

Article

Dynamic Interaction Mechanism Between Periphytic Algae and Flow in Open Channels

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Abstract

Periphytic algae, as representative aquatic epiphytic communities, play a vital role in the material cycling and energy flow in rivers. Through physiological processes such as photosynthetic carbon fixation and nutrient absorption, they perform essential ecological functions in water self-purification, maintenance of primary productivity, and microhabitat formation. This study investigates the interaction mechanisms between these highly flexible organisms and the hydrodynamic environment, thereby addressing the limitations of traditional hydraulic theories developed for rigid vegetation. By incorporating the coupled effects of biological flexibility and water flow, an innovative nonlinear resistance model with velocity-dependent response is developed. Building upon this model, a coupled governing equation that integrates water flow dynamics, periphytic algae morphology, and layered Reynolds stress is formulated. An analytical solution for the vertical velocity distribution is subsequently derived using analytical methods. Through Particle Image Velocimetry (PIV) measurements conducted under varying flow velocity conditions in an experimental tank, followed by comprehensive error analysis, the accuracy and applicability of the model were verified. The results demonstrate strong agreement between predicted and measured values, with the coefficient of determination R^2 greater than 0.94, thereby highlighting the model's predictive capacity in capturing flow velocity distributions influenced by periphytic algae. The findings provide theoretical support for advancing the understanding of ecological hydrodynamics and establish mechanical and theoretical foundations for river water environment management and vegetation restoration. Future research will build upon the established nonlinear resistance model to investigate the dynamic coupling mechanisms between multi-species periphytic algae communities and turbulence-induced pulsations, aiming to enhance the predictive modelling of biotic–hydrodynamic feedback processes in aquatic ecosystems.

Keywords: periphytic algae; velocity distribution; resistance characteristics; open-channel flow; analytical model



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1. Introduction

Periphytic algae are a group of algal communities that grow on and attach to various substrates in aquatic environments, commonly occurring in rivers, lakes, reservoirs, and even artificial channels. However, large-scale anthropogenic interventions, such as the construction of China's Three Gorges Dam and the "South-to-North Water Diversion" project (SNP), have led to the continuous degradation of river ecosystems. These projects have triggered a range of ecological issues, notably the proliferation of benthic algae and cyanobacterial blooms, which not only disrupt the ecological balance and threaten aquatic biodiversity but also compromise water supply functions and significantly increase water treatment costs [1,2]. These algae constitute an essential component of aquatic ecosystems, playing an irreplaceable ecological role through their photosynthetic activity. They contribute to nutrient removal and water purification and provide habitat for aquatic organisms. Periphytic algae can absorb nutrients such as nitrogen and phosphorus from the water, effectively reducing the concentrations of substances that promote eutrophication. Hennequin et al. found that periphytic algae exhibit significant nitrogen and phosphorus removal rates when treating agricultural non-point-source pollution [3]. Moreover, they can help enhance water transparency and oxygen levels by adsorbing organic matter and heavy metals from the water. Periphytic algae can attach to sediments, rocks, aquatic plants, and even the surfaces of animals, forming microhabitats that offer suitable shelter and food sources for various invertebrates, plankton, and juvenile fish [4,5]. Certain periphytic algae, notably filamentous macroalgae like *Cladophora*, not only contribute to primary biomass but also offer structural surfaces that facilitate the subsequent colonization of epiphytic microalgae and microbial assemblages [6,7]. Michalak and Messyasz found that diatoms settled more readily on some macroscopic green algae, while on others, much slower and in smaller amounts [8]. Battin et al. demonstrated that extracellular polymeric substances (EPS) secreted by periphytic algae enhance the adhesiveness of substrate surfaces, thereby stabilising algal and sediment particles, reducing their resuspension by water flow, and acting as "biological cement" to effectively reduce riverbed erosion and sediment transport [9]. Pan et al. suggested that hydrodynamic conditions affect the composition of EPS, thus affecting the biofilm formation. They found that under turbulent flow conditions, the overall biofilm structure was denser [10]. Salant suggested that periphytic algae can indirectly affect particle deposition and infiltration by altering the hydrodynamic properties of flowing water and can also directly affect particle deposition and infiltration through particle capture and adhesion [11]. Similarly to large-scale plant forms, the structure, density, and coverage of periphytic algae may determine the extent of their influence on aquatic ecological processes. Therefore, the role of periphytic algae in aquatic ecosystems extends beyond nutrient removal and water quality purification to include diverse effects on hydrodynamics, sedimentation processes, and ecological structures.

Compared to aquatic plants, periphytic algae lack complex structures such as roots, stems, and leaves. Instead, they form a "biofilm" by secreting adhesive substances, enabling them to attach and grow in various environments [12–14]. These algae are composed of interconnected cells and are typically highly sensitive to environmental changes such as water temperature, light, and nutrient levels. Owing to their relatively simple structure, periphytic algae exhibit a lower resistance to stress and are more vulnerable to disturbances such as water flow, pollution, or other external pressures, which can lead to their death. Following mortality, periphytic algae are decomposed by microbial action, releasing nutrients back into the water. If large quantities of algae die and are not properly managed, this can lead to eutrophication and algal blooms, resulting in the production of harmful substances and further degradation of water quality [15–17]. Harmful Algal Blooms (HABs) produce toxins that threaten aquatic biodiversity, contaminate drinking water, and cause economic

losses in fisheries and tourism [18–20]. The respiration and decomposition of algae consumes dissolved oxygen, while the formation of algal blooms reduces water transparency, thereby inhibiting the photosynthesis of other aquatic plants. This can potentially lead to hypoxic conditions, adversely affecting the survival of other aquatic organisms [21,22]. Therefore, research on periphytic algae has garnered significant interest, with the interaction mechanisms between water flow and periphytic algae emerging as a key topic in river dynamics and aquatic ecology. Understanding this relationship holds considerable scientific, ecological, and practical value.

Water flow not only supplies periphytic algae with a suitable growth environment and essential nutrients but also affects their morphological structure and spatial distribution through hydrodynamic forces [23,24]. Sun et al. found that the algal biomasses in the velocity environments of 0.211 and 0.418 m/s decreased by 30.19% and 39.88%, respectively [2]. Factors such as flow velocity, shear stress, and turbulence intensity can induce morphological adaptations in periphytic algae, such as the bending and stretching of algal filaments, to reduce resistance to water flow [25,26]. These morphological responses reflect the adaptive mechanisms of periphytic algae to hydrodynamic environments and simultaneously exert a feedback effect on the redistribution of local water flow and boundary layer structure, thereby influencing the interaction processes at the ecological interface [27]. Flow velocity, along with associated mass and momentum fluxes, is recognized as a critical factor affecting the growth and morphology of biological communities [28–31]. An appropriate flow velocity promotes the initial attachment and biomass accumulation of periphytic algal communities, whereas excessively high flow conditions can inhibit algal growth, potentially leading to filament breakage and detachment [29,32–35]. Under the influence of water flow, periphytic algae often undergo significant flexible deformations, including bending, swaying, and periodic undulation. These deformations alter the local flow structure and may induce the formation of vortices. Highly flexible plants behave similarly to porous media, swaying with water movement, and their dynamic responses enhance turbulence mixing and momentum transfer. Ejection and sweep events at the canopy top significantly promote momentum transfer from the vegetated layer to the free water layer [36,37]. Aquatic plants in rivers influence hydrodynamics and sediment transport processes by modifying flow velocity distribution, turbulence structure, and shear stress [38], while variations in plant types and river morphology also impact the longitudinal diffusion of pollutants in river systems [39].

Although previous studies have revealed the ecological role of periphytic algae, their interaction with water flow and its impact on hydrodynamics remain insufficiently understood. This study seeks to address gaps in existing theories by examining the dynamic interaction between periphytic algae and water flow in greater depth. This, in turn, provides novel theoretical support for river water environment management and vegetation restoration. This study systematically investigates the interaction mechanisms between periphytic algae and water flow. First, based on force analysis, a resistance model was developed to characterise the nonlinear response of periphytic algae under hydrodynamic influence, with a detailed examination of the components and variation patterns of frictional and drag forces. Building on this, the flow domain was divided into two parts: the periphytic algae layer and the free water layer. Analytical solutions for the velocity distribution within this two-layer structure were derived. In the periphytic algae layer, a novel resistance expression was employed, incorporating frictional flow velocity and dimensionless control parameters to derive the vertical velocity distribution. In the free water layer, the periphytic algae layer was treated equivalently as a “new riverbed,” and the velocity distribution was obtained using the first-order closure model proposed by Wang et al. [40]. This two-layer velocity structure model effectively elucidates the regulatory

mechanisms of periphytic algae in the hydrodynamic environment, thereby enriching the theoretical framework of ecological hydraulics. It offers important theoretical support and reference value for understanding the regulatory mechanisms of river ecosystems, as well as for guiding water environment management and ecological restoration practices.

2. Theory and Methods

This study examines the interaction between periphytic algae and water flow under the influence of periphytic algae. Under typical flow conditions, periphytic algae are generally submerged. Therefore, in analysing the flow structure, the flow is divided into two distinct layers: the periphytic algae layer and the free water layer, as illustrated in Figure 1.

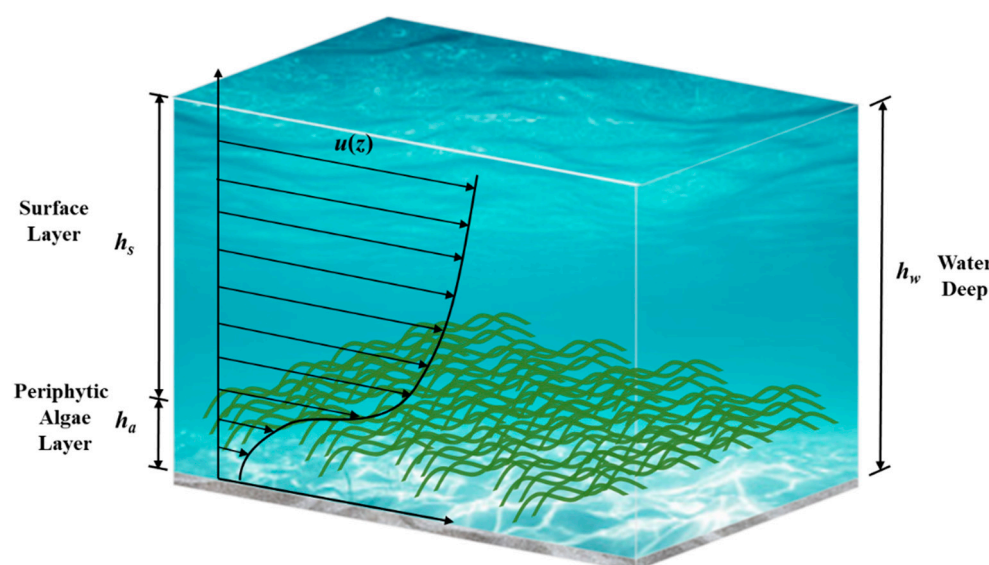


Figure 1. Schematic diagram of the two-layer model of periphytic algae and water flow. (Note: h_w denotes the water depth; h_a is the height of the periphytic algae after bending; h_s is the depth of the free water layer; $u(z)$ is the time-averaged flow velocity at vertical position z ; and θ is the bending angle of the periphytic algae).

2.1. Resistance Characteristics of the Periphytic Algae Layer

For rigid submerged vegetation, the projected area remains constant with varying flow velocity, and the resulting resistance is typically proportional to the square of the flow velocity [41–43]. However, this relationship holds true only within a limited range of velocity and scale.

$$F_d = \frac{1}{2} \rho C_d m D u_v^2 \quad (1)$$

In the equation, F_d represents the resistance exerted by the vegetation; ρ is the density of water; C_d is the resistance coefficient of the vegetation; m denotes the vegetation density, i.e., the number of vegetation per unit bed area; D is the frontal width of individual vegetation that blocks the water flow; and u_v is the time-averaged water flow velocity within the vegetation layer.

In the study of flexible vegetation, when subjected to aerodynamic or hydrodynamic loads, vegetation often undergoes reconfiguration, forming streamlined structures that effectively reduce the fluid resistance it experiences [25,44–49]. Under the scouring effect of water flow, the shape of the vegetation changes, resulting in more complex resistance behaviour [50]. Both the projected area and resistance coefficient vary dynamically with flow velocity, making the resistance characteristics difficult to predict accurately [51,52]. The classical resistance formula for rigid vegetation does not account for the reconfiguration

effects of flexible vegetation under flow conditions. For vegetation that bends, the relationship between the resistance and the square of the flow velocity is no longer applicable. Therefore, this formula is unsuitable for modelling natural flexible vegetation.

The classical resistance calculation formula for rigid vegetation is based on the assumption that vegetation morphology remains unchanged under the influence of water flow, thereby neglecting the morphological reconfiguration characteristics exhibited by flexible vegetation in dynamic flow environments. Consequently, it does not adequately capture the resistance behaviour of flexible vegetation. However, periphytic algae, as highly flexible organisms, exhibit fluid resistance characteristics that closely resemble those of flexible vegetation [25,51]. Therefore, despite structural and biological differences, research on the resistance properties of flexible vegetation can serve as a valuable theoretical reference for analysing the resistance behaviour of periphytic algae, contributing to a deeper understanding of the complex interaction mechanisms between water flow and periphytic algae.

Building on the interaction between vegetation and water flow, Wang et al. [40] proposed that the hydrodynamic forces acting on a single flexible plant can be decomposed into two orthogonal components, including the drag force perpendicular to the plant's stem and leaves and the frictional force parallel to the plant's stem and leaves (Figure 2). They introduced the bending deformation angle θ as a morphological parameter, establishing a quantitative relationship $F_x \propto f(\theta)$ between resistance and the bending angle, and forming a drag force function expression:

$$F_x = \frac{1}{2} \rho m (C_d D \cos^2 \theta + C_f C_p \frac{\sin^3 \theta}{\cos \theta}) u_v^2 \quad (2)$$

where F_x represents the total drag force along the flow direction, C_d is the drag coefficient, C_f is the frictional coefficient, $C_p = \pi D$ denotes the circumference of the cross-section of a single plant, and θ is the bending angle of the vegetation. The drag coefficient C_d can be determined from $C_d = 1 + 10Re^{-2/3}$ [53,54], and $C_d = \frac{50}{Re_v^{0.43}} + 0.7 \left[1 - \exp\left(-\frac{Re_v}{15000}\right) \right]$ [55], where Re and Re_v are both characteristic Reynolds numbers. The frictional coefficient C_f can be obtained from $C_f = \frac{1.328}{Re_F^{0.5}}$, $C_f = \frac{0.074}{Re_F^{0.2}} - \frac{1740}{Re_F}$, and $C_f = \frac{0.455}{\log(Re_F)^{2.584}} - \frac{1700}{Re_F}$ [56,57], and its value must be determined based on the range of the Reynolds number Re_F , $Re_F = \frac{u_v l \sin \theta}{\nu}$, where l is the arc length from the base of the plant to the point of calculation (in this case, it is taken as the top of the vegetation, i.e., the vegetation length), and ν is the kinematic viscosity coefficient. For computational convenience, the drag coefficient C_d is adopted as $C_d = 1 + 10Re^{-2/3}$. Calculations indicate that the values of Re_F are all less than 5×10^5 (Table 1), and the frictional coefficient is selected according to $C_f = \frac{1.328}{Re_F^{0.5}}$.

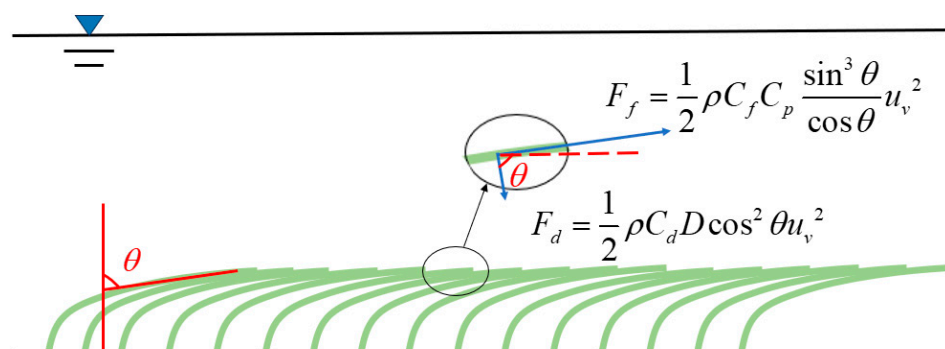


Figure 2. Force analysis of a single periphytic algae filament. (The blue triangle represents the water surface height, the blue arrows indicate the force direction, and θ is the bending angle of the vegetation).

Table 1. Parameters for different experimental conditions.

Case	Q (m ³ /s)	h_w (m)	h_v (m)	D (mm)	m (1/m ²)	Re	Re_F
A1	0.0172	0.175	0.030	0.05	1,200,000	97,348	5841
A2	0.0273	0.170	0.031	0.05	1,200,000	158,935	9854
A3	0.0356	0.170	0.032	0.05	1,200,000	207,609	13,287
A4	0.0407	0.160	0.029	0.05	1,200,000	252,806	14,663

Note: Q is the flow rate; h_w is the total water depth; h_v is the height of the vegetation after bending; D is the frontal width of a single vegetation that blocks the water flow; m is the vegetation density; and Re and Re_F are the characteristic Reynolds numbers.

Experimental observations have demonstrated that periphytic algae exhibit pronounced bending under flowing water, with bending angles frequently ranging from 80° to 90°. Within this range, the algal filaments undergo substantial morphological deformation, significantly reducing their effective frontal area and thereby diminishing the drag force. Concurrently, the increased surface contact between the algal filaments and the surrounding fluid enhances frictional resistance, which progressively emerges as the dominant component of the overall hydraulic resistance. A similar trend was reported by Rota et al. in their study of flexible canopies, where streamwise bending of flexible elements led to a reduced frontal area and drag coefficient, while contributions from shear and frictional interactions became more pronounced [58].

By incorporating the relevant resistance coefficients into the relationship between flow velocity and algal resistance, it is found that the total resistance of the periphytic algal layer exhibits a nonlinear dependence on the local time-averaged flow velocity. Specifically, when the average bending angle approaches 80°, fitting results reveal that the total resistance scales approximately with the 1.5 power of velocity $F_a \propto u_a^{1.5}$ (where F_a denotes the resistance of periphytic algae, and u_a is the time-averaged water flow velocity within the periphytic algae layer, with the subscript a denoting periphytic algae). Therefore, in analysing the hydrodynamic response of periphytic algae, it is crucial to consider the transition from drag-dominated to friction-dominated resistance induced by structural bending, rather than evaluate drag force in isolation.

Here, a new dimensionless parameter C_a is defined to calibrate the newly constructed resistance expression for periphytic algae, thereby simplifying the influence of variations in other parameters, as expressed below:

$$F_a = \rho C_a m D u_*^{0.5} u_a^{1.5} \quad (3)$$

In this equation, C_a is the newly defined resistance coefficient for periphytic algae, $u_* = \sqrt{gSh_s}$ ($h_s = h_w - h_a$) represents the frictional flow velocity at the top of the layer of the periphytic algae, h_w denotes the total water depth, h_a is the height of the periphytic algae after bending, h_s is the height of the free water layer, and S is the energy slope, defined as the sum of the bed slope and the water surface slope. In Equation (3), $u_*^{0.5}$ is introduced to ensure dimensional balance.

2.2. Analytical Solution for Velocity Distribution

2.2.1. Analytical Solution for Velocity Distribution in the Periphytic Algae Layer

In the periphytic algae layer, the velocity distribution of water flow is influenced by factors such as the morphological characteristics, bending degree, and density of the periphytic algae. To establish an analytical model for the velocity distribution, it is essential to account for the influence of periphytic algae on the flow. The presence of periphytic algae modifies the flow structure, thereby affecting the resulting velocity distribution. Under steady flow conditions, the water flow in the periphytic algae layer is influenced by

multiple forces, including the gravitational component, Reynolds stress, and the resistance of periphytic algae to the water flow. For steady and uniform flow, these three forces must be in equilibrium, and the following relationship should be satisfied:

$$\frac{\partial \tau}{\partial z} - F_a + \rho g S = 0 \quad (4)$$

where τ is the Reynolds stress; z represents the different water level heights in the water body; and g is the acceleration due to gravity.

The Reynolds stress τ within the periphytic algae layer is calculated using an exponential model [59,60], as follows:

$$\tau = -\overline{\rho u'w'} = -\overline{\rho u'w'} \Big|_{z=h_a} \exp[\alpha(z - h_a)] \quad (5)$$

where α is a constant, and the terms u' and w' represent the fluctuation quantities of the longitudinal and vertical flow velocities, respectively.

Through force analysis, the shear stress at the top of the periphytic algae layer $-\overline{\rho u'w'} \Big|_{z=h_a}$ (where $z = h_a$) is given by ρu_*^2 [61]. Substituting this expression into Equation (5) yields:

$$\tau = \rho u_*^2 \exp[\alpha(z - h_a)] \quad (6)$$

Substituting both Equations (3) and (6) into Equation (4), we can derive:

$$\frac{\partial}{\partial z} \left(u_*^2 \exp[\alpha(z - h_a)] \right) - C_a m D u_*^{0.5} u_a^{1.5} + g S = 0 \quad (7)$$

Solving Equation (7) provides the analytical solution for the vertical velocity distribution within the periphytic algae layer:

$$u_a(z) = \left(\frac{\alpha u_*^2 \exp[\alpha(z - h_a)] + g S}{C_a m D u_*^{0.5}} \right)^{\frac{2}{3}} \quad (8)$$

2.2.2. Analytical Solution for Velocity Distribution in the Free Water Layer

For water flow without periphytic algae, the vertical velocity distribution is primarily governed by the bed shear stress, reflecting the interaction between bed morphology and fluid flow. However, in rivers containing periphytic algae, the roughness of the periphytic algae layer significantly exceeds that of the underlying riverbed [62]. Consequently, the resistance effect of the periphytic algae layer becomes the dominant factor influencing the vertical velocity distribution in the free water layer. Therefore, the periphytic algae layer can be considered as a large-scale “new riverbed,” effectively constituting a part of the riverbed resistance. Consequently, the water flow above the periphytic algae layer can be regarded as flowing over this “new riverbed” within the free water layer [63]. Based on this assumption, this study adopts the “periphytic algae new riverbed” theory and models the free water layer as an open-channel flow characterized by high roughness, thereby deriving the analytical solution for the velocity distribution in the free water layer.

In open-channel flow, beyond the viscous bottom layer and away from the free water surface, the parameters influencing the time-averaged flow velocity include the frictional flow velocity u_* , the distance from the wall y , the fluid’s kinematic viscosity ν , and the Reynolds number Re . Kármán proposed a logarithmic formula $\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{u_* y}{\nu} + A$ for uniform open-channel flow [64], where κ is the Kármán constant and A is a constant. Barenblatt et al., based on the theory of incomplete similarity, argued that a fully similar Reynolds number does not exist and instead proposed an exponential formula $\frac{u}{u_*} = \left(\frac{1}{\sqrt{3}} \ln Re + \frac{5}{2} \right) \left(\frac{u_* y}{\nu} \right)^{3/2 \ln Re}$ for uniform open-channel flow [65]. Significant studies

have been carried out on the distribution of turbulent velocity in natural rivers, and the logarithmic velocity distribution formula is widely used [66]. The logarithmic formula $u = \frac{u_*}{\kappa} \ln\left(\frac{z-d}{z_0}\right)$ is based on the semi-empirical theory with universality, where parameters are mainly constants and do not depend on the Reynolds number [57,67], where d is the zero-plane displacement, and z_0 is the roughness heights.

However, this study adopts the first-order closure model proposed by Wang et al. to investigate the velocity distribution in the free water layer [40]. Based on this model, an analytical solution is derived to more effectively examine the velocity distribution in environments influenced by periphytic algae. The first-order closure model provides a simple yet effective approach for describing velocity distributions in open-channel flows. It is particularly suitable for studying fully developed turbulent flow and demonstrates high applicability and accuracy in predicting velocity profiles. By employing this model, flow velocity variation in complex environments can be reasonably represented, and parameters such as flow resistance can be accurately estimated.

In the free water layer, where the drag force exerted by periphytic algae is absent, the governing equation can be expressed as follows:

$$\frac{\partial \tau}{\partial z} + \rho g S = 0 \quad (9)$$

The Reynolds stress is calculated using the first-order closure formulation proposed by Wang et al. [40], as follows:

$$\tau = \rho k_s u_* z \frac{\partial u_s}{\partial z} \quad (10)$$

In this equation, k_s denotes the Kármán constant for the free water layer and u_s is the time-averaged velocity in the free water layer.

By substituting Equation (10) into Equation (9) and solving it, we obtain:

$$u_s(z) = k_s u_* \ln z + gS - \frac{gS}{k_s u_*} z + C \quad (11)$$

where C is an integration constant that can be determined through boundary conditions.

At the top of the periphytic algae layer, where $z = h_a$, the velocity in the periphytic algae layer should equal the velocity in the free water layer, i.e., $u_s(h_a) = u_a(h_a)$. Therefore, we solve for:

$$C = \left(\frac{\alpha u_*^2 + gS}{C_a m D u_*^{0.5}} \right)^{\frac{2}{3}} - k_s u_* \ln h_a - gS + \frac{gS}{k_s u_*} h_a \quad (12)$$

By substituting Equation (12) into Equation (11), the analytical solution for the velocity distribution in the free water layer can be derived as follows:

$$u_s(z) = \left(\frac{\alpha u_*^2 + gS}{C_a m D u_*^{0.5}} \right)^{\frac{2}{3}} + k_s u_* \ln \frac{z}{h_a} + \frac{gS}{k_s u_*} (h_a - z) \quad (13)$$

In summary, this section presents a nonlinear resistance model and a layered analytical velocity formulation that collectively capture the flow-regulating effects of flexible periphytic algae. These developments provide a theoretical basis for model validation using experimental data and for investigating the dynamic coupling between biological structures and open-channel flow, thereby contributing to the overarching objective of enhancing ecological hydraulic modelling.

2.3. Error Analysis Method

To quantitatively evaluate the predictive performance of the model, a series of statistical error metrics were adopted, including absolute error (*AE*), relative error (*RE*), root mean square error (*RMSE*), Normalized Root Mean Square Error (*nRMSE*), and coefficient of determination (R^2). These metrics are widely used in regression and model validation tasks.

The absolute error (*AE*) quantifies the difference between the predicted and measured values, directly reflecting the deviation between them. A smaller value indicates a better fit, and its expression is:

$$AE = \frac{1}{N} \sum_1^N |u_p - u_m| \quad (14)$$

where N is the number of measurement points under each operating condition, u_p is the predicted flow velocity for each condition, and u_m is the measured flow velocity for each condition.

The relative error (*RE*) is defined as the ratio of the absolute error to the measured value and is commonly used to standardise the magnitude of the error. A smaller value indicates a better fit, and its expression is:

$$RE = \left(\frac{1}{N} \sum_1^N \left| \frac{u_p - u_m}{u_m} \right| \right) \times 100\% \quad (15)$$

The root mean square error (*RMSE*) quantifies the degree of fit between the predicted and measured values and is a widely used statistical metric to evaluate the accuracy of a predictive model. A smaller value indicates a better fit, and its expression is:

$$RMSE = \sqrt{\frac{\sum_1^N (u_p - u_m)^2}{N}} \quad (16)$$

The coefficient of determination (R^2) represents the degree of correlation between the predicted and measured values. It is a commonly used statistical metric to evaluate how well-fit a model is, and a value closer to 1 indicates a better correlation. Its expression is:

$$R^2 = \frac{\left(\sum_1^N (u_p - u_p^{mean})(u_m - u_m^{mean}) \right)^2}{\sum_1^N (u_p - u_p^{mean})^2 \sum_1^N (u_m - u_m^{mean})^2} \quad (17)$$

where u_p^{mean} is the mean of the predicted flow velocities for each condition, and u_m^{mean} is the mean of the measured flow velocities for each condition.

The normalized root mean square error (*nRMSE*) is a statistical metric that evaluates the prediction accuracy of a model by expressing the RMSE as a percentage of the mean of the measured values. A smaller value indicates a better fit, and its expression is:

$$nRMSE = \sqrt{\frac{\sum_1^N (u_p - u_m)^2}{N u_m^{mean2}}} \times 100\% \quad (18)$$

3. Experiment

The periphytic algae velocity distribution experiment was conducted at the National Key Laboratory of River Basin Water Cycle Simulation and Regulation, Institute of Water Ecology and Environment, China Institute of Water Resources and Hydropower Research.

The experimental setup consisted of a recirculating water tank constructed from glass, measuring 10 m in length, 1 m in width, and 1 m in height. The upstream section of the tank was fitted with a valve equipped with an electromagnetic flowmeter, while the downstream section featured a tailgate with a flap gate. Flow rate and velocity were controlled by adjusting the water pump capacity and tailgate opening, allowing simulation of various flow conditions. To ensure water flow stability during measurements, a honeycomb energy dissipation pipe was installed at the upstream inlet to smooth the flow, maintaining a steady and uniform velocity within the tank. Water level gauges were positioned along the sidewalls to monitor water depth changes in real-time, thereby ensuring flow stability and data accuracy, as well as recording upstream and downstream water levels. To validate the velocity distribution affected by periphytic algae, a series of velocity distribution experiments were systematically designed and conducted. The flow velocity range was 0.2 m/s to 0.5 m/s, with increments of 0.1 m/s, comprising a total of four experimental groups. The parameters for each experimental condition are detailed in Table 1. During the experiments, periphytic algae were uniformly distributed along the bottom of the tank to reduce the randomness of spatial distribution.

Particle Image Velocimetry (PIV) is a non-intrusive optical measurement technique based on image recognition. It operates by introducing neutrally buoyant tracer particles into the fluid, which follow the flow dynamics. The seeded flow is illuminated by a high-frequency double-pulsed laser, while a high-speed camera captures two successive images within a short time interval. A cross-correlation algorithm is then employed to analyse particle displacement between the image pairs, yielding a two-dimensional velocity vector field. In this experiment, each test run produced a sequence of 2200 images. These images were processed using PIVlab (3.01), a MATLAB-based analysis toolbox, to extract instantaneous velocity vectors. The resulting data were then time-averaged to obtain a representative velocity field under steady-state conditions. Flow velocity measurements were obtained using a Particle Image Velocimetry (PIV) system (Figure 3). The resulting velocity data provided essential support for analysing the velocity distribution patterns and the influence of periphytic algae on the flow dynamics.

This study focuses on investigating the interaction between periphytic algae and water flow in natural river channels. To facilitate in situ observation and analysis, a dedicated cultivation platform was established within natural river environments (Figure 4). The platform allows periphytic algae to grow under naturally occurring environmental conditions, including appropriate temperature, light, and nutrient levels. The growth of the algae was regularly monitored, and samples were collected to ensure they remained in an active growth phase and were not approaching detachment. Under consistent environmental conditions, periphytic algae were cultivated in the natural river for over 30 days, ultimately providing suitable samples for subsequent experimental analysis.

The natural periphytic algae employed in this study is *Cladophora* (Figure 5), a filamentous, green, branched algae species widely distributed in both marine and freshwater environments. The cells of *Cladophora* are tubular, typically forming filamentous or spherical structures. They are commonly attached to substrates such as rocks, wooden stakes, and submerged plants. Under varying water flow conditions, periphytic algae exhibit different bending morphologies. In this experiment, *Cladophora* had a diameter of 50 μm [68] and an average length of 10 cm. The dry weight of *Cladophora* on a 10 cm $\times$ 10 cm plate was 2.2 g, with a density of 1,200,000 filaments/ m^2 . During the velocity distribution experiment, the water temperature was 20 $^{\circ}\text{C}$, and the viscosity coefficient of the flow was $1.0067 \times 10^{-6} \text{ m}^2/\text{s}$. The Reynolds numbers Re ranged from 9.7248×10^4 to 2.52806×10^5 , exceeding the critical Reynolds number of 2000 for turbulent flow in open channels, thereby

indicating that the experimental flow conditions were turbulent. The specific parameters for the experimental conditions are presented in Table 1.

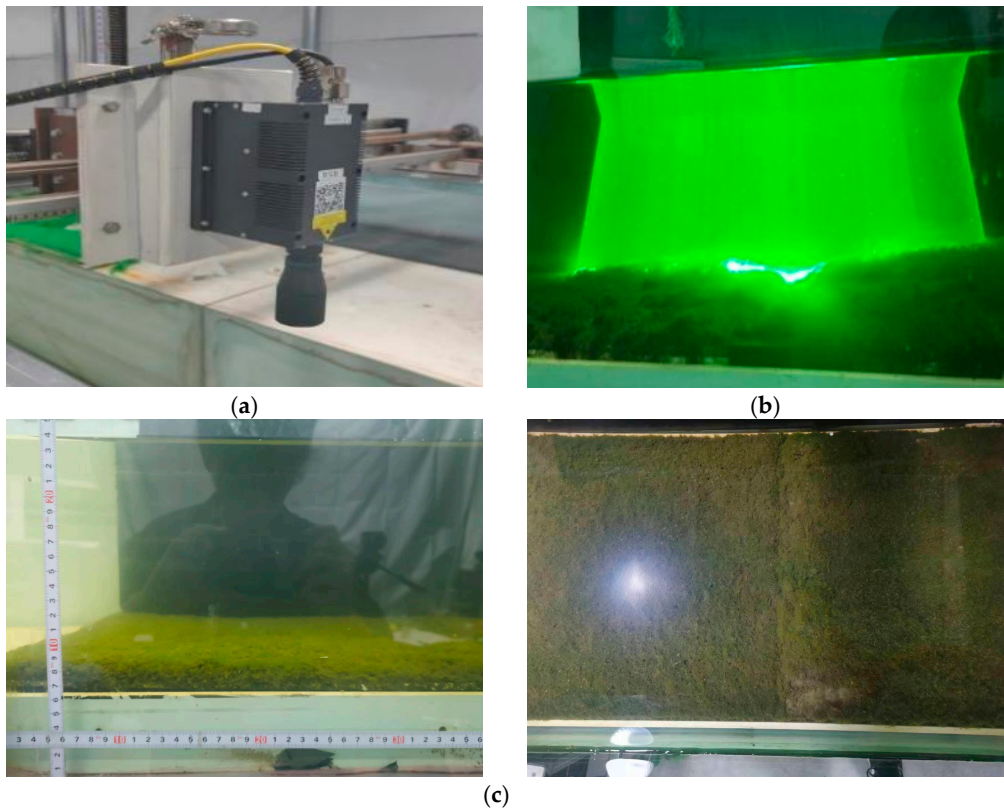


Figure 3. (a) PIV-based velocity measurement setup; (b) high-precision hydrodynamic measurement within the algae filament area; and (c) spatial distribution of periphytic algae.

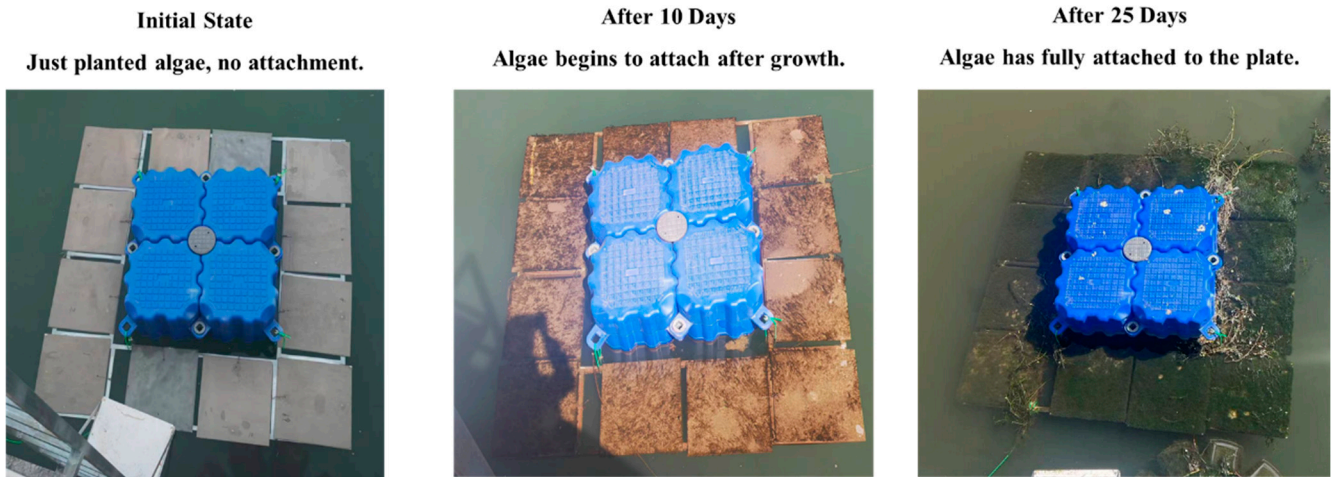


Figure 4. Cultivation process of periphytic algae.



Figure 5. Cladophora sample.

4. Results and Discussion

4.1. Velocity Model Validation

As shown in Figure 6, a comparison was made between the measured and predicted vertical velocity distributions under the influence of periphytic algae. Overall, the predicted results demonstrate strong agreement with the experimental measurements across the entire range of flow velocities.

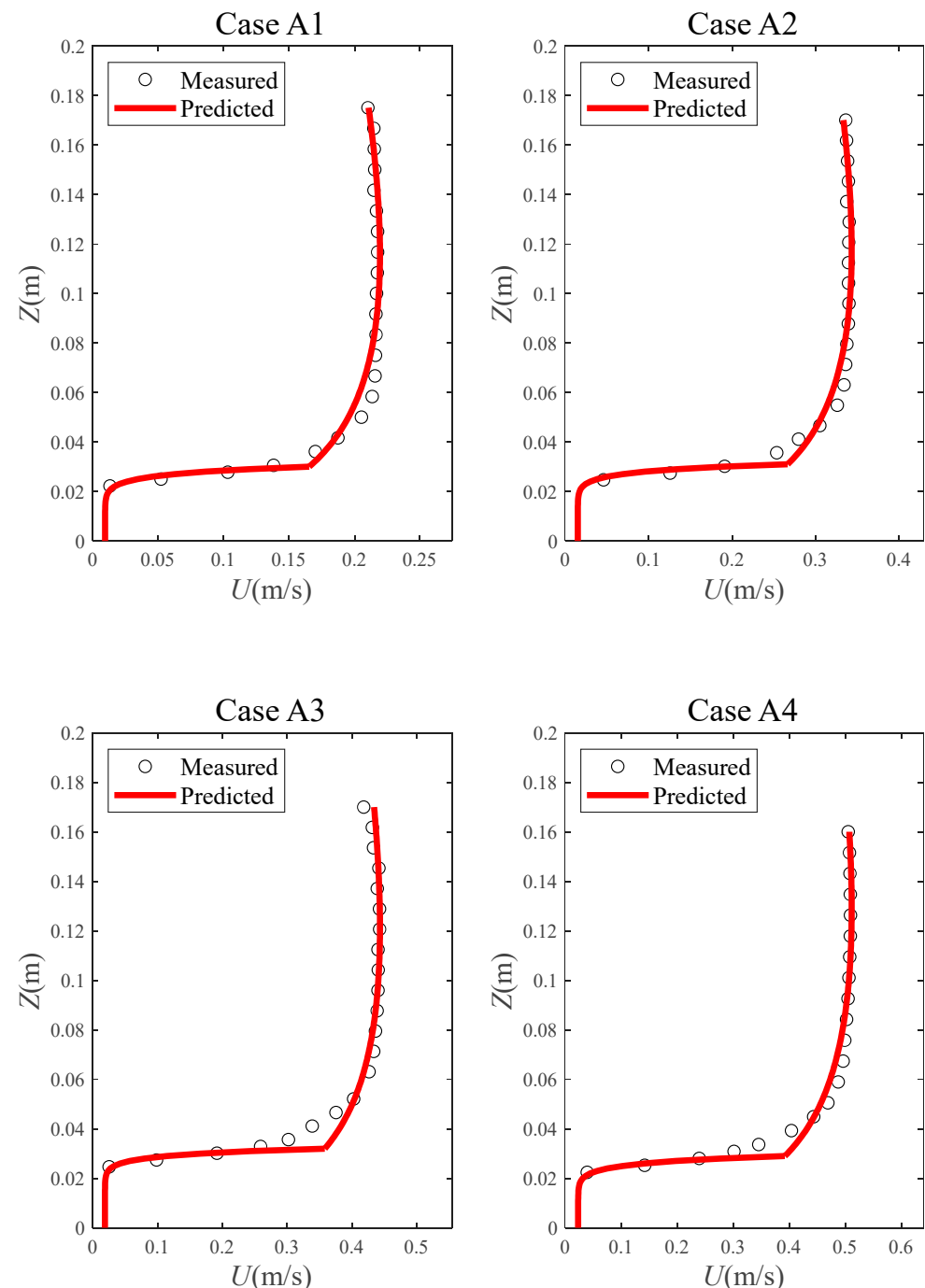


Figure 6. Comparison of measured and predicted velocity distributions (red line represents model-predicted velocity; black circles represent measured velocity).

Particle Image Velocimetry (PIV) tracks the movement of small particles suspended in the fluid over a defined time interval, utilizing high-speed imaging and advanced image analysis techniques to accurately calculate flow velocity. Experimental results revealed that

the flow velocity within the periphytic algae layer is relatively low. This reduction is attributed to the high density of periphytic algae, which obstructs water movement through the layer, thereby significantly reducing the local flow velocity. The dense structure of the periphytic algae not only increases flow resistance due to enhanced friction but also potentially induces localized turbulence, further contributing to the observed reduction in velocity.

4.2. Error Analysis

Figure 7 presents a more intuitive comparison between the measured and predicted flow velocities. To further assess the accuracy of the proposed model under varying operational conditions, a comprehensive and precise evaluation is conducted through error analysis. The specific error analysis can be referred to in Section 2.3. This analysis examines the magnitude, trends, and correlations of the errors between the measured data and the predicted data.

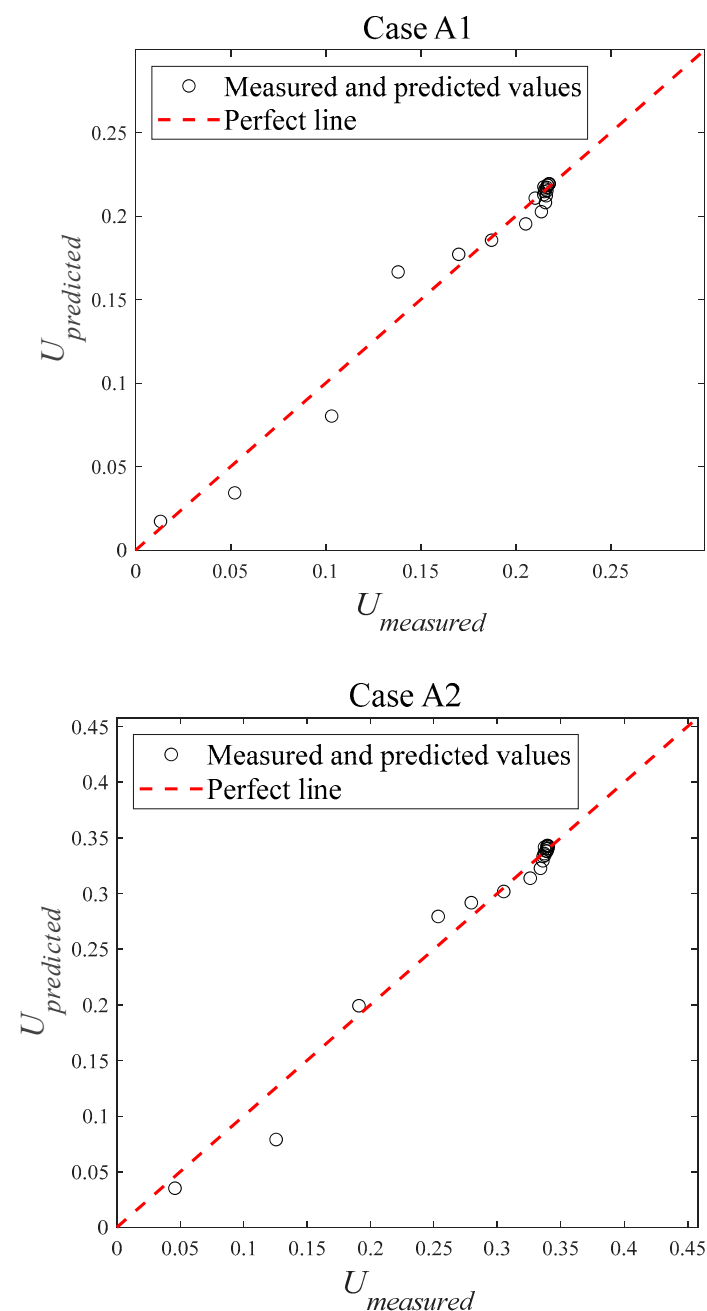


Figure 7. Cont.

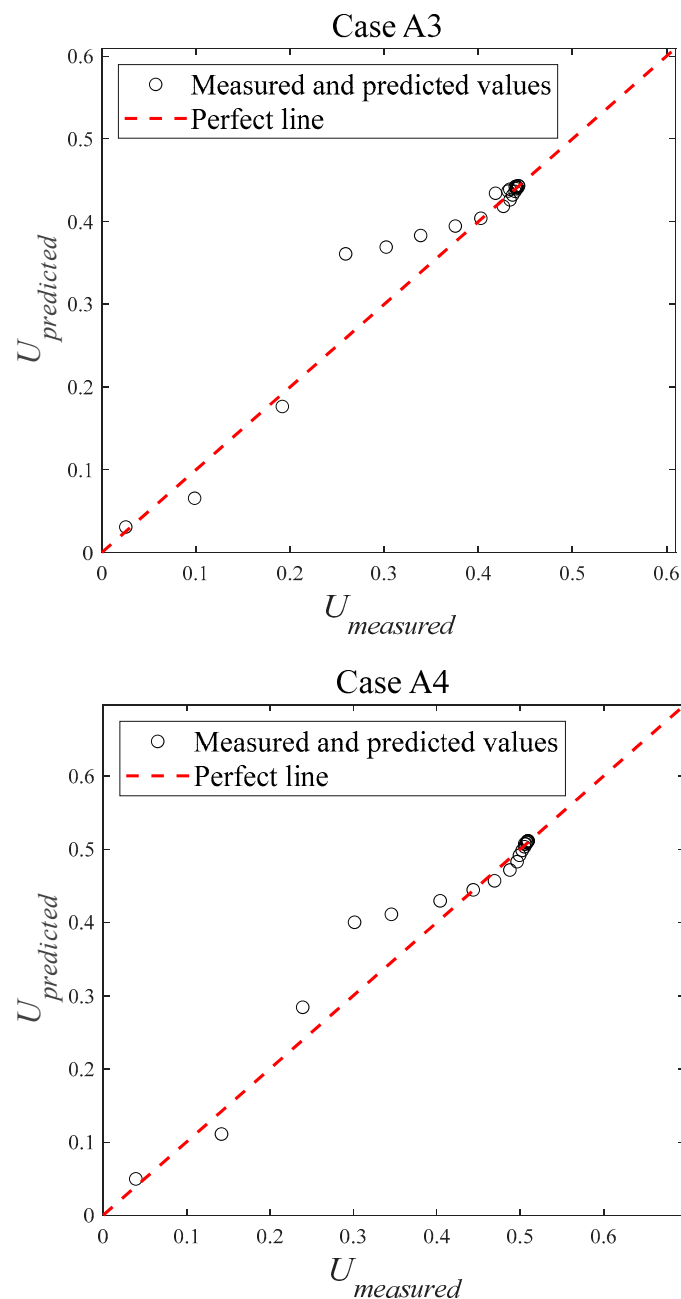


Figure 7. Comparison of measured and predicted flow velocities (red dashed line represents model-predicted velocity; black circles represent actual measured velocity).

The results of the error analysis are shown in Table 2.

Table 2. Statistical error analysis for different operating conditions.

Case	AE	RE	RMSE	nRMSE	R^2
A1	0.0060	6.21%	0.0096	5.16%	0.9740
A2	0.0078	4.64%	0.0131	4.39%	0.9796
A3	0.0157	7.12%	0.0294	8.00%	0.9448
A4	0.0164	6.63%	0.0297	6.97%	0.9543

As shown in Table 2, the average absolute error (AE) of the predicted flow velocity ranges from 0.0060 to 0.0164, the average relative error (RE) ranges from 4.64% to 7.12%, the root mean square error (RMSE) ranges from 0.0096 to 0.0297, and the normalized root

mean square error ($nRMSE$) ranges from 4.39% to 8.00%. The coefficient of determination (R^2) between the predicted and measured values ranges from 0.9796 to 0.9448. These results demonstrate that the model exhibits high predictive accuracy and reliability in capturing the velocity distribution characteristics under the influence of periphytic algae across various operating conditions.

4.3. Parameter Analysis

In this study, the analytical solution for the velocity distribution is primarily governed by three key parameters: the periphytic algae resistance coefficient C_a , the constant α , and the Kármán coefficient k_s . These parameters play a critical role in characterising the flow velocity and resistance dynamics between the periphytic algae layer and the free water layer. Specifically, the resistance coefficient C_a and the constant α predominantly influence the velocity distribution within the periphytic algae layer, whereas the Kármán coefficient k_s primarily affects the velocity distribution in the free water layer. The following section presents a detailed discussion of the values of these three parameters, aiming to further elucidate their influence on the model's predictive accuracy and the overall velocity distribution profile.

Based on the data presented in Figure 8, an analysis of the three key parameters reveals distinct trends with increasing flow velocity. The periphytic algae resistance coefficient C_a gradually decreases, indicating that the hydraulic resistance induced by periphytic algae diminishes as flow velocity increases. The constant α remains relatively stable, ranging between 500 and 600 across various flow conditions. Despite its relatively large magnitude, the limited variation suggests that, under conditions of high periphytic algae layer density, shear disturbances are rapidly attenuated, contributing to the overall stability of the flow system. Additionally, the Kármán coefficient k_s shows an increasing trend with rising flow velocity, reflecting the development of stronger vortex structures at the interface between the periphytic algae and the free water layer. This indicates an enhancement in turbulence intensity as flow velocity increases.

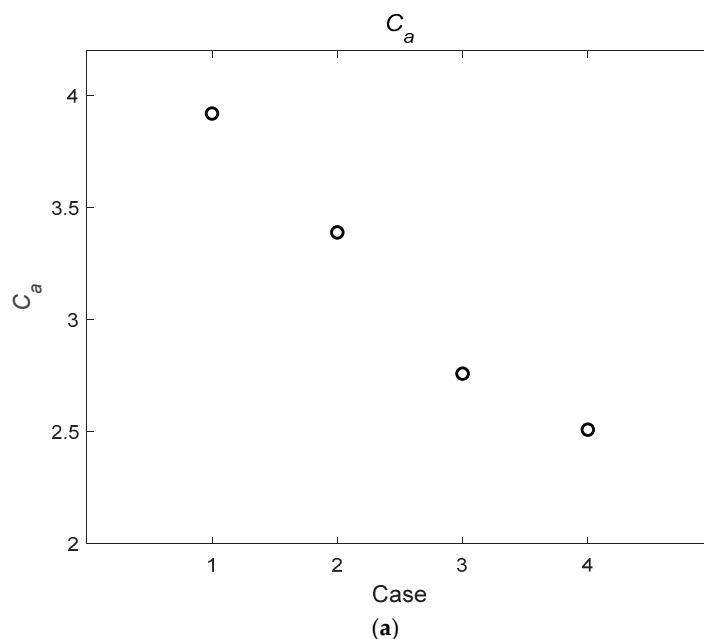


Figure 8. Cont.

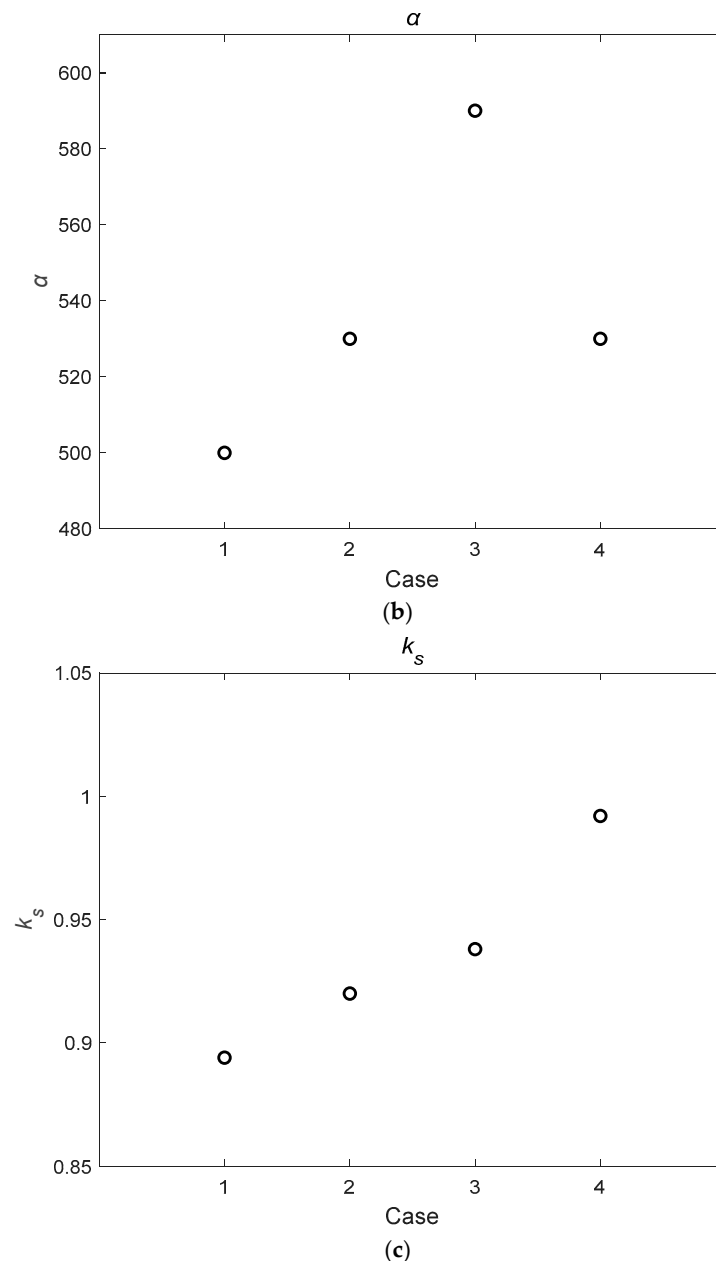


Figure 8. (a) Distribution of periphytic algae resistance coefficient C_d ; (b) distribution of constant α ; and (c) distribution of Kármán coefficient k_s .

The nonlinear resistance model and the corresponding analytical velocity structure proposed in this study offer novel theoretical support for modelling and mechanistic analysis of flexibly attached organisms within the field of ecological hydraulics. Moreover, the methodological framework established herein lays a solid foundation for future modelling efforts involving complex ecological processes, including multi-species cooperative dynamics and interactions between flexible organisms and turbulent flow.

It is important to note that this study is conducted under controlled laboratory conditions, with the primary objective of elucidating the fundamental interaction mechanisms between periphytic algae and water flow. Accordingly, the assumptions of steady and uniform flow are appropriate at this scale but inevitably simplify the complex hydrodynamic variability observed in natural environments. The Reynolds numbers employed reflect small-scale experimental conditions; however, we acknowledge the necessity of validating the model in natural river systems characterised by heterogeneous and unsteady flow regimes. Future research will prioritise extending the current framework to incorporate

unsteady and non-uniform flow conditions, thereby evaluating model performance under more realistic and complex hydrodynamic scenarios.

5. Conclusions

This study, focused on the highly flexible and deformable nature of periphytic algae, innovatively developed a nonlinear resistance model primarily governed by frictional effects. By conducting a comprehensive force analysis, key parameters such as the bending angle and friction coefficient were introduced, leading to the formulation of a quantitative resistance expression exhibiting a 1.5 power relationship with flow velocity.

This study developed a two-layer analytical model for velocity distribution in open-channel flow influenced by periphytic algae. Comparative analysis demonstrates that the proposed model exhibits high predictive accuracy across all conditions, with the coefficient of determination R^2 greater than 0.94. The absolute error, relative error, and root mean square error all fall within an acceptable range.

The study analysed the three principal parameters within the model: the periphytic algae resistance coefficient C_a , the constant α , and the Kármán coefficient k_s . The results indicate that the resistance coefficient C_a gradually decreases with increasing flow velocity, the constant α remains within the range of 500–600 under different flow conditions, and the Kármán coefficient k_s increases as the flow velocity rises.

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