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Abstract

The presence of floaters should be taken into account when dealing with hydraulic analyses, e.g. when boats are moored along the river banks or large wood is expected to be conveyed by the river flow during floods. Many approaches have been proposed so far in order to consider the effects of floaters upon the flow features. Usually, they rely on the numerical resolution of the governing equation for both the fluid and the solid phases. Hence, their computational cost can be inadequate at the early stage of hydraulic studies or when large scale analyses have to be performed. A simplified method to compute the value of the resistance coefficient able to reproduce the effects of floaters upon the flow levels is proposed herein. The method is intended to provide the hydraulic parameters to be used within standard hydraulic

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Keywords (separated by '-')	Floaters - Free-surface levels - Hydraulic resistance - Large wood transport - One-dimensional models
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ORIGINAL ARTICLE

Effects of floaters on the free surface profiles of river flows

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Abstract

The presence of floaters should be taken into account when dealing with hydraulic analyses, e.g. when boats are moored along the river banks or large wood is expected to be conveyed by the river flow during floods. Many approaches have been proposed so far in order to consider the effects of floaters upon the flow features. Usually, they rely on the numerical resolution of the governing equation for both the fluid and the solid phases. Hence, their computational cost can be inadequate at the early stage of hydraulic studies or when large scale analyses have to be performed. A simplified method to compute the value of the resistance coefficient able to reproduce the effects of floaters upon the flow levels is proposed herein. The method is intended to provide the hydraulic parameters to be used within standard hydraulic simulations for which the effects of floaters must be accounted for; this is obtained by means of a modified resistance coefficient. AQ1

Keywords Floaters · Free-surface levels · Hydraulic resistance · Large wood transport · One-dimensional models

1 Introduction

The banks of large rivers can often host up to a few thousand moored boats. Similarly, large wood may occur and floaters can occupy the entire river free surface for several hundred meters as well. Therefore, the presence of floaters may influence the flow levels. This is tremendously important when dealing with hydraulic analyses aimed at reproducing the floods propagation within the frame of flood hazard analysis (e.g. [3, 6, 27, 36]). Nevertheless, the additional flow resistance that occurs is not usually included in the model equations used to perform hydraulic analyses.

Indeed, the effects of floaters are usually taken into account only by using numerical models able to describe in detail the interaction between moving logs and fluid flow (e.g. [21, 25]). With this aim, the numerical modeling of a two-phase (i.e. fluid and large wood)

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system needs to be performed. As pointed out by Persi et al. [21], either Lagrangian-Lagrangian (i.e. a Lagrangian approach for both phases, e.g. [2]) or Eulerian–Lagrangian (i.e. Eulerian approach for the fluid and Lagrangian approach for the large wood, e.g. [23]) approaches may be used. These numerical strategies, however, may be too expensive when large scale flooding hazard analyses are needed. Then, a simplified method able to describe the effects of floaters on the free surface profiles of river flows can be useful.

The main goal of this research is to propose a general method that can be easily applied to standard hydraulic analyses while taking into account the presence of floaters within the computational domain with a low computational cost.

The rationale of the method relies on the hypothesis that any floaters (boats moored along the banks or large wood accumulation gathered at existing fixed structures or transported by the current) are subjected to a force exerted by the current. In turn, this action is counteracted by the mooring lines, by the fixed structure or by neighbor floaters and an equal and opposite force is exerted by the floaters on the current. The forces may be expressed as average tangential stress on the flow, i.e. by an increase of the hydraulic roughness. Of course, any claim to describe local flow feature cannot be made, as the interest is put on the larger spatial scale of water depth profile. The proposed method provides a general formulation able to estimate the increase of the hydraulic roughness as a function of the floaters' dimensions and arrangements along the river stretch.

The paper is structured as follows. First, Sect. 2 illustrates how the effects of fixed floaters may be modeled as an increase of flow resistance, as suggested by Sammarco and Di Risio [26] for the particular case of boats moored along the river banks. Then, Sect. 3 deals with the extension of the model proposed by [26] to moving floaters, i.e. to large wood transported by the current. Section 4 discusses the practical application of the proposed methods and the need for either experimental or field observations to estimate model parameters. Concluding remarks close the paper.

2 Fixed floaters

As proposed by Sammarco and Di Risio [26], the friction slope j may be expressed by using the *equivalent friction slope method* (e.g. [14, 24]) when dealing with the influence of moored floaters along the banks of the considered river stretch. Within the framework of one-dimensional gradually varied free surface flows the friction slope reads as follows:

$$j = \frac{U^2}{gR_0}\left(\frac{1}{C_0^2} + \frac{1}{2LP_0}\sum_i^N C_{Di}S_i\right) = \frac{U^2}{gR_0C_{eq}} \tag{1}$$

where U is the mean velocity of the current, g is the gravitational acceleration, C_0 is the dimensionless resistance coefficient of the riverbed material (i.e. without floaters), R_0 is the hydraulic radius of the section, L the length of the considered river stretch, P_0 is the wetted perimeter, C_{Di} and S_i are the drag coefficient and the surface transversal to the current of the $i-th$ floater respectively, N is the number of floaters, C_{eq} is the equivalent dimensionless resistance coefficient that takes into account the floaters effects. Equation (1) can be also expressed by using either Manning or Strickler coefficient:

$$j = \frac{U^2}{R_0^{4/3}}\left(n_0^2 + \frac{R_0^{1/3}}{gP_0}\frac{1}{2L}\sum_i^N C_{Di}S_i\right) = \frac{n_{eq}^2U^2}{R_0^{4/3}} \tag{2}$$

$$j = \frac{U^2}{R_0^{4/3}} \left(\frac{1}{k_{s0}^2} + \frac{R_0^{1/3}}{gP_0} \frac{1}{2L} \sum_i^N C_{Di} S_i \right) = \frac{U^2}{k_{seq}^2 R_0^{4/3}} \tag{3}$$

where n_0 and k_{s0} are the Manning and Strickler coefficients of the riverbed respectively, n_{eq} and k_{seq} are the equivalent Strickler and Manning coefficients with floaters respectively.

Either one of the equations (1), (2) or (3) expresses the linear superposition of the contributions to the flow resistance of the channel flanks and of the floaters. Then, it is valid if the transversal (to the current) immersed section of the floaters is smaller than the river cross-section area and if the vertical velocity profile shape is not significantly affected by the floaters.

Either one of the equations (1), (2) or (3) is the core of the method together with a criterion aimed to estimate the drag coefficient (C_{Di}) and the transversal section of the floaters (S_i). The work of Sammarco and Di Risio [26] demonstrated by means of an experimental investigation that formulations developed for the design of mooring lines (e.g. [18]) can be applied to evaluate the effect of moored boats on the flow. However, the drag force approach has been used also for large wood (e.g. [10, 11]) and the same approach of equivalent friction slope method has been proposed for large wood transport. Indeed, Manga and Kirchner [15] proposed the *stress partitioning method* in order to evaluate the stress component due to large wood. The method has been then largely used by several studies by relying on the use of drag coefficients to evaluate the force on logs (e.g. [13, 22, 31, 34]) or to analyze experimental observations (e.g. [4]).

From a practical point of view, the equivalent friction slope (almost similar to the stress partitioning method) may be applied within the framework of hydraulic analyses by solving the one-dimensional momentum equation of gradually varied free surface flows coupled with the continuity equation (i.e. the well-known de Saint Venant's equations, e.g. [7]).

More in detail, the method can be used by estimating the hydraulic parameters (i.e. the hydraulic radius R_0, the wetted perimeter P_0 and the current velocity U) needed to compute the equivalent resistance coefficients. Hence, the computational domain has to be divided into a series of river stretches (length L_j) that are homogeneous in terms of both riverbed roughness (related to C_0) and characteristics and arrangement of the floaters. Then, a first numerical estimate of the free-surface profile without floaters suffices to evaluate the initial values of the wetted perimeter (P_0), hydraulic radius (R_0) and current velocity (U). The values of the equivalent resistance coefficient along the one-dimensional computational domain may be therefore estimated by using equation either (1) or (2) or (3) and used to further estimate the updated values of the wetted perimeter (P_0), hydraulic radius (R_0) and current velocity (U). The procedure is repeated up to its convergence, usually reached in few iterations with low computational cost (of course related to the extension of the computational domain).

It has to be stressed that the influence of the floaters in the stretches is globally (note, not locally) described by their drag coefficients (C_d), the floater surface transversal to the current (S_i, related to L_b, i.e. the length of the floater measured along the direction normal to the current) and the total number of floaters (N). As a guidance, the drag coefficient of an isolated floater (C_d) moored orthogonally to the current may be estimated as (e.g. [29], Fig. 1):

$$C_d = C_{d0} + (3.2 - C_{d0}) \left(\frac{T_b}{Y} \right)^2 \tag{4}$$

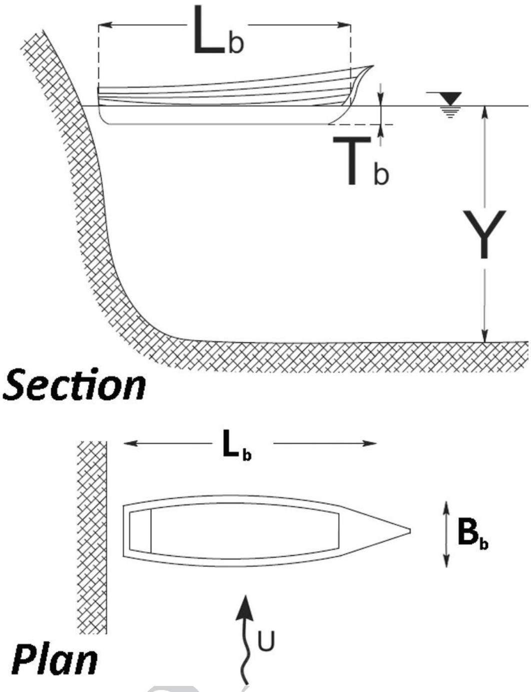

Fig. 1 Sketch of the problem (modified from [26]; U is the mean velocity of the current, T_b is the draft of the floater, B_b the floater width, Y is the mean water depth, L_b is the length of the floater)

where T_b is the draft of the floater, Y is the mean water depth and C_{d0} may be expressed as

$$C_{d0} = 0.22 L_b \sqrt{\frac{A_m}{B_b V}} \tag{5}$$

with B_b the floater width (measured along the current direction), V is the displaced water volume, A_m the midsection transversal area of the floaters (not shown in Fig. 1).

On the other hand, if the floater is moored parallel to the current, the term S_i represent the wetted surface and C_D is the friction coefficient for fully turbulent flow, which can be expressed as follows (e.g. [20]):

$$C_D = \frac{0.075}{\left[\log_{10}(UL_b/\nu) - 2\right]^2} \tag{6}$$

where ν is the kinematic fluid viscosity.

As a first estimate, Eqs. (4)–(5) or (6), valid for boats, may be also extended to describe the effect of large wood accumulations at fixed structures or large wood deposited along the river banks on the flow. Shields and Gippel [30] experimentally confirmed this rationale. Indeed, many research works dealt with the local effects of wood accumulation on the flow in terms of drag forces (e.g. [1, 22, 28, 34]).

3 Moving floaters

The method described in Sect. 2 can be applied when large wood is kept in fixed location due to the interaction with banks or large wood accumulation at existing structures (i.e. bridge piers). If large wood is free to be advected by the current, it is no longer valid to evaluate the influence of floaters on the flow resistance.

Herein, we illustrate an extension of the model to be applied to floaters transported downstream by the current without the occurrence of large wood accumulation at an obstruction or close to the banks.

As suggested by Braudrick et al. [5], individual logs are advected downstream by rolling, sliding or floating. In this section, only the latter movement type is considered, i.e. only when the water depth is large enough to avoid the large wood accumulation. Braudrick et al. [5] observed different transport regimes depending on the interaction piece-to-piece between logs. For single log transport (i.e. uncongested transport [5]) the action of the flow is not counteracted by the presence of the isolated floaters and negligible (global) resistance arises from the presence of the freely moving object. However, if the number of logs increases (i.e. congested or semi–congested transport [5]), additional resistance will occur due to the shear velocity of the large wood carpet.

With the same rationale used for fixed floaters, if the forces due to the presence of floaters are known, the friction slope j will be expressed by using the equivalent friction slope method. The same hypotheses apply, i.e. it is valid if the transversal (to the current) immersed section of the logs is smaller than the river cross-section area and if the vertical velocity profile shape is not significantly affected by the floaters.

In the case of floaters spanning the whole cross-section (width B, see Fig. 2), the total force F_{max} per unit longitudinal length (i.e. along the river axis) can be expressed as follows:

$$F_{max} = F_F\left(\frac{B}{D} + 1\right) \tag{7}$$

where D is the mean transversal dimension of the logs, $B\,/\,D$ ($=N_{max}$) is the maximum number of floaters spanning the whole river width and F_F is the contact force occurring between two logs and at the river banks due to the shear velocity. In few words, equation

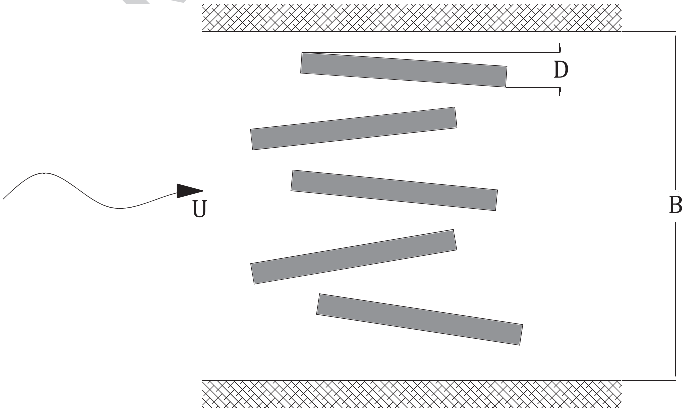

Fig. 2 Sketch of the problem of large wood transport (B is the river width, D is the mean transversal dimension of logs, U is the mean velocity of the current)

(7) is the linear superposition of the contact forces (F_F) occurring between two floaters. As the floaters span the whole cross-section, $N_{max} + 1$ ($= B/D + 1$) contact forces exist (i.e. $N_{max} - 1$ piece-to-piece contacts and the two contacts at the river banks). The contact force (F_F) may be conceptually expressed as

$$F_F = \mu W \beta \tag{8}$$

where μ is the representative friction coefficient between floaters, dependent upon the material of the exposed surface, W is the immersed weight (per unit length) of the log, and β is an empirical parameter aimed to describe that only a fraction of the log weight is responsible for the lateral transfer of momentum. It can be observed that the value of β is influenced by the flow velocity that may induce strong logs fluctuations.

Consider now a concentration parameter α:

$$\alpha = \frac{ND}{B} = \frac{b}{B} \tag{9}$$

that takes into account the actual number N of logs along the direction transversal to the main flow, which in turn can be expressed by the transversal length b occupied by the floaters divided by the total river width (B). The concentration parameter α is therefore a measure of the fraction of the maximum force F_{max} given by Equation (7) that actually occurs for a given configuration of floaters.

Then, the actual force acting on the flow when the concentration parameter is lower than unity may be expressed as follows:

$$F = F_{max}\Phi(\alpha) = \mu W \beta \left(\frac{B}{D} + 1\right)\Phi(\alpha), \tag{10}$$

where $\Phi(\alpha)$ may be expressed as a normal function:

$$\Phi(\alpha) = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\alpha - 0.5}{\sigma\sqrt{2}}\right)\right] \tag{11}$$

with a mean value equal to $0.5 (= \alpha)$ and a standard deviation σ. The function Φ is an empirical model of the influence of the concentration of the floaters upon the total force acting on the flow, accounting for the occurrence of contact probability between floaters.

The fraction of the log weight that is transferred between floaters is described by the parameter β. The mean value of $\Phi(\alpha)$ has been empirically selected by imposing that the actual force F is a half of F_{max} for $\alpha = 0.5$. On the other hand, the standard deviation σ has to be regarded as the parameter of the proposed simplified model. Figure 3 shows the behavior of Φ as a function of α for various σ. The lower the standard deviation (σ), the higher the influence of the concentration parameter (α). Just as examples, for $\sigma = 0.1$ the 90% of the maximum force (i.e. $F = 0.90\,F_{max}$) occurs for $\alpha \simeq 0.63$, for $\sigma = 0.2$ the 90% of the maximum force occurs for $\alpha \simeq 0.76$. On the other hand, the large wood transport may be considered as uncongested ([5]) for $\alpha \simeq 0.37$ (i.e. $F = 0.10F_{max}$) if $\sigma = 0.1$ and for $\alpha \simeq 0.25$ if $\sigma = 0.2$.

Once the total force due to the floaters influence is estimated, the friction slope reads as follows:

$$j = \frac{U^2}{gR_0}\left(\frac{1}{C_0^2} + \frac{F}{\rho P_0 U^2}\right) = \frac{U^2}{gR_0 C_{eq}}, \tag{12}$$

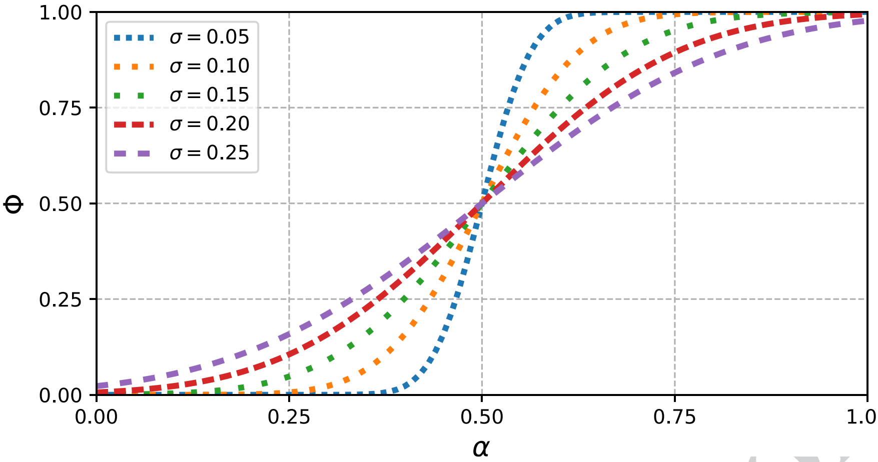

Fig. 3 Behavior of $\Phi(\alpha)$ for varying standard deviation

or, in terms of either Manning's or Strickler's coefficient, as follows:

$$j = \frac{U^2}{R_0^{4/3}}\left(n_0^2 + \frac{R_0^{1/3}F}{\gamma P_0 U^2}\right) = \frac{n_{eq}^2 U^2}{R_0^{4/3}}, \tag{13}$$

$$j = \frac{U^2}{R_0^{4/3}}\left(\frac{1}{k_{s0}^2} + \frac{R_0^{1/3}F}{\gamma P_0 U^2}\right) = \frac{U^2}{k_{seq}^2 R_0^{4/3}}, \tag{14}$$

with F given by Eq. 10.

Hence, it is shown that the method proposed for fixed floater may be extended to moving logs if a different model computation for the forces acting on the current is employed. Then, the application of the model is the same as described in Sect. 2.

A first numerical estimate of the free-surface profile without floaters is needed to evaluate the initial values of the wetted perimeter (P_0) and hydraulic radius (R_0). The values of the equivalent resistance coefficient along the one-dimensional computational domain may then be estimated by using either one of the equations (12), (13) or (14) and used to further estimate the updated values of the wetted perimeter (P_0) and hydraulic radius (R_0). The procedure is repeated up to its convergence.

4 Discussion

The method proposed herein is intended to be useful for a first rough estimate of modified roughness when the influence of floaters (moving within the considered river stretch or fixed along the banks) on the free surface profile has to be accounted for within the framework of flooding hazard assessment (e.g. [9]). As pointed out by many research works (e.g. [21, 37]), a long series of numerical suites are available to solve the de Saint Venant's equations in the one-dimensional framework (e.g. [8, 12, 17, 19, 32]).

HEC-RAS, developed by the Hydrologic Engineering Center River Analysis System ([35]) is an example of a widely used one-dimensional model that solves the non conservative form of the de Saint Venant's equations. It is recognized as a useful tool to model hydraulic characteristics in real cases, at least by reproducing the main features of the phenomena at hand. Generally speaking, the selection of appropriate values to be assigned to the roughness coefficients is crucial. Song et al. ([33]) pointed out that "it is a challenge to find the proper Manning coefficient for each cross section" in order to model the role of vegetation and large wood during a different season. The method proposed herein is intended to provide a physically based approach to modify the base roughness coefficient (either k_{s0}, n_0 or C_0, e.g. [16, 19]) in order to take into account the presence of floaters either moored (boats) or accumulated along the banks (large wood blockage) or advected downstream (large wood logs).

Figure 4 shows the results of an example calculation in terms of the relative increase of Manning coefficient n_{eq} with respect to the base value n_0 (= 0.025 s/m$^{1/3}$), defined in the absence of floaters. The representative diameter of floaters has been selected as $D = 0.15$ m. An ideal river stretch with a rectangular section (width $B = 100$ m) and constant flow rate ($Q = 300\ \mathrm{m}^3/s$) has been considered. The example computation has been performed simply within the normal flow hypothesis (talweg slope equal to 0.001), hence by applying the proposed method and solving the normal flow equation. The configuration has been selected in order to easily accept the hypotheses of the proposed method, i.e. that the immersed section of the floaters is smaller than the river cross-section area and the vertical velocity profile shape is not significantly affected by the floaters.

The results are shown in order to assess the effect of the parameter β. Indeed, β takes into account the fraction of floaters weight that is responsible of the lateral transfer of momentum, which in turn is transferred to the flow. It can be observed that the roughness parameter increase is strongly influenced by this parameter, ranging from about 4% ($\beta = 0.1$) and 40% ($\beta = 1.0$). This aspect makes the proposed method suitable for

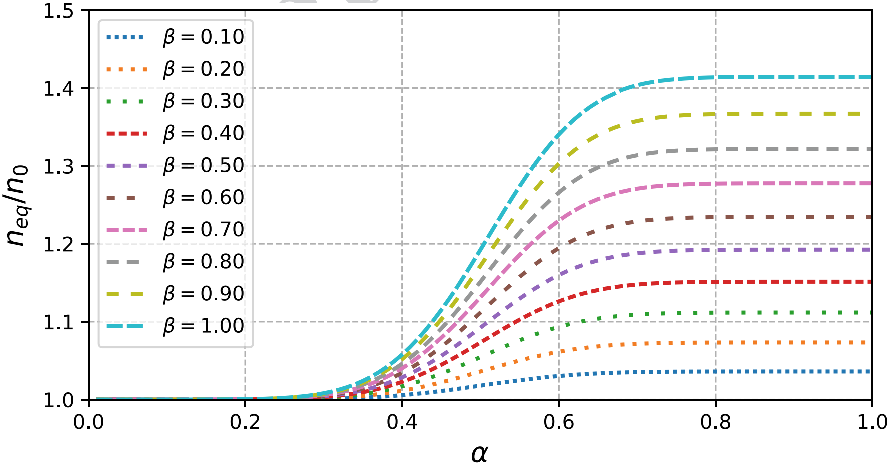

Fig. 4 Relative increase of Manning coefficient n_{eq} with respect to the base value n_0 (= 0.025 s/m$^{1/3}$) as a function of the concentration parameter α and parameter β for given standard deviation σ (= 0.1) of the function $\boldsymbol{\Phi}$

experimental calibration, as the importance of additional resistance due to the presence of the floaters may be easily assessed by performing ad hoc experimental trials aimed at identifying the functional dependence of the parameter β from the (mean) flow velocity.

Figure 5 shows the influence of the standard deviation σ, i.e. the influence of the concentration parameter on the additional resistance. Once again, it can be underlined that the proposed method is prone to be calibrated via experimental observations in order to quantify the role of the concentration parameter α on the additional resistance.

5 Concluding remarks

This paper deals with the practical estimation of roughness coefficients to be used when large scale river flooding hazard analyses have to take into account the effect of floaters. This aspect may be of great importance when large wood is expected to be conveyed by the river flow during floods or when boats or accumulated large wood are likely to be present at the river banks.

A physics-based model is proposed. It is simple to use and relies on the hypothesis that the transversal (to the current) immersed section of the floaters is small if compared to the river cross-section area so that the vertical velocity profile shape is not significantly affected by the floaters as well. It is intended to be applied for fixed floaters (i.e. moored boats or floaters accumulated along the banks or gathered to fixed structures along the river, such as the piers of crossing bridges) or for moving floaters advected downstream by the current for varying concentration.

The method basically provides a physics-based formulation of the friction slope to be used within standard hydraulic analyses that takes into account the influence of floaters on free surface profiles of river flows.

In the case of fixed floaters, the method relies on the computation of drag forces acting on the floaters.

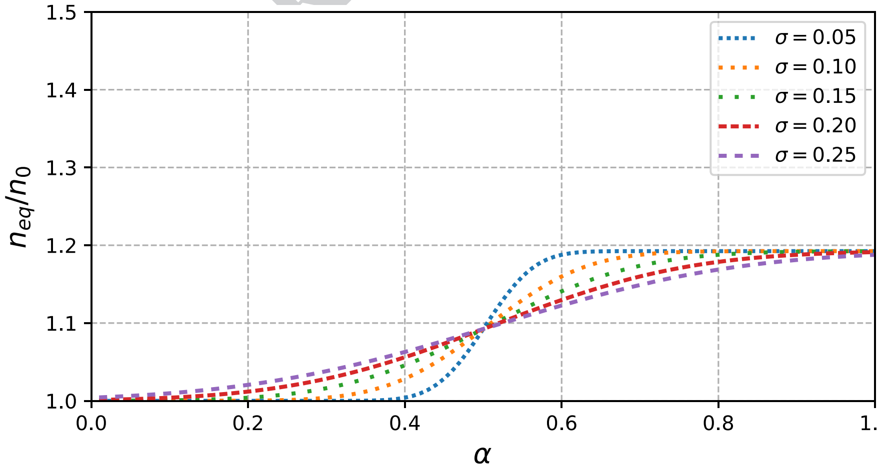

Fig. 5 Relative increase of Manning coefficient n_{eq} with respect to the base value $n_0 (= 0.025\ \mathrm{s/m^{1/3}})$ as a function of the concentration parameter α and parameter σ for given value of the parameter β (=0.4)

For congested and uncongested large wood transport, the model is parametric and therefore can be calibrated by ad hoc experimental or field campaigns. Indeed, it is capable to take into account the role of the moving floaters concentration, as well as the role of turbulent fluctuations upon the lateral transfer of momentum, which in turn is transferred to the flow as additional resistance. The proposed model relies on the definition of two empirical parameters aimed at describing the lateral transfer of momentum between logs (parameter β in equation 8) and the probability of contacts between logs (parameter σ in Eq. 11).

Future research development, mainly related to large wood transport, includes an experimental campaign in the Environmental and Maritime Hydraulic Laboratory (LIam) of the University of L'Aquila. It will be aimed at reproducing in a controlled environment the variation of water levels for varying flow rate and logs concentrations in order to provide empirical formulations for the estimation of the parameters β and σ.

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