The porosity allows for the modeling of obstacles too small to be represented in the mesh, for instance, individual stems of vegetation. The porosity acts as a continuous property representing the ratio of free and obstructed area in a mesh element of the domain [35].

To address the reduction in vegetation density (death of plants) due to variations in water depth in vegetated areas, a specified time in which a node is flooded (1 month) over a given threshold depth was established (0.1 m); the decay of density (m^{-2}) or biomass (g m^{-2}) is modeled using the logistic relationship [42] expressed in Equation (19). Additionally, an effective area for each node in the computational mesh (the surface available for vegetation growth) was assumed. This effective area is defined as the sum of one-third of

the areas of the neighboring mesh elements surrounding a central node and is represented by an equivalent square with the same area as the patch. The decay of biomass is modeled by the following equation:

$$y = Y \left[1 + \exp \left(10 \left(\frac{T_{flood}}{T_{max}} - 0.5 \right) \right) \right]^{-1} \quad (19)$$

where y is the magnitude of a plant's characteristics (e.g., biomass, density), Y is the value of this characteristic at the current time, T_{flood} (s) is the duration of the flood in a node, and T_{max} (s) is the maximum time allowed before a plant dies because of anoxia. In this way, the influence of water depth variations on vegetation can be evaluated even if ATYS is uncoupled from the hydrodynamics.

2.4. Study Case

The Mezcalapa River is a perennial stream located in the southwest of Mexico (Figure 2a) that flows through a low plain (Figure 2b). The river shows channel width variations and multiple bars (Figure 2c); additionally, the river planform exhibits several meanders, and the river can be defined as braided (the discharge/slope and the stream-power/grain-size indexes [43] were used). The riverbed has a mean slope of 0.0005, a Manning roughness coefficient of $n = 0.035 \text{ s m}^{-1/3}$ (estimated through field measurements), and width-to-deep ratios ranging from 20.35 in the upstream region to 235 in the downstream region.

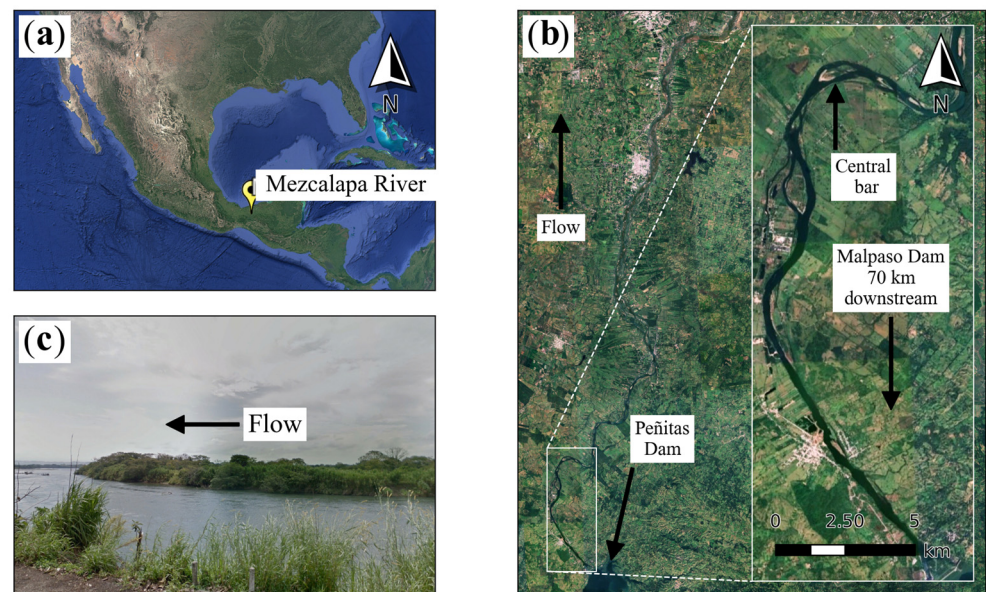


Figure 2. Images of the study site: (a) location of the Mezcalapa River in Mexico (Google Earth), (b) a vegetated midstream bar located at the lowest part downstream of the reach (Google Earth), (c) a composite Landsat 8 image of the study area.

This river belongs to a fluvial system currently regulated by four dams constructed during the period 1958–1987. Prior to the commissioning of the first dam, Nezahualcoyotl (1958–1966), the maximum recorded discharge was $8140 \text{ m}^3 \text{ s}^{-1}$, with a mean daily discharge of $715 \text{ m}^3 \text{ s}^{-1}$ (a standard deviation of $762 \text{ m}^3 \text{ s}^{-1}$). The behavior of the river has been modified by the change in the flow regime (suppression of peak discharge and limited low-flow conditions) driven by the upstream dams; a consequence is a reduction in braiding intensity (e.g., [44]).

After the commissioning of the last dam, Peñitas (built between 1979 and 1987), the maximum discharge decreased to $3299 \text{ m}^3 \text{ s}^{-1}$ (1987–2011), with a mean daily discharge of $621 \text{ m}^3 \text{ s}^{-1}$ (a standard deviation of $326 \text{ m}^3 \text{ s}^{-1}$). The regulation introduced by the system of dams significantly altered the hydrological regime of the Mezcalapa River (downstream of the last dam), reducing the sediment supply and consequently affecting the river's morphological characteristics. Regarding the sediments, the riverbed is composed of sand with grain diameters ranging between 0.28 and 1.9 mm.

The bars in the river support a variety of plant species (Figure 2c). The riparian vegetation is characterized by tree species such as *Ficus* sp., *Inga vera*, *Muntinga calabura* and *Salix humboldtiana*, where *Salix* is the most frequent tree species in the river. Regarding herb species, *Typha domingensis*, *Thalia geniculata*, *Cladium jamaicense* and *Phragmites australis* can be found in bars and floodplains [45].

For this study, an 18 km river reach downstream of the Peñitas Dam (Figure 2b) was selected for the application of the ATYS model; the domain is shown in Figure 3. The simulations were carried out using a numerical mesh composed of 88,500 triangular elements, with 20 m per side on average, with a bed slope of 0.0011 (the mean slope of the reach). A hydrograph of mean daily discharges (Figure 4a) (1987–2008) was used as the upstream boundary condition; note that it does not show a typical wet/dry flow regime observed in natural rivers since this reach is regulated by the upstream system of dams. A stage–discharge curve calculated under steady flow conditions for normal water depth was established as the downstream boundary condition (Figure 4b).

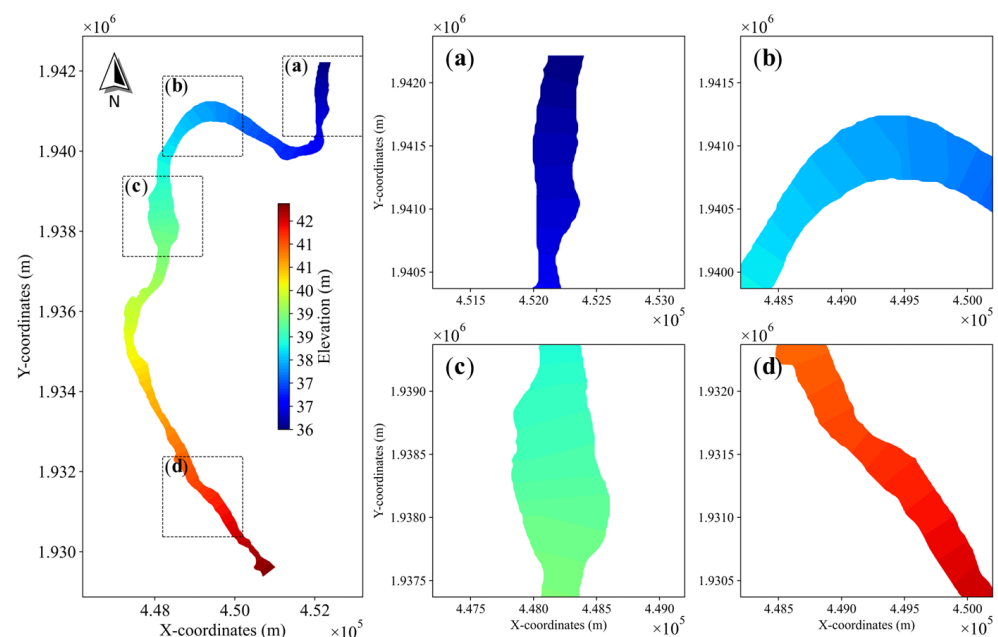


Figure 3. Computational domain used in the simulations: (a) part upstream de outlet, (b) part with the most curvature, (c) widest part of the reach, (d) part downstream the Peñitas Dam.

In order to simulate the bed morphology, three representative grain size diameters were used: $d_{15} = 0.032 \text{ mm}$, $d_{50} = 0.063 \text{ mm}$ and $d_{85} = 1.4 \text{ mm}$. The simulations were conducted using a morphological factor, $MF = 2$, which is applied by SISYPHE to the Exner equation (Equation (4)) to accelerate bed evolution. This is valid given the different time scales of the hydraulic and riverbed evolution processes; also, a zero-sediment inflow discharge was established as the upstream boundary condition for sediments due to retention in the upstream dams. Simulations were conducted using a time step of 2 s for hydrodynamics, 20 s for morphodynamics, and 1 month for vegetation; the latter following Asaeda & Rashid and Asaeda et al.'s [31,32] approach.

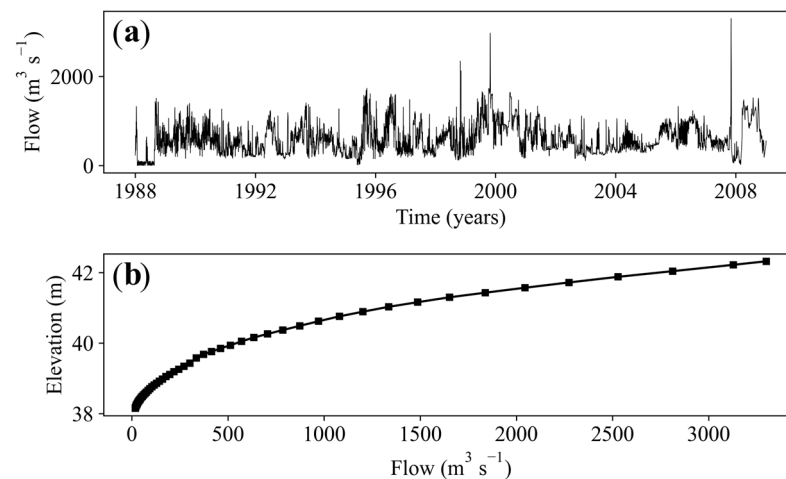


Figure 4. Boundary conditions used in the simulations: (a) hydrograph of mean daily discharges; (b) stage–discharge curve.

Information from diverse sources was collected due to the absence of site-specific data for the vegetation (e.g., height, stem diameter and density). Data for *Salix humboldtiana* [46,47], *Salix* spp. [48] and *Phragmites australis* [31,32] were used in the simulations.

Phragmites australis (common reed) and *Typha latifolia* are two macrophytes commonly present in wetlands, and both grow through rhizomatous propagation; this is the reason for employing the common reed information. Both vegetation areal density and age started at zero with the aim of analyzing their development pattern. The data for the nitrogen concentration in the soil was taken from Jarquín-Sánchez et al. [49].

With the aim of comparing the effect of vegetation on the morphological development of bed evolution and bar growth, two scenarios were simulated. The first scenario was simulated without vegetation, and the second one considered the presence of vegetation. Bed topography of 2012 and satellite imagery covering the period 1986–2003 (the Landsat 7 satellite failed after this period) were used for validation, considering the number, location and dynamics of bars developed by the proposed model.

3. Results

3.1. Mezcalapa Riverbed Morphology Assessment

For the period analyzed (1986–2003) with satellite imagery data, five years were absent (1987, 1988, 1989, 1991, and 1993), and 13 images were available. Indices such as the Normalized Difference Vegetation Index (NDVI) and different band compositions, including NRG (Near-Infrared Red Green) and SNR (Shortwave-Infrared Near-Infrared Red), were utilized to classify soil cover using GIS (Geographic Information System) tools. Four different types of soil cover were considered: water, bare soil in bars, vegetation in bars, and margins. Margins were defined as bars covered with vegetation that at some point in time were joined with riverbanks after their initial formation.

According to the satellite imagery analysis, 82 bars were identified in the reach. The analysis suggests that their persistence (the lasting time a bar appeared during the period) is related to their surface area. Larger bars tend to remain for larger periods (Figure 5a); this trend can be approximated with a power-law (with a correlation of 0.67), also depicted in Figure 5. In addition, Figure 5b shows the number of bars (frequency) as a function of mean surface area.

It is shown that the larger the area of a bar is, the more persistent it is. Although the area of a bar is an important factor that contributes to its persistence, the presence of

vegetation also supplies additional stability in time. For instance, the margins (aggradation), whose behavior shows that they required less area to be stable during the study period.

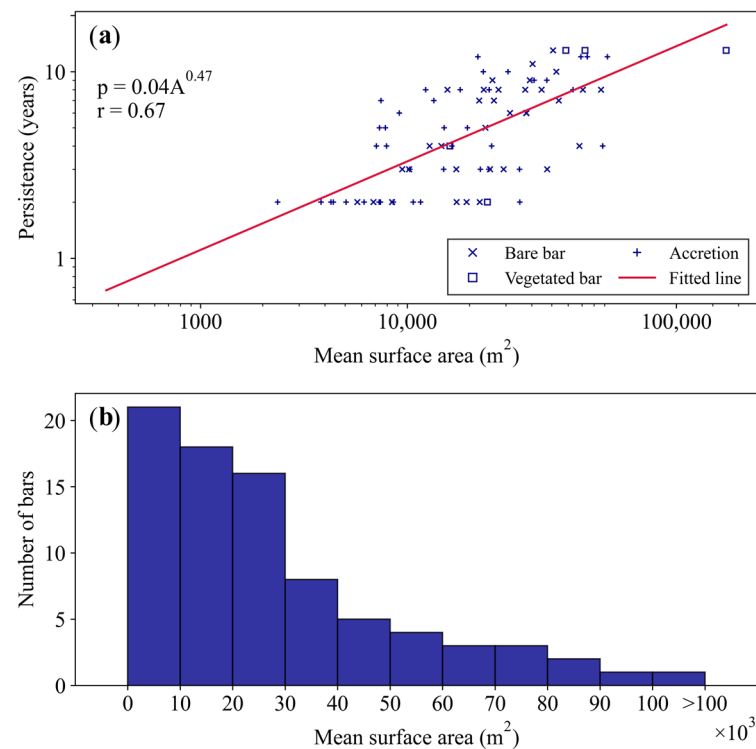


Figure 5. Comparison between mean area of the bars in the Mezcalapa River with their (a) persistence and (b) frequency. p is persistence (years), and A is the mean surface area (m^2).

3.2. Numerical Simulation

3.2.1. Vegetation Development

Figure 6a shows the evolution of the mean and maximum herb biomass over the 20-year simulated period. It highlights temporal variations in biomass where one of the main drivers is flow fluctuation (Figure 6b); for instance, the peak values of mean biomass are observed in months 32, 64, 86, and 148, with the highest value in month 164 and the lowest values in months 44, 104 and 176, which were observed after high flows. The effect of flooding is illustrated in Figure 7, which shows that reed populations grow mainly in elevated areas, where they are less affected by flushing.

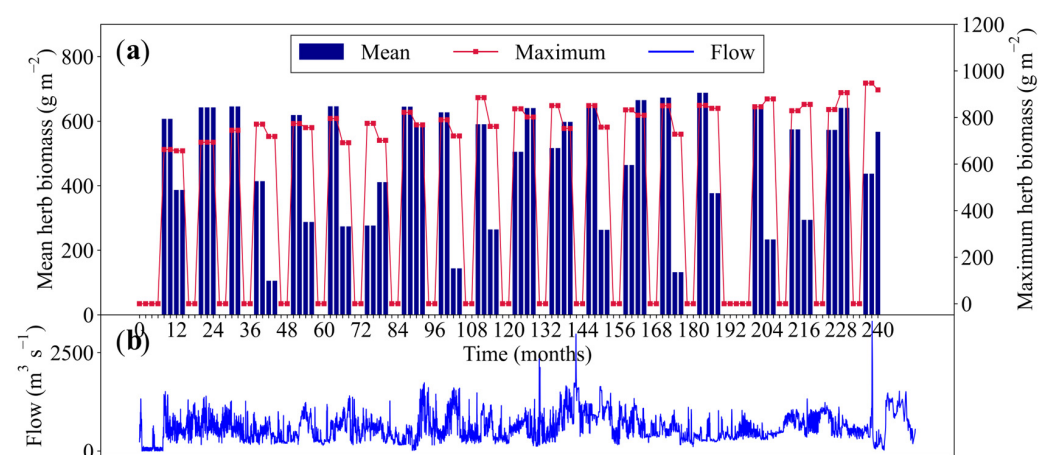


Figure 6. Monthly variation of herb biomass simulated in the study reach: (a) mean, (b) maximum.

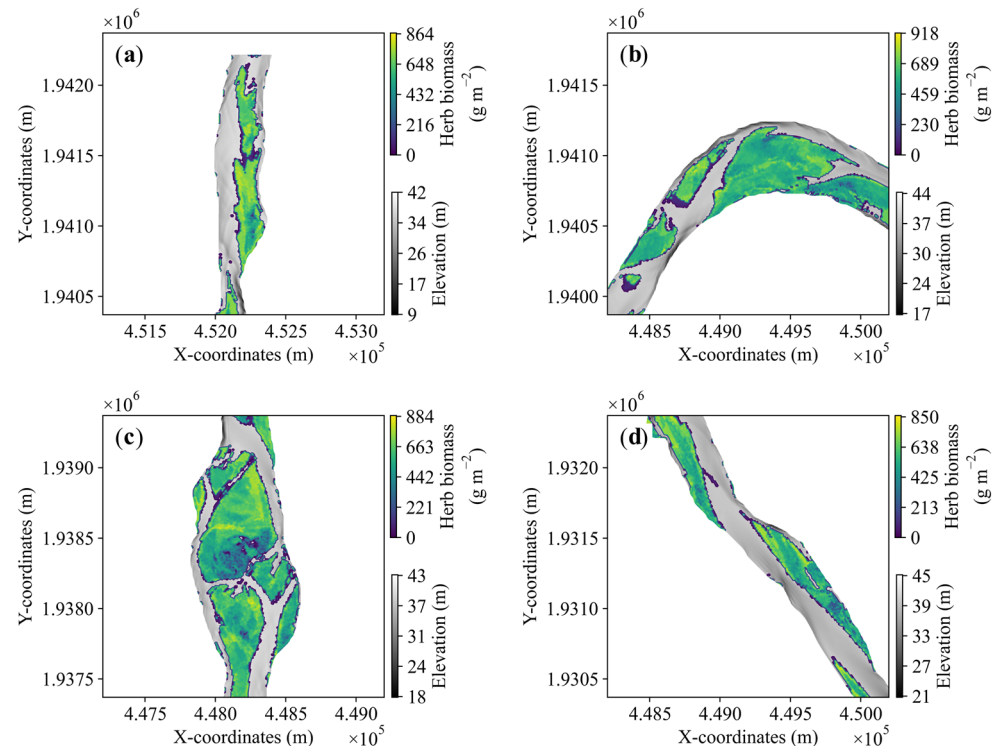


Figure 7. Herb biomass and bed elevation in the reach after a 20-year simulation in: (a) part upstream the outlet, (b) part with the most curvature, (c) widest part of the reach, (d) part downstream the Peñitas Dam.

Concerning tree development, Figure 8 illustrates the variation in tree density and age over time, considering sprouts passing from saplings to maturity, according to their age. The mean tree age increases during the first 56 months, rising from 0.16 to 2.1 years. However, it decreases afterwards, dropping to 0.35 years. This behavior continues over the following months, although a substantial rise occurs starting in month 168, when the mean age rises from 0.76 to 6.0 years by month 224. The maximum simulated tree age was 19.6 years. In addition, Figure 8 shows that the mean tree density decreases as the mean age increases. This is according to the inverse relationship between age and density used in the model.

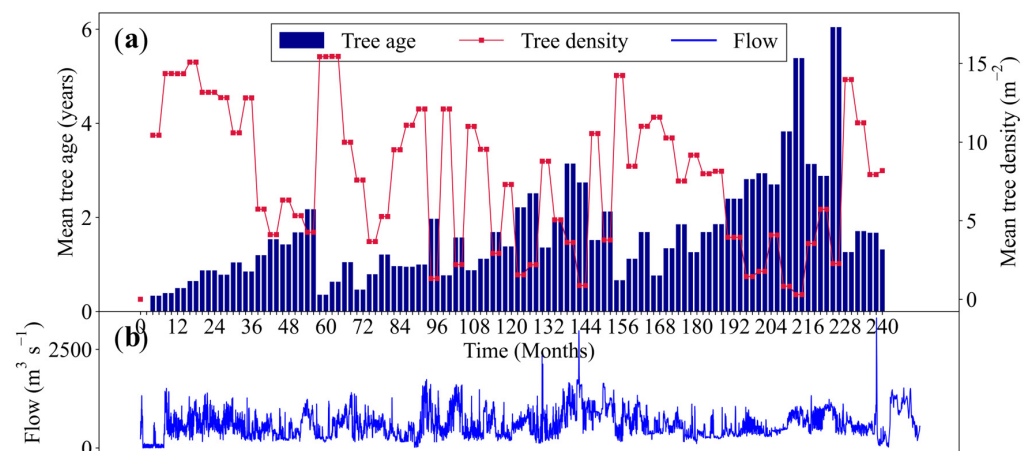


Figure 8. Monthly variation of tree traits: (a) mean age, (b) mean density.

3.2.2. Vegetation Effect on Flow Patterns

Figure 9 shows the spatial variation in water depth and velocity vectors through cross-sections along the reach, considering the vegetated and non-vegetated scenarios.

Figure 9a,c,e,g correspond to a non-vegetated scenario, while Figure 9b,d,f,h show the water depth computed by TELEMAC-2D coupled with the ATYS model. Differences in the flow patterns and the velocity magnitudes can be observed.

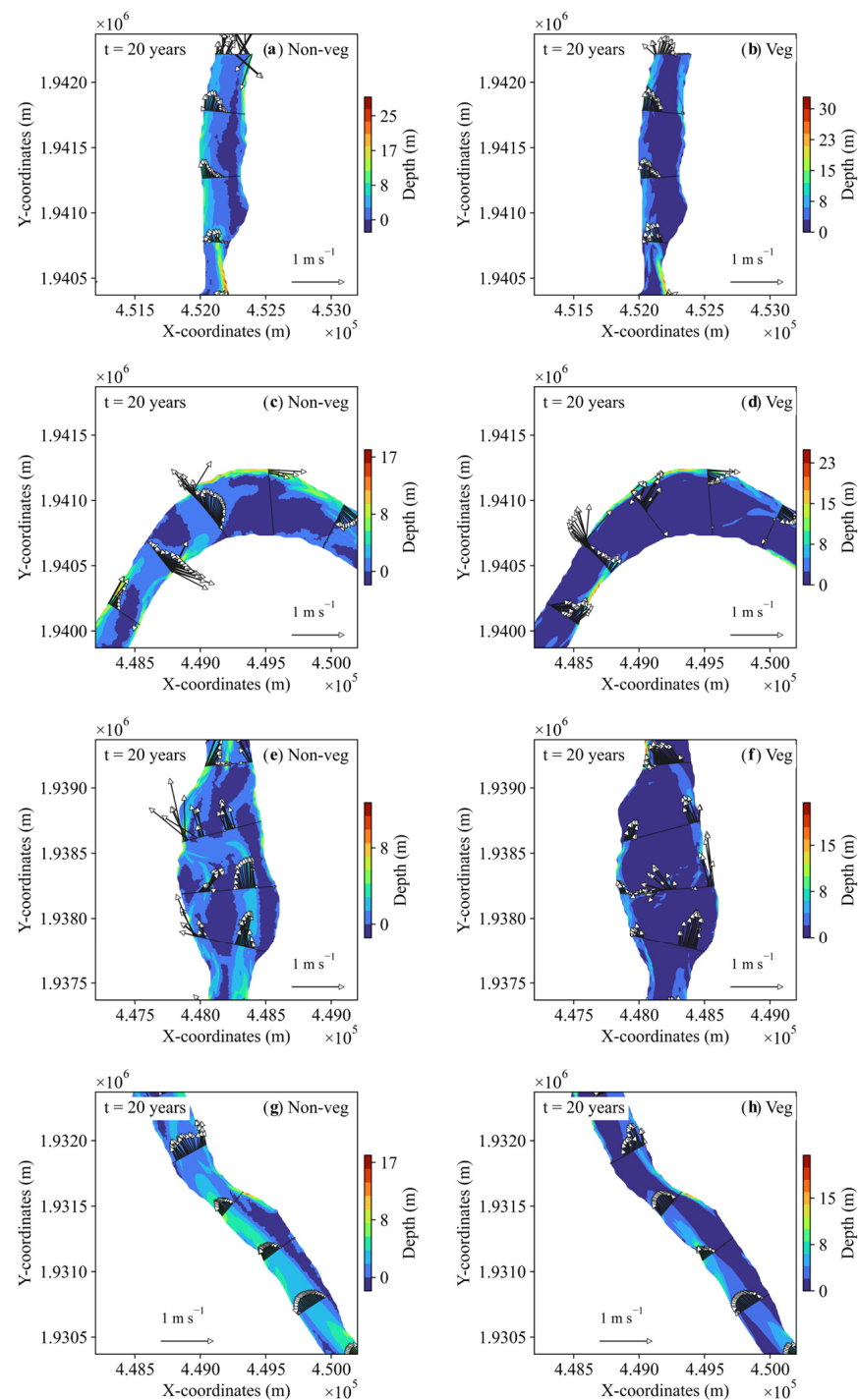


Figure 9. Velocity vector field along the reach after a 20-year simulation: (a,c,e,g) non-vegetated scenario; (b,d,f,h) vegetated scenario.

In the scenario without vegetation, the velocity field displays a swinging pattern (Figure 9e) around bars (vegetated areas in Figure 7). In the vegetated scenario, velocities are concentrated in definite paths that increase their magnitude. It means that vegetation enhances conditions for homogeneous flows.

The differences previously mentioned are appreciated in Figure 10, which compares the mean velocity magnitude in the simulation domain over time. Mean velocity varies throughout the simulation in both scenarios (Figure 10a); however, vegetation reduces these variations compared with the first one, and a decreasing trend in mean velocity can be observed. The absolute differences between velocities in each month range from 0.001 to 0.39 m s^{-1} . Scaled velocities are shown in Figure 10b; the maximum difference is in month 74 with $+0.0076 \text{ m s}^{-1}$ (1.06%), and the minimum difference occurred in month 92 with -0.28 m s^{-1} (−27.48%).

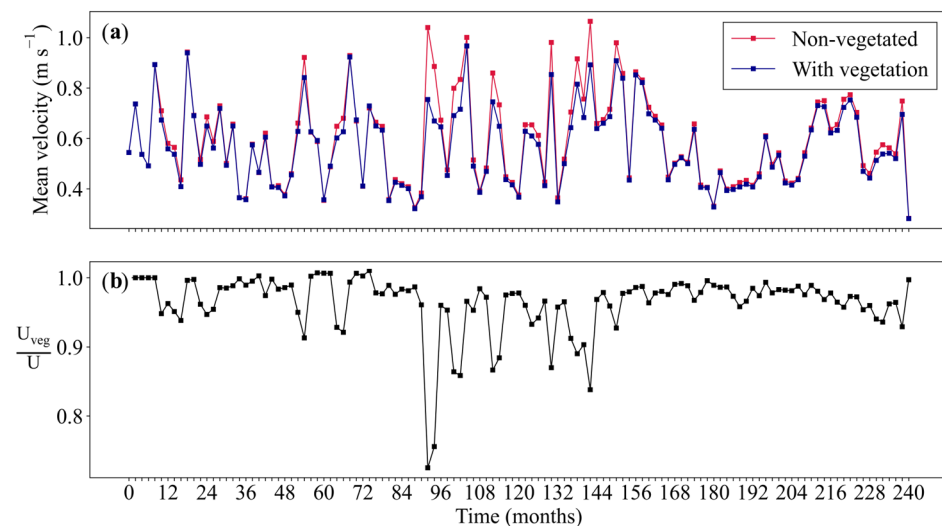


Figure 10. Variation of velocity in the domain during a 20-year simulation: (a) mean velocity of vegetated and non-vegetated scenarios, (b) ratio between velocity with vegetation (U_{veg}) and without vegetation (U).

3.2.3. Erosion and Deposition Processes

The bed evolution of the simulations is illustrated in the bar chart in Figure 11. This figure displays the difference between mean erosion and mean deposition across the reach; they are scaled by the data of the non-vegetated scenario. The maximum reductions in mean erosion and mean deposition are approximately 37.49% (−0.15 m) and 41.33% (−0.16 m), respectively, in month 94, and the maximum increment is 30.86% (0.05 m) for erosion and 14.91% (0.05 m) for deposition, both in month 96.

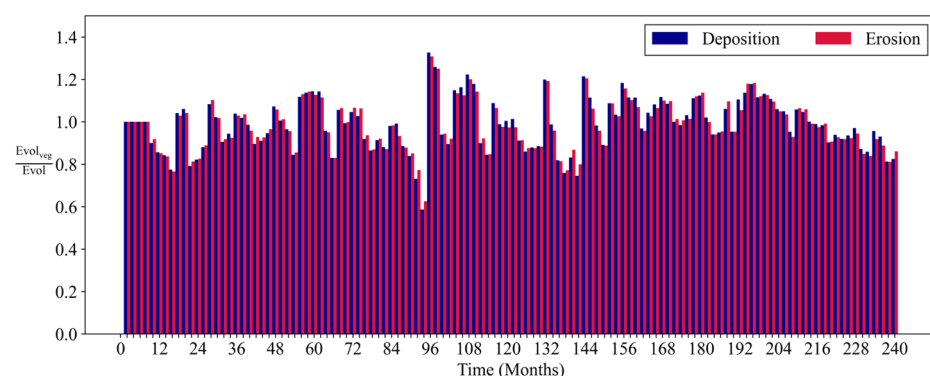


Figure 11. Ratio of mean bed evolution of scenarios with vegetation ($Evol_{veg}$) and without vegetation ($Evol$) for the 20-year period of simulation.

In addition, regarding the total evolution in the domain, the differences in bed elevation between the initial and last time step for non-vegetated and vegetated scenarios

are -1.64×10^4 and -1.69×10^4 m, respectively, which indicates that vegetation slightly promotes erosion in certain areas of the domain during the simulation.

When the bed configuration of the simulated scenarios (vegetated and non-vegetated) and the actual river are compared (Figure 12), the bed in the non-vegetated scenario (Figure 12a,d,g,j) is more irregular, while in the vegetated scenario (Figure 12b,e,h,k), bed forms in the bed are clearly visible, such as well-defined bars. In the bend of Figure 12e, a bar is located at the outer bank, and another one has developed upstream at the inner bank. In Figure 12j,k, an alternate bar configuration is developed.

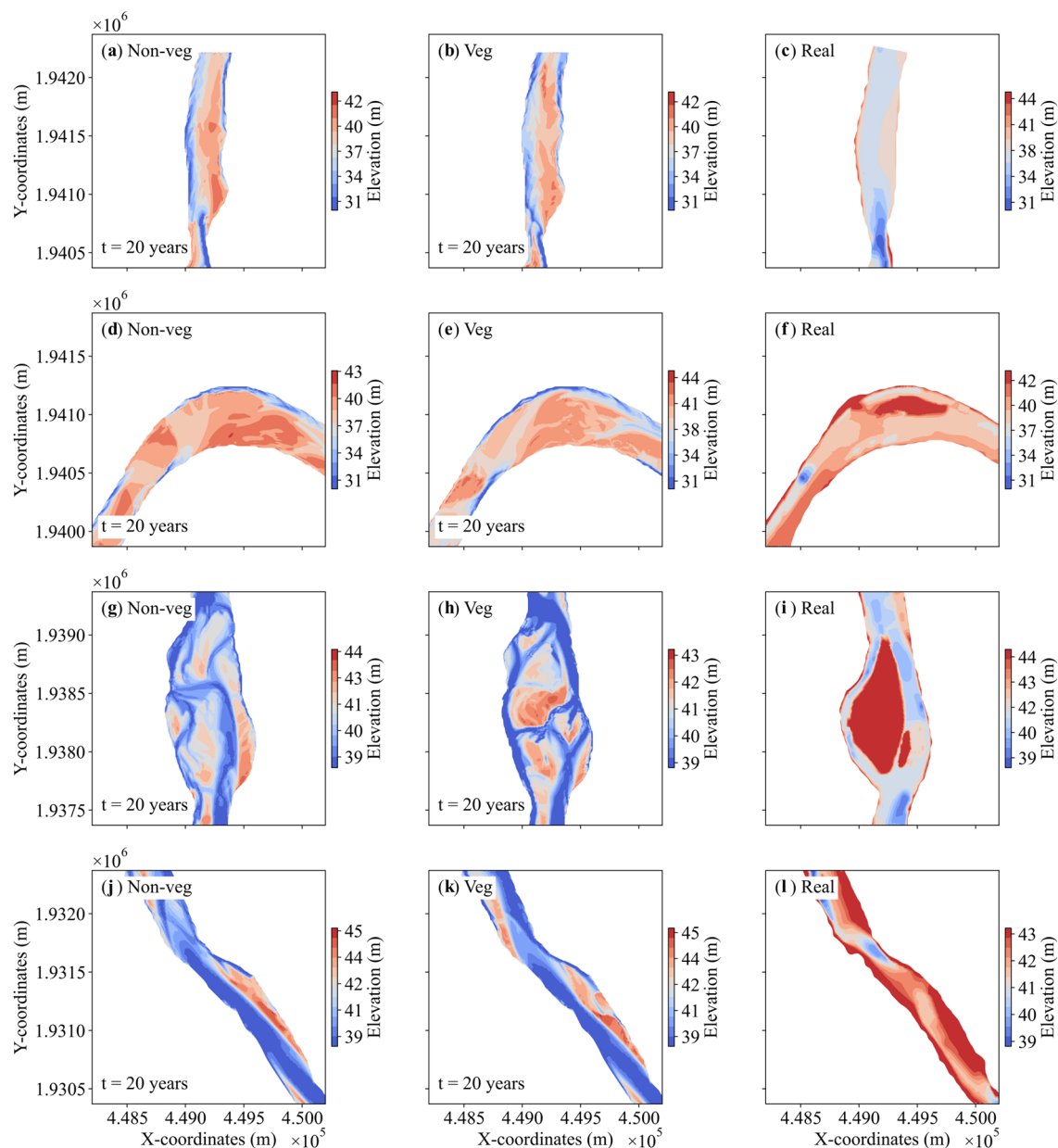


Figure 12. Difference in bed elevation between simulated scenarios and real data: (a,d,g,j) non-vegetated, (b,e,h,k) vegetated, (c,f,i,l) topography of 2012.

The simulated bed with vegetation (Figure 12b,h,k) shows agreement with the measurements (Figure 12c,i,l); for example, bars tend to develop in similar locations observed in the field, although their shape is not identical. Moreover, tendencies are reproduced well enough in Figure 12b and c with the growth of forced bars generated by the curvature of the river and in Figure 12k with the growth of alternate bars (Figure 12l).

4. Discussion

According to the results, riparian vegetation has a significant impact on both flow patterns and riverbed morphology. Contrasting the flow patterns developed by the vegetated and non-vegetated scenarios, Figure 9 reveals well-defined flow paths for the first case; in contrast, these patterns are more dispersed in the scenario without vegetation.

Furthermore, a larger velocity magnitude is observed in the vegetated scenario, suggesting that vegetation patches not only promote a change in flow direction but also in magnitude, driven by the concentration of flow in non-vegetated regions of the river; such conditions may enhance the development of secondary currents when the concentrated flow is curved, for instance, when the flow surrounds bars, adding complexity to the development of the riverbed.

This change in the flow alters both the sediment transport rate and its direction. In meandering rivers, the erosion–deposition patterns in the bed and banks are highly influenced by secondary flow [5], which in turn is intensified by the addition of vegetation [50]. The secondary flow creates a process where the momentum transfer in the vertical direction can interact with the stems of vegetation, which contributes to the dispersion of sediments [51–53]. This process controls the distribution and amount of nutrients [2,51], which are necessary for both growth and the lateral expansion of vegetation.

The results show that the mean velocity magnitude at the reach scale (in time throughout the domain) has a weak relationship with mean herb biomass ($r = -0.25$); this is shown in Figure 13a, where a linear regression fit was plotted. Conversely, herb biomass is not related to water depth (Figure 13b); this is suggested by the regression coefficient calculated: $r = -0.07$. These results consider only the nodes of the computational mesh, with herb and water depth higher than 0.1 m.

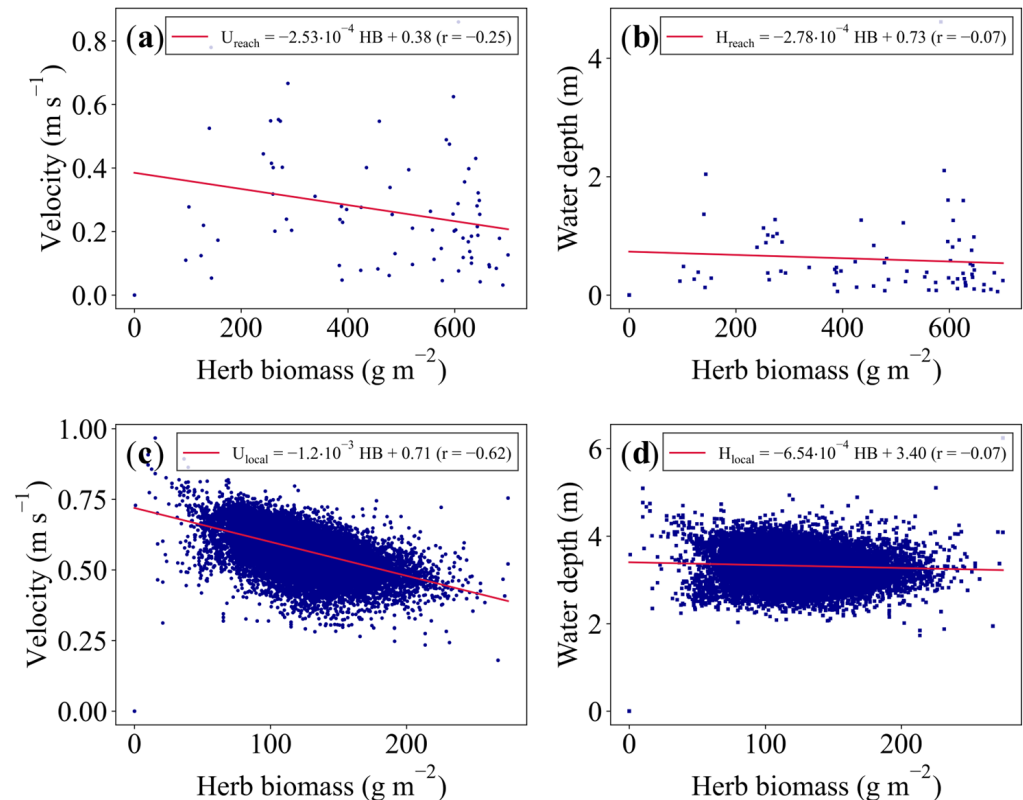


Figure 13. Relationship between flow variables and vegetation: (a,c) mean herb biomass and mean velocity at local and reach scales, respectively; (b,d) mean herb biomass and mean water depth at local and reach scales, respectively.

When the mean herb biomass is compared with velocity magnitude at the local or patch scale (each node of the computational mesh during time), the correlation coefficient shows even better agreement (Figure 13c), but in the case of water depth, the correlation is the same: -0.07 (Figure 13d). This means that, according to the simulations, the velocity is more strongly influenced by vegetation at the local scale than at the reach scale, whereas water depth has no relationship with herb biomass.

The flow–bed interaction in rivers with erodible banks can form meanders, where centrifugal forces generate deposition at the inner bends and scour in the outer ones, while in straight rivers with non-erodible banks, an instability mechanism produces a perturbed configuration in which disturbances can occur on a mega-scale, originating bars [54]. The outcomes of the simulation performed herein suggest that bar development is improved by the presence of plants in the river; for instance, when vegetation is present (Figure 12k), the bottom exhibits a well-defined pool–riffle sequence in the straight part of the reach. Furthermore, in the bend of Figure 12h, the oscillating pattern is reduced by vegetation, enhancing bottom stability. Therefore, not only does the interaction between flow and sediment determine the shape of the channel, but vegetation also modulates the morphological processes.

With vegetation, the sedimentation is higher; this shows that vegetation can enhance the deposition in bars, which in turn promotes scour in zones of flow surrounding the bars. In fact, the secondary flow induced by curvature enhances the development of bars, which are stabilized by the effect of gravity, sediment transport [55], and flow resistance supplied by riparian vegetation.

Plant growth contributes to holding bars through deposition, representing a positive feedback mechanism for more plant development [2]. Thus, vegetation can rework rivers and their floodplain characteristics [2,3]. Flow variability by itself produces changes in the bed configuration, as shown in Figure 11; however, vegetation modulates the magnitude of erosion and deposition, as shown by the ratios between vegetated and non-vegetated areas in Figure 11. At least in this study, the flow discharge has an important effect in modifying the riverbed morphology at the reach scale, whereas vegetation has an important effect at the local scale. Flow characteristics and plant traits, such as stem density and patch area, can determine the result of vegetation influencing the river structure [52].

The comparison between real and simulated bed development shows reasonable agreement in their morphological characteristics; notwithstanding, some reaches of the river (in the simulations) show different bar and bed development, as shown in Figure 12d,e,g,h. The ATYS model could not reproduce the bar observed in Figure 12f. The simulated reach needs enough time to achieve a stable configuration; in this study, only a 20-year period was simulated. Furthermore, in the satellite imagery analysis, it was found that the larger the surface area is, the more stable the bar is. In the vegetated scenario, multiple deposits developed during the simulations; also, compared with the other ones, the bar in Figure 12i is the largest one in the reach. Third, the historical flow discharges used in simulations are regulated by the Peñitas Dam, which implies that the natural fluctuation in flow prior to the construction of the dam was not considered. Finally, a zero-sediment income was set at the inlet boundary, which resembles the sediment retention in the dam. In both conditions, flow regime homogenization and sediment retention may have limited the development of bars during the simulation.

5. Conclusions

The literature review performed here indicates that the most recent approaches, while focused on improving our understanding of the interactions between vegetation, hydro-

dynamics, and morphodynamics, typically model the flow–vegetation interplay either by representing vegetation as rigid stems or by increasing the local bed roughness [56–59].

A comprehensive framework for modeling river morphodynamics influenced by riparian vegetation has been proposed herein to assess the effect of the plant life cycle on riverbed morphology using plant biomass. Other studies support the use of dynamic plant biomass to represent the increased flow resistance associated with the presence of vegetation (e.g., [56–58,60]).

In the ATYS model proposed here, the vegetation is represented as a dynamic patch capable of lateral expansion, which reflects its broad effect beyond just the local scale [3]. The effect of vegetation patches is incorporated into the momentum equation through a drag term, while their physical obstruction is accounted for using the porosity function in TELEMAC-2D. This approach aligns with methodologies adopted in previous studies [12,13,61–64]. This framework is focused on the flow–vegetation interaction; however, an effect that was not considered is the interaction of vegetation with the underlying soil, specifically, the reinforcement of banks by the roots of riparian vegetation, which is considered for future developments of ATYS.

The model was tested in an 18 km long reach of the Mezcalapa River located downstream of the Peñitas Dam in the southwest of Mexico. Thus, the interactions between flow, riverbed, and vegetation were evaluated. The results illustrate that bed evolution patterns are primarily influenced by flow variations at the reach scale, while vegetation tends to influence morphological changes at the local scale. However, a notable relationship between the increased herb biomass and the reduced velocities at the reach scale is observed. Overall, alterations in flow and sediment transport affect vegetation, which in turn modifies both erosion and deposition patterns, creating a positive feedback cycle that amplifies these disturbances [1,2].

The outcomes indicate that vegetation significantly influences flow structures by increasing flow resistance; furthermore, vegetation patches contribute to concentrating the flow in regular paths and affect not only the direction but also the magnitude of velocity, which in turn has an important effect on erosion and deposition rates at the local scale. Moreover, the proposed approach reproduces most of the observed tendencies in the river reach well enough, suggesting the significant role of vegetation in modulating the instability of bars.

Furthermore, when obstructions such as vegetation stems are present, changes in velocity gradients, increased shear stresses and alterations in secondary flow are observed [59,65]. Deposition is enhanced around vegetation patches, while reduced sedimentation takes place in the main channel [64]. These results highlight not only the importance of modeling vegetation dynamics at the patch scale using drag force and porosity approaches but also the importance of accounting for stem bending since incorporating flexible vegetation improves the accurate estimation of flow characteristics [65,66].

Although alternative approaches that use Manning’s roughness coefficients to represent vegetation have been proposed, these methods have some limitations. The use of overestimated roughness coefficients to parameterize vegetation patches often fails to accurately capture vegetation-induced drag: this misrepresents the effects of emergent plants and inadequately reflects the downstream boundary conditions. Furthermore, this can lead to overestimated sediment transport due to elevated local bed shear stresses [6,12,15].

The ATYS model provides a framework for the numerical modeling of vegetation dynamics and their influence on hydrodynamics and sediment transport. Since the model does not require the solution of differential equations, its implementation does not noticeably increase computational costs. Finally, at this stage, the model offers a qualitative solution to addressing river morphodynamics influenced by riparian vegetation, but it is

necessary to validate ATYS's performance with field data, especially the data associated with herb and tree growth.

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Abbreviations

The following abbreviations are used in this manuscript:

NDVI	Normalized Difference Vegetation Index
NRG	Near-Infrared, Red, Green
SNR	Shortwave-Infrared, Near-Infrared, Red
GIS	Geographic Information System

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