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Estimating time-varying stage-discharge relations in rivers with aquatic vegetation

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ABSTRACT: Stage-discharge relations at hydrometric stations with aquatic vegetation vary continuously in time due to the vegetation evolution. Maintaining such rating curves for establishing discharge time series is a challenge. Generally, the curves are adjusted manually as convenient stage-discharge models are missing. To fill this gap, we developed a practical model that accounts for transient changes due to aquatic vegetation. It is restricted to hydraulic controls that can be described by the Manning-Strickler equation for wide rectangular channels. In most situations, aquatic plants induce changes in bed roughness and mainly affect flow resistance. Bed roughness is characterized using a time-varying Manning coefficient, estimated using a friction equation accounting for the vegetation development (growth and decay) and for the plant flexibility (bending). In this paper, we illustrate the need to take into account flow-induced plant bending in the friction equation even though vegetation development remains the main factor affecting the flow resistance.

1 INTRODUCTION

At hydrometric stations, streamflow records are generally computed using stage-discharge models, also called rating curves. Hydrometric stations are commonly installed on river sections where it is possible to obtain a unique relation between the water level (stage) h and the discharge Q for a given time period. The standard form of the rating curve for a given hydraulic control (section or channel control) is a power equation (Le Coz et al., 2014):

$$Q = a(h - b)^c \quad (1)$$

where a = coefficient related to the type of control ($=B\sqrt{S_0}/n$ for a wide and rectangular channel control, with B = channel width, S_0 = channel slope and n = Manning friction coefficient), b = offset; and c = exponent related to the type of control ($=5/3$ in the case of a wide rectangular channel control). These parameters are estimated based on expert knowledge and using gaugings, which are occasional measurements of stage and discharge carried out at the studied station. This simple power equation is no longer suitable when the system is subject to instabilities that modify the hydraulic control. In practice, sudden (e.g. due to morphological evolution induced by a flood) or transient (e.g. due to the evolution of vegetation) rating changes can happen (Mansanarez et al., 2019). Then, the discharge needs to be computed using h and other variables (e.g. time-varying variables).

In this paper, we focus on stations affected by the presence of aquatic vegetation. Stage-discharge relations vary continuously in time due to the vegetation evolution. To our knowledge, no standardized methods nor convenient stage-discharge models exist to manage such transient changes. Some countries use manual adjustments to compensate for the effect of plants (e.g. the *corTH* method used by the French hydrometric services) but such procedure is subjective, labor-intensive and rather uncertain.

From a physical point of view, the presence of vegetation essentially induces a resistance to water flow, just like the resistance due to bed material, bed forms, etc. (Coon, 1998, Green, 2005). All of these factors contribute to the total flow resistance, which can be expressed as a friction coefficient such as the Manning coefficient n . The impact of plants growing from the bank, which can obstruct the flow and reduce the wetted flow section, is generally assumed negligible compared to the effect of plants on the flow resistance. This assumption can be arguable during some extreme flow events. Several decomposition methods for n have been proposed in the literature (Cowan, 1956, Morin et al., 2000). The expression of Morin et al. (2000) is chosen for this study in order to particularly focus on the vegetation effect on the flow:

$$n^2 = n_b^2 + n_v^2 \quad (2)$$

where n = total Manning coefficient, n_b = Manning coefficient of the bed when there is no vegetation; and n_v = Manning coefficient related to additional friction due to plants. The resistance related to plants is the most likely to vary in time and one of the most difficult to estimate. Indeed, $n_v(t)$ depends on the type of plants, their spatial distribution, their density, their development, their relative submergence, their flexibility, etc. Few friction equations exist to compute $n_v(t)$ in contrast to the numerous equations or look-up tables for n_b (Meyer-Peter and Müller, 1948, Limerinos, 1970, Coon, 1998). Unfortunately, these friction equations related to vegetation are either too simple to represent the effect of natural plants (see the analogy of the vertical rigid cylinder in Petryk and Bosmajian (1975) or in Pasche and Rouvé (1985)) or too complex (Aberle and Järvelä, 2013) and require too much information to be used for operational purposes (e.g. such as plant elasticity, Leaf Area Index, plant growth rate depending on a range of external factors such as the water temperature).

In this paper, we aim to better predict the stage-discharge relation at stations affected by aquatic vegetation. We develop a new rating curve model that varies in time, based on the standard power model and on a time-varying friction equation. The model intends to be used for operational purposes, using information that can be easily retrieved in the field. The model is tested on data from a French hydrometric station affected by aquatic vegetation. The objective is to show that the simple use of a time-varying friction coefficient in the model improves the discharge prediction in presence of plants. We also discuss the importance of the choice of the friction equation. In particular, we emphasize the need to account for plant bending and not only for plant biomass evolution, even if the latter is the main factor influencing the flow resistance.

2 TIME-VARYING FRICTION EQUATION RELATED TO AQUATIC VEGETATION

The new rating curve model is similar to the standard power equation (Eq. 1), except for the Manning friction coefficient n now varying in time because of the component $n_v(t)$ related to the vegetation (see Eq. 2). Our study is restricted to hydraulic controls that can be described by the Manning-Strickler equation for wide rectangular channels.

2.1 Simplified Järvelä (2004) equation

Friction equations were developed in specific conditions (i.e. emergent or submerged plants, flexible plant or not). In this study, we focus on aquatic plants (e.g. macrophytes) that are located in the main channel and submerged (with low relative submergence). Most of the time, these plants are flexible. We also assume that their spatial distribution is homogeneous throughout the channel section. The friction equation of Järvelä (2004) was developed for evaluating the friction coefficient related to those types of plants at the reach-scale:

$$n_v^2(t) = \frac{4C_{D\chi}LAI(t)[h(t)-b]^{1/3}}{8g} \min\left(\left(\frac{U_m}{U_\chi}\right)^\chi; 1\right) \quad (3)$$

where $C_{D\chi}$ = drag coefficient related to the plants, LAI = Leaf Area Index, g = gravity acceleration, χ = reconfiguration coefficient specific to the plant species (e.g. $\chi = 0$ for rigid plants and $\chi = -1$ for leafy flexible plants), U_m = mean velocity; and U_χ = the lowest velocity used during the experimental determination of χ . The plant can bend only when the mean velocity exceeds a minimum velocity U_χ . Below this value, there is no bending and the bending function equals 1.

We add this condition to the original Järvelä (2004) equation using the $\min()$ function. The Järvelä (2004) equation can be seen as a combination of two main functions that account for two main factors: the plant development (using the LAI) and the plant capacity to bend and align under the action of flow (using the mean velocity). Plants bend to limit their frontal areas impacted by the flow, which leads to reduced bed roughness induced by the vegetation when flow velocity increases. In practice, the LAI data are scarce and no biomass measurements are generally performed at hydrometric stations. Equation 3 is thus too complex for our study. We propose a new friction equation, which is a simplification of the Järvelä (2004) equation:

$$n_v^2(t) = \frac{G(t)[h(t)-b]^{1/3}}{8g} \min\left(\left(\frac{U_m(t)}{U_\chi}\right)^\chi; 1\right) \quad (4)$$

$G(t)$ = potential of hydraulic resistance due to the development of plants (growth and decay). It is assumed that $G(t)$ evolves similarly in shape as the plant biomass. $G(t)$ is thus a proxy of the evolution of the plant biomass. It cannot be measured specifically, but can be modelled using models for biomass development.

2.2 Proxy of biomass evolution

We assume that the biomass (and consequently the proxy $G(t)$) is a function of time during the year (i.e. during the plant cycle of growth and decay). A bell-shaped model as presented in Figure 1 is chosen for modeling $G(t)$ (Yin et al., 2003):

$$G(t) = G_{max} \left(\frac{t-t_b}{t_e-t_b}\right)^{t_e-t_b/t_e-t_m} \left(\frac{2t_e-t_m-t}{t_e-t_m}\right) \quad (5)$$

where G_{max} = maximum plant proxy biomass, t_b = beginning of plant growth, t_m = time at which the growth rate is maximum; and t_e = end of plant growth and beginning of decay. Equation 5 is built such as no negative biomass is allowed. Equation 5 reflects the general trend of the biomass evolution, but does not take into account any external perturbations (e.g. flood, sudden drop in water temperature) that might induce some changes in the shape of the biomass evolution. More complex models for the biomass evolution exist such as dynamic models depending on external factor (nutrient, light intensity, water temperature, etc.) (Lazár et al., 2016) but they require much more information not always available for operational purposes.

Figure 1. Shape of the model used for modelling the biomass proxy $G(t)$.

2.3 Final friction equation

The final time-varying friction equation to include in the power equation (Eq.1 combined with Eq. 2) is the following:

$$n_v^2(t) = \frac{G_{max} \left(\frac{t-t_b}{t_e-t_b}\right)^{t_e-t_b/t_e-t_m} \left(\frac{2t_e-t_m-t}{t_e-t_m}\right) [h(t)-b]^{1/3}}{8g} \min\left(\left(\frac{Q(t)}{U_\chi B[h(t)-b]}\right)^\chi; 1\right) \quad (6)$$

The discharge is present on both sides of the rating curve equation when using Equation 6. No explicit solution exists. The power equation can nevertheless be solved using the Newton-Raphson algorithm, after rewriting it in a polynomial form. This numerical solution will not be

detailed in this paper. For more details about the rating curve model accounting for vegetation, please refer to Perret et al. (2020, in prep).

3 APPLICATION OF DISCHARGE PREDICTION

3.1 Test case

The hydrometric station used for testing our model is located in East France on the Ill River at Colmar-Ladhof (station code: A1350310, catchment area: 1784 km²). This station is influenced by flexible aquatic vegetation and is frequently gauged. The gaugings are sometimes supplemented with visual observations transcribed into comments about the presence of vegetation in the main channel (e.g. “plants are present”, “there is plenty of plants”, “there are no plants”). At low and medium flows, the hydraulic control is approximated as a wide rectangular channel.

A series of 22 years of data are available at this station, including a period of 11 years of data where no sudden rating changes due to strong morphological evolutions were observed (from 22/03/2002 to 27/02/2013). The focus is made on this period, since our model deals with transient changes due to vegetation only. Around 270 gaugings were carried out during this period including 175 with comments about the presence of vegetation.

3.2 Statistical tool – *BaM!*

The rating curve model with time-varying friction equation is implemented in a numerical code, called *BaM!*, which enables estimating the model parameters (with their uncertainties) through Bayesian inference using prior knowledge on hydraulic controls of the station and observational data. We do not detail *BaM!*, which is a generalization of the method *BaRatin* frequently used for evaluating rating curves with their uncertainty (Le Coz et al., 2014).

In our case, the main observational data used for the calculation are the gaugings. The comments on vegetation are also used to refine the parameter estimations, but, to be used, they need to be transcribed manually into positions within the annual plant cycle, which are then converted into a proxy biomass. These vegetation observations are associated with large uncertainties. A 15% uncertainty (at 95% probability level) is affected to the discharge measurements, because of the difficulty to measure discharge at low flows and especially in presence of plants.

All the priors related to the hydraulic control are determined using the knowledge of the station managers. Wide priors for parameters related to the plant evolution are selected since little information is known about the plant behavior and species. The parameters of Eq. 5 are re-estimated every year (every growth cycle) and the others are evaluated only one time over the 11-year period.

4 RESULTS

4.1 Comparison between models without and with time-varying friction coefficient

When aquatic vegetation is present, discharge predictions are improved when using a time-varying friction coefficient instead of a constant friction coefficient. Figure 2 shows the comparison of the relative errors for the model with constant friction coefficient (Eq. 1) with those for the new model with time-varying friction coefficient (Eq. 6). Relative errors can exceed 50% when the friction coefficient is constant whereas they mostly range between $\pm 20\%$ when a time-varying friction coefficient is used. These results are promising since the uncertainty of the discharge measurements is equal to 15%.

Figure 2. Relative error E_r as a function of the observed water discharge (Q_{obs}) according to the chosen rating curve model (with constant or time-varying Manning coefficient).

Figure 3a shows the discharge time series $Q(t)$ with uncertainty, computed over the studied period using the continuous stage record at the station and our rating curve models. The 95% total uncertainty interval is displayed on Figure 3a, including parametric (i.e. related to the parameter estimation) and structural (i.e. related to the model) uncertainties. Solid lines correspond to the maxpost curves, which have been calculated with the parameters of the model maximising the posterior pdf (the Maximum A Posteriori estimators, MAP). The gaugings are best approximated with the model with time-varying Manning coefficient (see the details for year 2008 in Fig. 3b for more clarity). The total discharge uncertainty is also much smaller.

Figure 3c presents the evolution of the proxy biomass with parametric uncertainty deduced from the model with time-varying Manning coefficient. Proxy biomass $G(t)$ is strongly varying from year to year in both amplitude and shape. This reflects strong flow resistance variations hence the need to take into account bed roughness changes due to plant development when computing discharge for such hydrometric station.

4.2 Relative hydraulic importance of plant bending and development

In our new rating curve model, we assumed that two main effects drive the variations of the friction coefficient related to the vegetation: the growth and decay of the plant (i.e. biomass evolution) and the capacity of the plant to bend (i.e. its flexibility). The relative importance of these two effects is investigated. Discharges calculated when the bending correction is activated ($Q_{bending}$) or not ($Q_{no-bending}$) are compared. To evaluate $Q_{no-bending}$, we use the same rating curve model as for estimating $Q_{bending}$, except χ is set to 0 for evaluating the time-varying friction coefficient. Indeed, in case there is no bending, plants are assumed rigid so their reconfiguration coefficients χ equal 0. The Newton-Raphson algorithm is no longer required for computing $Q_{no-bending}$ since the discharge is no longer present in the friction equation $n_v(t)$. To compute $Q_{no-bending}$, we decide to use the same MAP parameters as those estimated when plant bending was taken into account, except for $\chi = 0$. No new simulation is launched with the statistical tool *BaM!* in order to avoid compensating the absence of plant bending by other model parameter during their estimation. That way, we investigate the importance (in terms of amplitude) of using the bending correction in the global calibrated model (with bending).

Figure 4 shows the relative discharge differences due to the plant bending function in the calibrated model. Only observational data for which vegetation was present (i.e. when $G(t) \neq 0$) are kept on Figure 4. The difference in discharge can reach up to 80%, which reflects the importance of the part related to the bending in the discharge computation with the new rating curve model. The variation in discharge seems correlated to the quantity of plant biomass and to

the gauged mean velocity. It is stronger if vegetation biomass is important and if gauged mean velocity is high. In addition, the variation is negative. As rigid plants grow, their frontal areas impacted by the flow become more important. They cannot bend or align in the flow direction to reduce them. The flow is thus obstructed and the discharge reduces. When $U_m < U_c$, the relative difference should in theory go to zero. Unfortunately, no gauging was made in those conditions, so this statement cannot be verified.

Figure 3. a) Computed water discharge time series $Q(t)$, b) details for year 12 (corresponding to year 2008) and c) evolution of the proxy biomass $G(t)$ over the 11-year of data with uncertainty. Blue lines mark the transition to another hydraulic control for higher flows: computed discharges are not valid above these lines.

Figure 4. Relative discharge differences due to the plant bending function in the calibrated model with aquatic vegetation effect as a function of the gauged mean velocity and the proxy biomass at the station.

5 CONCLUSIONS

A rating curve model accounting for the presence of aquatic vegetation based on a time-varying friction coefficient was developed. It is restricted to hydraulic controls that can be described by the Manning-Strickler equation for wide rectangular channels and to submerged (with low relative submergence), flexible or rigid macrophytes. The time-varying coefficient is estimated using a friction equation accounting for vegetation biomass evolution and for plant flexibility. The friction equation needs to be selected according to the type of plants growing at the station. The information needed to compute discharge is easily measurable or estimable (i.e. stage record, expertise on hydraulic controls and simple information about plants such as comments from visual observations), which makes the model interesting for operational purposes.

The performance of the model was highlighted using tests performed on a French hydrometric station affected by aquatic plants. The prediction of discharge was improved when rating curve models with varying friction coefficient are used, as opposed to constant friction coefficient. Relative errors between computed and observed discharges ranged within $\pm 20\%$ with the new model. One interest of this new model is that the potential resistance of the plant related to its development can be modelled, which informs about the general trend of the plant evolution.

In this study, we emphasized the importance of the part related to the bending correction in the discharge calculation. Indeed, in certain conditions, not only the vegetation development but also the plant bending controlled the flow resistance related to plants. Results showed that the bending correction substantially modifies the estimated discharge (sometimes up to 80% compared to setting the bending correction to zero). The bending effect is particularly large when the mean velocity is high and when the plant biomass is significant.

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