



HAL
open science

A rating curve model accounting for cyclic stage-discharge shifts due to seasonal aquatic vegetation

Emeline Perret, Benjamin Renard, Jérôme Le Coz

► To cite this version:

Emeline Perret, Benjamin Renard, Jérôme Le Coz. A rating curve model accounting for cyclic stage-discharge shifts due to seasonal aquatic vegetation. *Water Resources Research*, In press, 57 (3), pp.28. 10.1029/2020WR027745 . hal-03121201

HAL Id: hal-03121201

<https://hal.science/hal-03121201>

Submitted on 26 Jan 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **A rating curve model accounting for cyclic**
2 **stage-discharge shifts due to seasonal aquatic**
3 **vegetation**

4 **E. Perret ¹, B. Renard ¹, J. Le Coz ¹**

5 ¹INRAE, UR RiverLy, F-69625, Villeurbanne, France

6 **Key Points:**

- 7 • A rating curve model accounting for aquatic vegetation was developed and esti-
8 mated through Bayesian inference.
9 • Information on the vegetation development state should be used to estimate the
10 rating curve.
11 • Discharge prediction in presence of aquatic plants was improved using the new model
12 (relative errors decrease from $\pm 50\%$ to $\pm 20\%$).

Corresponding author: Emeline Perret, emeline.perret@inrae.fr

Abstract

Managing stage-discharge relations at hydrometric stations affected by aquatic vegetation is challenging. Ratings vary continuously in time due to the plant development, which makes the streamflow time series difficult to predict. To the best of our knowledge, no rating curve model exists to deal with stations with a vegetated channel control, only manual adjustment methods. To address this issue, a temporal rating curve model accounting for transient changes due to vegetation is developed. The model is built on basic concepts from open-channel hydraulics and plant physiology. In the model, the flow resistance varies through time as a function of the plant development (growth and decay) and of the plant ability to reconfigure. Model parameters and uncertainty are estimated through Bayesian inference combining prior knowledge on the hydraulic controls at the station and observational data. In addition to the traditionally-used stage-discharge gaugings, the model allows the use of qualitative observations on the plant development state (e.g. no plant, growth, decay). The model is tested and validated for a French hydrometric station where frequent gaugings (twice a month) and written comments about vegetation are available over more than 20 years. Relative errors between the simulated discharges and the observed discharges mostly range between $\pm 20\%$ for the temporal rating curve. In contrast, they are higher than $\pm 50\%$ with a standard model with no vegetation module. This case study highlights the importance of using observations about plant development to predict water discharge. We finally discuss some possible improvements and extensions of the model and recommend methods for data collection.

1 Introduction

1.1 Rating curve management

Establishing the streamflow time series and its uncertainty is a priority for most hydrological studies and water management applications. The streamflow record is commonly computed by transforming a continuous water level record into water discharge using a stage-discharge relation, also known as a rating curve (World Meteorological Organization, 2010). Rating curves are site-specific and are usually built using occasional measurements of water discharge Q and stage h (i.e. gaugings), combined with information about hydraulic controls (section or channel controls) at the hydrometric station (Rantz, 1982). The process of building a rating curve is subject to a large uncertainty that needs to be quantified in order to make important water-related decisions (McMillan et al., 2017). Many methods exist to estimate rating curve uncertainty and have been applied with increasing frequency (Kiang et al., 2018).

One of the main problems for rating curve management is to deal with rating changes or “shifts” (Mansanarez et al., 2019). Indeed, stage-discharge relations are not always stable and can evolve in time, which leads to non-unique h - Q relations. Rating instabilities can be caused by sudden changes (e.g. morphological evolution induced by a flood, human constructions that affect the hydraulic control) and/or by transient changes (e.g. vegetation growth, accumulation of debris or ice). The challenge is to detect these changes and update the curve accordingly, e.g. modifying the rating curve model and/or re-estimating the model parameters. Some procedures exist to deal with sudden changes and are reported in Mansanarez et al. (2019). However, these methods are not suitable for transient changes due to aquatic vegetation. In that case, the stage-discharge relation varies continuously in time according to the vegetation evolution. Water discharge therefore needs to be estimated from the stage and other variables depending on time. To the best of our knowledge, no rating curve models accounting for aquatic vegetation exist in the literature.

In case of a section control, removing vegetation from the critical section (e.g. weir) is a frequent and common practice to avoid any effect of plants. This procedure is in general unrealistic in case of a channel control, because vegetation should be removed from

64 the entire controlling channel to totally cancel the plant effect at the station. In addi-
 65 tion, it is considered as ecologically unacceptable in some countries and is hence forbid-
 66 den or at least banned from actual practice. In case of channel controls, the rating curve
 67 shifts due to vegetation are generally not managed in real time, but instead are accounted
 68 for with manual and non-standardized methods, according to the station manager ex-
 69 pertise. As far as we know, there exist no publications reviewing how different countries
 70 and hydrometric services actually manage these transient changes. For example, the French
 71 hydrometric services use a method called *corTH* that does not modify the base rating
 72 curve (BRC) derived with vegetation-free gaugings. Instead, it replaces the observed stage
 73 by a corrected stage that, once transformed by the BRC, leads to the estimated vegetation-
 74 affected discharge. This method is based on the assumption that the presence of plants
 75 leads to a temporary and overall translation of the stage-discharge relation. This approach
 76 heavily relies on gaugings to track the effect of vegetation in time. Such manual meth-
 77 ods have many limitations, in particular because adjustments strongly rely on the ex-
 78 pertise of the station manager. This expertise is in general poorly documented, making
 79 manual methods hardly reproducible. As a time-varying rating curve model that accounts
 80 for the hydraulic effects of seasonal aquatic vegetation is lacking, it is difficult to pre-
 81 dict and keep track of actual changes in the stage-discharge relation.

82 1.2 Modelling flow/plant interactions

83 Many studies examined the flow-vegetation interactions in rivers at different scales
 84 (from the leaf, branch, plant, patch to the entire section) for diverse types of plants (rigid
 85 or flexible) and for diverse levels of submergence (submerged or emergent) with a focus
 86 on the effect of vegetation on the flow (Nikora, 2010; Folkard, 2011; Neary et al., 2012;
 87 Nepf, 2012; Luhar & Nepf, 2013; Albayrak et al., 2014). These studies indicate that aquatic
 88 vegetation induces a change in roughness, which modifies the flow resistance of a chan-
 89 nel. Plants also act as obstacles that prevent water from flowing through the part of the
 90 channel cross-section that they occupy. When plant height and density increase, flow ve-
 91 locity decreases and channel resistance increases (Green, 2005).

92 Depending on the spatial scale of the study, the effect of the vegetation on the flow
 93 is either described by the drag force or by resistance coefficients such as the Darcy-Weisbach
 94 friction factor f_v [-] and the Manning coefficient n_v [$\text{m}^{-1/3}.\text{s}$] (Västilä & Järvelä, 2017;
 95 Shields et al., 2017). The resistance coefficients are generally preferred for stand-scale
 96 or reach-scale studies. Although it would be better to work with dimensionless Darcy-
 97 Weisbach friction factors, dimensional Manning coefficients are still widely used in prac-
 98 tice and remain the most popular in hydraulic equations and in rating curve models.

99 Many formulae and look-up tables exist to evaluate the Manning coefficients of beds
 100 without aquatic vegetation. They are generally based on the grain size distribution of
 101 the bed surface material and other physical characteristics of a river (Meyer-Peter & Müller,
 102 1948; Limerinos, 1970; Arcement & Schneider, 1989; Coon, 1998; Hicks & Mason, 1999).
 103 By contrast, few methods exist to estimate the Manning coefficient n_v related to the pres-
 104 ence of plants (Petryk & Bosmajian, 1975; Fathi-Maghadam & Kouwen, 1997; Järvelä,
 105 2004; Whittaker et al., 2013; Västilä & Järvelä, 2014; Shields et al., 2017). In addition,
 106 most of them were developed for floodplain vegetation, which does not necessarily have
 107 the same properties as in-stream vegetation. Some tabulated data are available in the
 108 literature (Chow, 1959; Barnes, 1967; Coon, 1998; Hicks & Mason, 1999; Fisher & Daw-
 109 son, 2003) but they just enable evaluating n_v at a given time for a given density and type
 110 of vegetation. These classic tables cannot be used for estimating the hydraulic effects
 111 of plants through time.

112 Flow resistance equations for vegetated flows were historically developed for rigid
 113 plants using the analogy of the vertical rigid cylinder showing that the drag force ap-
 114 plied to the cylinder increases with the squared average flow velocity (Petryk & Bosma-

115 jian, 1975; Pasche & Rouvé, 1985). However, they were not applicable in the case of nat-
 116 ural rivers where the vegetation is often flexible. Models for flexible plants, or for a com-
 117 bination of rigid and flexible plants, were created subsequently (Järvelä, 2004; Whittaker
 118 et al., 2013; Västilä & Järvelä, 2014). A distinction between models for submerged and
 119 for emergent plants is also important. Indeed, depending on relative submergence, i.e.
 120 the ratio between the water depth and the height of the (deflected) plant H_p , the flow
 121 structure changes significantly within the reach (Vargas-Luna et al., 2015), so different
 122 parameterizations for the flow resistance equation need to be made (Wu et al., 1999; Shields
 123 et al., 2017; Västilä & Järvelä, 2017). In particular, the choice of a suitable flow veloc-
 124 ity is crucial for evaluating the drag force generated by the plants and to calculate the
 125 resulting flow resistance (Västilä & Järvelä, 2017).

126 Most flow resistance equations relative to aquatic vegetation depend on the den-
 127 sity of the plants over the channel section, their spatial distribution and their flexibil-
 128 ity. Unfortunately, these equations were not developed from a practical and operational
 129 viewpoint (Aberle & Järvelä, 2013). The models require thorough knowledge of the plant
 130 characteristics, or measurements, that most often are not available at the stations (e.g.
 131 elasticity, size, age, growth rate). The plant flexibility is often used to model the abil-
 132 ity of the plant to reconfigure under flow stress (Jalonen, 2015). Indeed, plants can align
 133 in the flow direction and bend to reduce their frontal area impacted by the flow and thus
 134 exert less resistance than if they were rigid (Kouwen & Fathi-Moghadam, 2000; de Lan-
 135 gre, 2008). Vegetation density is often represented in models using the ratio between a
 136 characteristic reference area of vegetation, commonly defined as the frontal projected area
 137 of the plants perpendicular to the flow (A_p), and the ground area (A_b) occupied by the
 138 plants (Västilä et al., 2013). For leafy plants, the density is given by the Leaf Area In-
 139 dex: $LAI = A_L/A_b$, where A_L is the one-sided leaf area (leaves measured flat). How-
 140 ever, information on the type of plant present on the riverbed is scarce at hydrometric
 141 stations, and measurements of plant development are also rare (e.g. no biomass samplings,
 142 no camera monitoring of the plant development, etc.). Hence, the literature models for
 143 n_v are too complex to use for operational purposes in hydrometry. It is nevertheless pos-
 144 sible and valuable to organize measurement campaigns to estimate punctually the plant
 145 density in the channel, but it is difficult to monitor it continuously. A continuous-time
 146 model is therefore needed to describe plan development.

147 1.3 Modelling aquatic plant development in rivers

148 Numerous plant development models exist for terrestrial plants but fewer are avail-
 149 able for aquatic plants (Carr et al., 1997; Adams et al., 2017). Some of them require a
 150 large number of parameters to be estimated. Others relate the growth rate to other vari-
 151 ables, such as the water temperature, the incident radiation, the nutrients within the wa-
 152 ter and the dissolved oxygen. These measurements are rarely available at hydrometric
 153 stations (with the possible exception of water temperature).

154 Originally, growth and decay models for aquatic plants were developed for inves-
 155 tigating vegetation development in lakes or reservoirs and problems of eutrophication
 156 (Asaeda et al., 2001; Hilton et al., 2006). Processes governing growth in lakes are partly
 157 similar to those in rivers, with the notable difference that plants in lakes are not sub-
 158 ject to significant time-varying flows and drags (Hilton et al., 2006). In rivers, the light
 159 intensity and the water temperature are found to be the main driving factors for plant
 160 development (Carr et al., 1997). However, many models relate plant growth to water tem-
 161 perature only because temperature is easier to measure than irradiance (Yan & Hunt,
 162 1999; Brière et al., 1999; van der Heide et al., 2006).

163 Plant development models relating growth rate to water temperature take a vari-
 164 ety of mathematical forms: linear (Tollenaar et al., 1979), bi-linear (Olsen et al., 1993),
 165 multi-linear (Coelho & Dale, 1980), exponential (Room, 1986) and bell-shaped (Yin et

166 al., 1995; Yan & Hunt, 1999). Adams et al. (2017) tested 12 different growth rate-temperature
 167 models on tropical seagrass species and found that the bell-shaped model of Yan & Hunt
 168 (1999), which is a simplified version of the model of Yin et al. (1995), was the most ac-
 169 curate. This model best fits the data presented in Adams et al. (2017) and has biologically-
 170 meaningful parameters, such as: the base temperature that triggers plant growth, the
 171 optimal temperature inducing the maximal growth rate and the ceiling temperature that
 172 marks the end of growth and the beginning of the plant decay. Following the growth rate-
 173 temperature model of Yin et al. (1995), Yin et al. (2003) propose a bell-shaped tempo-
 174 ral equation for modelling plant growth using characteristic times of the plant growth
 175 cycle only. The Yin et al. (2003) model is derived from biological concepts and based
 176 on the assumption that the plant development can be described according to the sea-
 177 sons, i.e. to the time during the year. The underlying assumption is that the season evo-
 178 lution reflects the evolution of key forcings such as irradiance and water temperature.
 179 The bell-shaped form accounts for slow growth at the beginning of the plant develop-
 180 ment and close to the growth end time. This model is attractive for operational purposes
 181 as it uses time directly, rather than some additional physical parameters, which are not
 182 always measured at hydrometric stations.

183 **1.4 Objectives**

184 The main objective of this paper is to develop a temporal rating curve model for
 185 channel controls built on both hydraulic and biological concepts in order to better com-
 186 pute discharge at hydrometric stations affected by seasonal aquatic vegetation. The model
 187 is intended to be used for operational purposes and hence only relies on information that
 188 can be easily retrieved at hydrometric stations. Specific objectives also include: (i) as-
 189 sessing the relative importance of various model components such as those related to veg-
 190 etation growth/decay and plant reconfiguration and (ii) highlighting useful observations
 191 (e.g. gaugings and information on vegetation development) that improve the estimation
 192 of the rating curve.

193 The rest of the paper is organized as follows. Section 2 presents the formulation
 194 of the temporal rating curve model that accounts for the presence of seasonal aquatic
 195 vegetation. Section 3 describes the Bayesian approach used to estimate the model pa-
 196 rameters using prior knowledge on the hydraulic controls at the station and observational
 197 data (hydraulic gaugings and vegetation observations). The uncertainties of both sources
 198 of information are included. In Section 5, the model performance is tested using data
 199 from a French hydrometric station presented in Section 4 for which frequent measure-
 200 ments are available. Sensitivity tests are also carried out to assess the importance of the
 201 reconfiguration effect in the model and of having observations about plant development
 202 for its estimation. Finally, Section 6 discusses the results and limitations of the model
 203 and presents some suggestions for improving it.

204 **2 Formulation of the rating curve model**

205 **2.1 Hydraulic basis**

206 The rating curve model for channel controls is constructed considering that veg-
 207 etation essentially induces channel roughness changes, which modifies the flow resistance.
 208 Vegetation dissipates flow energy through a multitude of mechanisms, such as by wav-
 209 ing in the flow or by simply blocking the flow. At the channel cross-section scale, the re-
 210 sulting effect of those processes can be lumped into one single resistance coefficient (e.g.
 211 Manning coefficient).

212 The model can be used at hydrometric stations fulfilling the following conditions:

- 213 1. The stage-discharge relation is governed by a channel control that can be assim-
 214 lated to a wide rectangular channel; section controls (e.g. rectangular weir) are
 215 not explored because, in those cases, the stage-discharge relation does not depend
 216 on bed roughness (Rantz, 1982). The effect of vegetation, if it exists, should be
 217 taken into account in another way than with a roughness change.
- 218 2. The in-stream vegetation is made of rigid or flexible macrophytes that are just-
 219 submerged (i.e. the height of deflected plant equals the water depth) or not deeply
 220 submerged (i.e. the relative submergence can be slightly greater than 1 but stays
 221 close to 1). The cases of emergent plants and plants staying deep and close to the
 222 bed are excluded.
- 223 3. The wetted area reduction by the plants from the bank or from the bed is neg-
 224 ligible. The channel width is not reduced by plants growing from the bank and
 225 the flow is not obstructed by a dense and permanent vegetative cover on the main
 226 channel bed.
- 227 4. The spatial distribution of the in-stream vegetation is quite homogeneous at the
 228 station.

229 The standard form of a rating curve for a given hydraulic control is a power equa-
 230 tion (Rantz, 1982; World Meteorological Organization, 2010; Mansanarez, 2016). In case
 231 of a wide and rectangular channel control, the rating curve model is generally derived
 232 from the Manning-Strickler equation, expressed as follows (Le Coz et al., 2014):

$$233 \begin{cases} Q(h, \tau) = \frac{1}{n(\tau)} B \sqrt{S_0} [h(\tau) - b]^c & \text{for } h > b \\ Q(h, \tau) = 0 & \text{for } h \leq b \end{cases} \quad (1)$$

234 with Q the discharge, h the stage, τ the time, n the total flow resistance coefficient, B
 235 the channel width, S_0 the bed slope (approximating the energy slope in the case of a uni-
 236 form flow), b the offset of the control (i.e. in our case the bottom level of the channel)
 237 and $c = 5/3$ the exponent related to the wide rectangular channel control. This kind
 238 of standard power-law rating curve can be used for modeling a single channel control af-
 239 fected by aquatic vegetation provided that temporal roughness variations are assessed.

240 The Manning-Strickler equation has the advantage to take into account the total
 241 flow resistance through the total Manning coefficient n . The total flow resistance is com-
 242 monly decomposed into several resistance contributions with different and additive co-
 243 efficients (Cowan, 1956): the resistance due to bed material, to bed irregularity, to chan-
 244 nel geometrical variations, to obstacles in the channel and the resistance due to vege-
 245 tation. The resistance component related to vegetation ($n_v(\tau)$) is the most likely to vary
 246 in time and the one that has the strongest temporal effect on the total flow resistance
 247 (Coon, 1998). A simplified decomposition of the total flow resistance is often adopted
 248 in flow-vegetation interaction studies (Morin et al., 2000):

$$249 n^2(\tau) = n_b^2 + n_v^2(\tau) \quad (2)$$

250 where n_b is the Manning coefficient of the bed without vegetation (or at least with veg-
 251 etation that do not evolve over the years) and $n_v(\tau)$ is the Manning coefficient related
 252 to the presence of aquatic vegetation varying in time τ . Equation 2 comes from the lin-
 253 ear superposition principle for Darcy-Weisbach friction factors f (Aberle & Järvelä, 2013)
 254 simply converted into Manning coefficients n as follows (Smart et al., 2002):

$$255 n^2 = \frac{f R_h^{1/3}}{8g} \quad (3)$$

256 where g is the gravity acceleration (9.81 m/s²) and R_h is the hydraulic radius, which can
 257 be approximated by flow depth ($h - b$) in the case of a wide rectangular channel.

258 Combining Morin's decomposition of flow resistance (Equation 2) with Equation
 259 1, the actual discharge can be written as a product of a base discharge Q_0 not affected

260 by the vegetation and a correction factor reflecting the effect of vegetation on the chan-
 261 nel roughness:

$$262 \begin{cases} Q(h, \tau) = Q_0(h, \tau) \left(1 + \frac{n_v^2(\tau)}{n_b^2}\right)^{-1/2} & \text{for } h > b \\ Q(h, \tau) = 0 & \text{for } h \leq b \end{cases} \quad (4)$$

263 with:

$$264 Q_0(h, \tau) = \frac{B\sqrt{S_0}}{n_b} [h(\tau) - b]^c \quad (5)$$

265 2.2 Flow resistance induced by aquatic vegetation

266 After a literature review, the physically-based flow resistance equation of Järvelä
 267 (2004) is chosen for computing $n_v(\tau)$ because it was developed for similar conditions than
 268 those presented in Section 2.1. This equation was initially created for riparian vegeta-
 269 tion and is suitable for modeling flow resistance related to flexible (or rigid) just-submerged
 270 or emergent plants over a channel cross-section, assuming a homogeneous spatial distri-
 271 bution of the plants. The Järvelä (2004) equation expresses the Darcy-Weisbach flow re-
 272 sistance coefficient f_v relative to vegetation as follows:

$$273 f_v(\tau) = 4C_{D_\chi} LAI(\tau) \left(\frac{U_c(\tau)}{U_\chi}\right)^\chi \quad (6)$$

274 with LAI the Leaf Area Index, C_{D_χ} the species-specific drag coefficient, χ the species-
 275 specific reconfiguration exponent also called the Vogel exponent, U_c the characteristic
 276 flow velocity and U_χ the lowest velocity used in determining χ (in other words a veloc-
 277 ity that scales U_c). Equation 6 takes into account the plant density over the cross-section
 278 (mainly through the LAI parameter) as well as the plant ability to reconfigure under
 279 flow power using $(U_c(\tau)/U_\chi)^\chi$ (i.e. plant bending and streamlining). The coefficient χ
 280 was evaluated using laboratory experiments for several plant species (Järvelä, 2004; Västilä
 281 & Järvelä, 2014, 2017). For a rigid plant, $\chi = 0$ and a leafy flexible plant has a χ equal
 282 to around -1, typically.

283 We extend the applicability of the Järvelä (2004) equation to in-stream plants that
 284 are not deeply submerged, by assuming that the water volume flowing over the vegetated
 285 part of the cross-section is negligible. Then, the vegetation induces a drag all over the
 286 water column.

287 According to Järvelä (2004), Equation 6 can readily be used for engineering ap-
 288 plications. An operational procedure has been proposed for calculating f_v (Västilä & Järvelä,
 289 2017). However in practice, continuously monitoring the evolution of $LAI(\tau)$ remains
 290 a difficult task. In addition, these measurements are not common at hydrometric sta-
 291 tions, nor is the evaluation of the type of plants present on the riverbed. Equation 6 is
 292 thus too complex for our purpose and therefore needs to be simplified. The Järvelä (2004)
 293 model can be seen as a combination of two functions: one describing the impact of the
 294 plant development (growth, increase in density, etc.) and one characterising the effect
 295 of plant reconfiguration:

$$296 f_v(\tau) = d(\tau) \times \left(\frac{U_m(\tau)}{U_\chi}\right)^\chi \quad (7)$$

297 where $d(\tau) = 4C_{D_\chi} LAI(\tau)$ is a function describing the hydraulic resistance due to the
 298 plant development cycle (growth and decay) and $(U_m(\tau)/U_\chi)^\chi$ is a function character-
 299 izing the plant reconfiguration. Note that in case of just-submerged or not deeply sub-
 300 merged plant, the characteristic velocity U_c can be assimilated to the mean velocity U_m .
 301 The function $d(\tau)$ is seen as a proxy of the plant biomass evolution and could be mod-
 302 eled using an empirical temporal equation not relying on $LAI(\tau)$, as will be described
 303 in the next section.

304 It is important to note that the plant is able to bend and/or align in the flow di-
 305 rection only when the mean velocity U_m exceeds a minimum velocity U_χ . Below this value,
 306 the reconfiguration should not be taken into account, so the reconfiguration function needs
 307 to be set to 1. This condition is formally added in the flow resistance equation:

$$308 \quad f_v(\tau) = d(\tau) \times \min \left\{ \left(\frac{U_m(\tau)}{U_\chi} \right)^x ; 1 \right\} \quad (8)$$

309 Going from f_v to n_v using Equation 3 and replacing the mean velocity U_m by the
 310 discharge Q divided by the wetted area $B[h(\tau) - b]$, the time-varying Manning coeffi-
 311 cient related to vegetation is finally expressed as follows:

$$312 \quad n_v^2(\tau) = \frac{d(\tau)[h(\tau) - b]^{1/3}}{8g} \min \left\{ \left(\frac{Q(\tau)}{U_\chi B[h(\tau) - b]} \right)^x ; 1 \right\} \quad (9)$$

313 **2.3 Model for plant development**

314 The proxy $d(\tau)$ is assumed to evolve over time in a similar way as the biomass $w(\tau)$.
 315 Therefore, a model for plant development (biomass growth and decline) is used to es-
 316 timate $d(\tau)$. Remember that $d(\tau)$ and $w(\tau)$ cannot be compared in terms of values, just
 317 in terms of temporal evolution.

318 We first need to introduce the shorthand notation t to represent the within-year
 319 time, i.e. the time within the cycle of plant development. If the time τ is expressed in
 320 years, then t is simply the fractional part of τ , varying between zero and one from an
 321 arbitrary start date in the year. If possible, the start date should be chosen under the
 322 guidance of experts in aquatic plants (i.e. according to the plant species and its devel-
 323 opment cycle). In this paper, it is fixed to January 1st. The growth rate temporal model
 324 of Yin et al. (2003) is chosen for modelling the plant biomass evolution $w(t)$ within a year
 325 (see Figure 1):

$$326 \quad \frac{dw}{dt} = GR_{max} \left(\frac{t_e - t}{t_e - t_m} \right) \left(\frac{t - t_b}{t_m - t_b} \right)^{\frac{t_m - t_b}{t_e - t_m}} \quad (10)$$

327 with dw/dt the growth rate, t_b the time at which the plant begins to grow, t_m the time
 328 at which the growth rate is maximum, t_e the time corresponding to the end of the growth
 329 and the beginning of plant decline, and GR_{max} the maximal growth rate. The Yin et
 330 al. (2003) model has a unimodal bell-shaped form like the usual growth rate models tak-
 331 ing water temperature as input instead of time. In the Yin et al. (2003) study, t_b is as-
 332 summed equal to zero, meaning that the plant start to grow at the beginning of the year.
 333 We do not make this assumption here.

334 Integrating Equation 10 and assuming the maximum of biomass w_{max} is reached
 335 at $t = t_e$ leads to the following equation for $w(t)$ (see Appendix A for details):

$$336 \quad \begin{cases} w(t) = w_{max} \left(\frac{t - t_b}{t_e - t_b} \right)^{\frac{t_e - t_b}{t_e - t_m}} \left[\frac{2t_e - t_m - t}{t_e - t_m} \right] & \text{for } t_b < t < t_f \\ w(t) = 0 & \text{otherwise} \end{cases} \quad (11)$$

337 Before t_b , nothing grows and the biomass is set to zero. After $t = t_e$, the growth rate
 338 dw/dt becomes negative, which corresponds to the beginning of the biomass decline. Once
 339 the final time $t_f = 2t_e - t_m$ is reached, the biomass is fixed to 0 to avoid having neg-
 340 ative biomass. The time t_f marks the end of the plant cycle.

341 The model illustrated in Figure 1 describes a kind of vegetation which completely
 342 disappears at the end of its growth cycle. Plants that live through the dormant period
 343 are not considered. Their effect on flow can be included in the constant Manning coef-
 344 ficient n_b in our rating curve model. Note also that Equation 11 does not account for

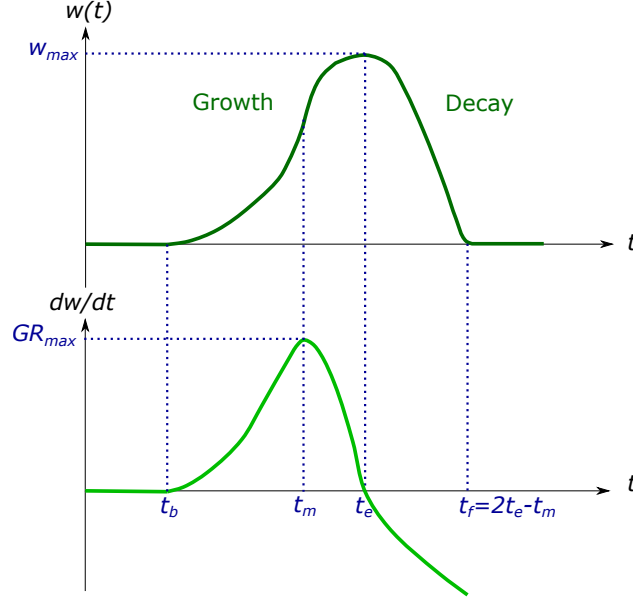


Figure 1: Evolution of the biomass $w(t)$ (Equation 11) and of the growth rate dw/dt (Equation 10) with characteristic times. See text for definition of variables.

345 external perturbations (e.g. flood, sudden drop in water temperature, changes in nutri-
 346 ent loads) that can impact the plant development and change its cyclic shape. These im-
 347 portant factors will be discussed later in the section 6.3, but for the rating curve model
 348 we choose to keep this cyclic approach (Figure 1).

349 The plant development model depends on parameters t_b , t_m , t_e and w_{max} only. Keep-
 350 ing these parameters constant from year to year implies that the vegetation cycle is ex-
 351 actly the same every year. This assumption is too restrictive. Consequently, these pa-
 352 rameters are allowed to vary from year to year in the model. The case study will explore
 353 this issue in more depth and will evaluate whether at least some of these parameters can
 354 reasonably be fixed.

355 2.4 The final rating curve model

356 The final rating curve model is expressed using a proxy $d(\tau)$ for time-varying plant
 357 biomass:

$$358 \begin{cases} Q(h, \tau) = Q_0(h, \tau) \left[1 + \frac{d(\tau)[h(\tau) - b]^{1/3}}{8gn_b^2} \min \left\{ \left(\frac{Q(h, \tau)}{U_x B [h(\tau) - b]} \right)^x ; 1 \right\} \right]^{-1/2} & \text{for } h > b \\ Q(h, \tau) = 0 & \text{for } h \leq b \end{cases} \quad (12)$$

359 with:

$$360 d(\tau) = d_{max} \left(\frac{t - t_b}{t_e - t_b} \right)^{\frac{t_e - t_b}{t_e - t_m}} \left[\frac{2t_e - t_m - t}{t_e - t_m} \right] = d_{max} d_0(\tau) \quad (13)$$

361 where $Q_0(h, \tau)$ is the stage-discharge relation not affected by the presence of vegetation
 362 (see Equation 5), d_{max} is the maximal proxy biomass and $d_0(\tau)$ is the dimensionless time-
 363 varying component of $d(\tau)$. In practice, the discharge time series can be estimated from
 364 Equation 12 using the stage time series $h(\tau)$ and the plant evolution $d(\tau)$ deduced from
 365 Equation 13.

366 No explicit solution exists for Equation 12 because the discharge Q is present on
 367 both sides of the equation. Nevertheless, Equation 12 can be rewritten in a polynomial
 368 form by squaring both sides and then solved using the Newton-Raphson algorithm:

$$369 \quad Q^2 + \gamma_1 \min \left\{ \frac{Q^\chi}{\gamma_2}; 1 \right\} Q^2 - Q_0^2 = 0 \quad (14)$$

370 with:

$$371 \quad \gamma_1 = \frac{d(\tau)[h(\tau) - b]^{\frac{1}{3}}}{8gm_b^2} \quad (15)$$

$$372 \quad \gamma_2 = U_\chi^\chi B^\chi [h(\tau) - b]^\chi \quad (16)$$

374 For mathematical convenience, the reconfiguration coefficient χ ranges between 0 and
 375 -2 (i.e. same range as in Vogel (1994) according to Luhar & Nepf (2013)). This limita-
 376 tion is reasonable regarding the values found for χ in literature, i.e. varying around -1
 377 (Västilä & Järvelä, 2014), and ensures that Equation 14 has a unique solution.

378 The model is generic but needs to be estimated using local information. It can be
 379 applied to any stations that comply with the conditions presented in Section 2.1, for in-
 380 stance using the code released with this paper (see Data availability statement).

381 **3 Bayesian inference**

382 **3.1 Extending the model to return the vegetation state**

383 The final rating curve model of Equation 12 requires computing the dimensionless
 384 time series $d_0(\tau) = d(\tau)/d_{max}$, which can be interpreted as a dimensionless indicator
 385 of the vegetation development state at time τ (Figure 2a): $d_0(\tau) = 0$ means that there
 386 is no vegetation; $d_0(\tau) = 1$ denotes the vegetation peak; $0 < d_0(\tau) < 1$ corresponds
 387 to vegetation growth (before t_e) and decline (after t_e). Extending the model to return
 388 the vegetation state will allow to use vegetation observations as estimation data, by com-
 389 paring the observed vegetation state with the one simulated by the model through $d_0(\tau)$.
 390 To do so, two steps are required in practice, as described next.

391 The first step is to convert $d_0(\tau)$ into an angle $\eta(\tau)$ of values comprised between
 392 0 and 2π (Figure 2b). This procedure is done to distinguish more readily between the
 393 growth ($\eta < \pi$) and the decline ($\eta > \pi$) stages. Formally:

$$394 \quad \begin{cases} \eta(\tau) = \pi d_0(\tau) & \text{if } t \leq t_e \\ \eta(\tau) = 2\pi - \pi d_0(\tau) & \text{if } t > t_e \end{cases} \quad (17)$$

395 The second step is to extend the rating curve model of Equation 12 so that it re-
 396 turns this angle, in addition to discharge. Because handling circular variables such as
 397 angle η requires specific care, it is more convenient to return its sine and cosine. Con-
 398 sequently, the model to be estimated can be viewed as a model with two inputs (stage
 399 h and time τ) and three outputs (discharge \hat{Q} , $\cos(\hat{\eta})$ and $\sin(\hat{\eta})$), as formalized below:

$$400 \quad \mathcal{M}(h, \tau; \boldsymbol{\theta}) = \begin{pmatrix} \hat{Q}(h, \tau; \boldsymbol{\theta}) \\ \cos(\hat{\eta}(\tau; \boldsymbol{\theta})) \\ \sin(\hat{\eta}(\tau; \boldsymbol{\theta})) \end{pmatrix} \quad (18)$$

401 Equation 18 makes the unknown parameters $\boldsymbol{\theta} = (B, S_0, n_b, b, c, \chi, U_\chi, \mathbf{t}_b, \mathbf{t}_m, \mathbf{t}_e, \mathbf{d}_{max})$
 402 to be inferred explicit. The components of the \mathbf{t}_b , \mathbf{t}_m , \mathbf{t}_e , \mathbf{d}_{max} vectors are year-specific

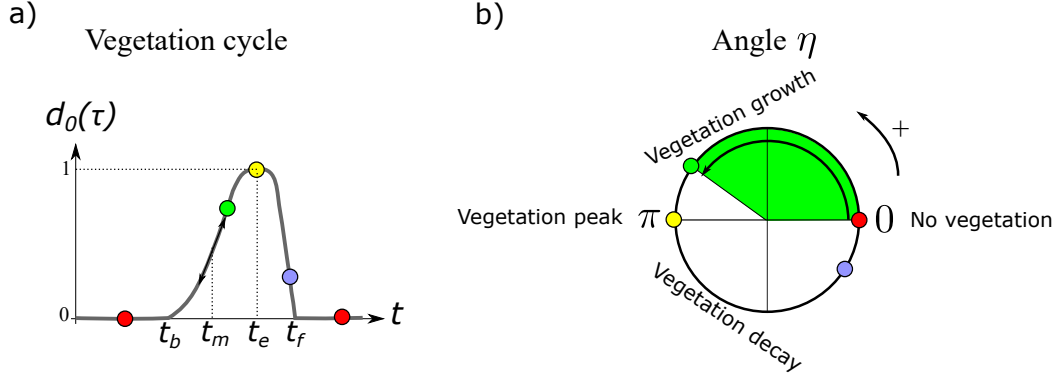


Figure 2: Interpretation of the dimensionless biomass proxy $d_0(\tau)$ as a position within the vegetation cycle (a) and its translation in terms of an angle η (b).

403 so for each year these components are estimated. The first output is obtained by apply-
 404 ing Equation 12; the second and third outputs are obtained by first applying Equation
 405 13 to compute $d_0(\tau)$, then by transforming it into angle $\hat{\eta}(\tau)$ through Equation 17.

406 3.2 Inference setup and assumptions

407 Let $(\tilde{\tau}_i, \tilde{h}_i, \tilde{Q}_i, \cos(\tilde{\eta}_i), \sin(\tilde{\eta}_i))_{i=1:M}$ denote the observational data used to estimate
 408 the model \mathcal{M} . Estimation data are vectors comprising all input/output variables of model
 409 \mathcal{M} . The vector can further be interpreted as a “traditional” gauging $(\tilde{h}_i, \tilde{Q}_i)$ augmented
 410 with a vegetation observation $(\tilde{\tau}_i, \cos(\tilde{\eta}_i), \sin(\tilde{\eta}_i))$. Note that the vegetation observation
 411 can be derived from a qualitative assessment of the vegetation state. Importantly, it may
 412 be uncertain, so that it can accommodate more or less vague statements as shown in Ta-
 413 ble 1.

Table 1: Correspondence between qualitative assessments of the vegetation state and the vegetation observations used for model estimation.

| Statement | angle $\tilde{\eta}_i$ | $\cos(\tilde{\eta}_i)$ | $\sin(\tilde{\eta}_i)$ |
|---------------------------------------------------------------------------|------------------------|------------------------|------------------------|
| 1/ there is no vegetation | 0 ± 0 | 1 ± 0 | 0 ± 0 |
| 2/ there are few developing plants | $\pi/4 \pm \pi/4$ | 0.5 ± 0.5 | 0.5 ± 0.5 |
| 3/ there is vegetation, and the vegetation cycle is in its growing stage | $\pi/2 \pm \pi/2$ | 0 ± 1 | 0.5 ± 0.5 |
| 4/ there is vegetation, and the vegetation cycle is in its decaying stage | $3\pi/2 \pm \pi/2$ | 0 ± 1 | -0.5 ± 0.5 |

Note: depending on the statement details, these values can be reviewed and their associated uncertainty can be adjusted.

414 The following assumptions are made to relate estimation data to the model pre-
 415 dictions:

$$\begin{cases} \tilde{Q}_i = \hat{Q}(\tilde{h}_i, \tilde{\tau}_i; \boldsymbol{\theta}) + \delta_{Q,i} + \varepsilon_{Q,i} \\ \cos(\tilde{\eta}_i) = \cos(\hat{\eta}(\tilde{\tau}_i; \boldsymbol{\theta})) + \delta_{\cos,i} + \varepsilon_{\cos,i} \\ \sin(\tilde{\eta}_i) = \sin(\hat{\eta}(\tilde{\tau}_i; \boldsymbol{\theta})) + \delta_{\sin,i} + \varepsilon_{\sin,i} \end{cases} \quad (19)$$

417 This equation states that for each output variable, the observed value is equal to
 418 the corresponding value simulated by the model plus an observation error $\delta_{.,i}$ plus a struc-
 419 tural error $\varepsilon_{.,i}$. All errors are assumed to be mutually independent, and the following
 420 probabilistic assumptions are made:

$$421 \quad \begin{cases} \delta_{Q,i} \sim \mathcal{N}(0, u_{Q,i}) ; \varepsilon_{Q,i} \sim \mathcal{N}(0; \gamma_{Q,1} + \gamma_{Q,2}\hat{Q}_i) \\ \delta_{cos,i} \sim \mathcal{N}(0, u_{cos,i}) ; \varepsilon_{cos,i} \sim \mathcal{N}(0; \gamma_{cos}) \\ \delta_{sin,i} \sim \mathcal{N}(0, u_{sin,i}) ; \varepsilon_{sin,i} \sim \mathcal{N}(0; \gamma_{sin}) \end{cases} \quad (20)$$

422 For each output variable, the standard deviation $u_{.,i}$ is assumed to be known and
 423 may vary between observations. This standard deviation quantifies measurement uncer-
 424 tainty and should ideally be specified following an uncertainty analysis of the measure-
 425 ment process (see Le Coz et al., 2014, for more details). Conversely, the standard devi-
 426 ation of structural errors is more difficult to specify before model estimation even though
 427 reasonable bounds can be defined; it is therefore assumed to be unknown and is inferred
 428 along with model parameters θ . Note that for the discharge output, the standard devi-
 429 ation of structural errors is allowed to increase linearly with the simulated discharge;
 430 this is made to account for the frequently-observed fact that structural uncertainty of
 431 rating curves tends to increase with the simulated discharge (Mansanarez et al., 2019).
 432 Conversely, the standard deviation of structural errors is assumed to be constant for the
 433 sine and cosine outputs.

434 3.3 Posterior distribution

435 Due to the mutual independence assumption for all error terms in Equation 19, the
 436 likelihood resulting from the assumptions discussed in the previous section can be com-
 437 puted as follows:

$$438 \quad \begin{aligned} p(\tilde{Q}, \cos(\tilde{\eta}), \sin(\tilde{\eta}) \mid \theta, \gamma, \tilde{\tau}, \tilde{h}) = & \\ \prod_{i=1}^M \phi\left(\tilde{Q}_i; \hat{Q}(\tilde{h}_i, \tilde{\tau}_i; \theta), \sqrt{u_{Q,i}^2 + (\gamma_{Q,1} + \gamma_{Q,2}\hat{Q}_i)^2}\right) & \\ \times \prod_{i=1}^M \phi(\cos(\tilde{\eta}_i); \cos(\hat{\eta}(\tilde{\tau}_i; \theta)), \gamma_{cos}) & \\ \times \prod_{i=1}^M \phi(\sin(\tilde{\eta}_i); \sin(\hat{\eta}(\tilde{\tau}_i; \theta)), \gamma_{sin}) & \end{aligned} \quad (21)$$

439 where $\phi(z; m, s)$ is the probability density function (pdf) of a Gaussian distribution $\mathcal{N}(m, s)$
 440 with mean m and standard deviation s evaluated at z . Note that the multiplicative na-
 441 ture of this likelihood makes the handling of missing data straightforward: correspond-
 442 ing terms can simply be omitted in the product of Equation 21.

443 Based on Bayes theorem, this likelihood can be combined with a prior pdf on un-
 444 known parameters, $p(\theta, \gamma)$, to yield the following posterior pdf:

$$445 \quad p(\theta, \gamma \mid \tilde{Q}, \cos(\tilde{\eta}), \sin(\tilde{\eta}), \tilde{\tau}, \tilde{h}) \propto p(\tilde{Q}, \cos(\tilde{\eta}), \sin(\tilde{\eta}) \mid \theta, \gamma, \tilde{\tau}, \tilde{h}) \times p(\theta, \gamma) \quad (22)$$

446 Note that the specification of prior distributions is case-specific and will be further
 447 discussed in the case study. Guidelines and examples related to the Bayesian method used
 448 here can also be found in Le Coz et al. (2014); Lundquist et al. (2016); Horner et al. (2018);
 449 Mansanarez et al. (2019).

450 3.4 MCMC sampling

451 The posterior pdf of Equation 22 is explored by means of a Markov Chain Monte
 452 Carlo (MCMC) sampler, described in Renard et al. (2006). In this paper a total of 100,000
 453 MCMC iterations are performed. The first half is discarded as a burn-in period, and the
 454 remaining iterations are further thinned by a factor of 10; this implies that subsequent
 455 computations are based on a MCMC subsample of size 5,000, which is sufficient to achieve
 456 an acceptable accuracy while avoiding storage and computing time issues. MCMC con-
 457 vergence is checked by visualising all MCMC traces.

458 4 Study case

459 4.1 The Ill River at Ladhof, France

460 The Ladhof hydrometric station is located on the Ill River in Colmar, East France,
 461 and is operated by the national hydrological service DREAL Grand-Est (station code:
 462 A1350310, WGS84 coordinates: Lon=7.384773 Lat=48.102498). This station is of in-
 463 terest since it is affected by aquatic seasonal vegetation and has been gauged frequently.
 464 A pressure gauge has recorded continuously the stage since 1958. Gaugings were made
 465 either with current meters or hydroacoustic profilers (ADCP). Figure 3 gives details about
 466 the station location, its surrounding environment and the type of plant present on the
 467 site.

468 Around the station, floodplains are bounded by well-maintained dikes on both sides.
 469 A small dam and a weir with a fish-way are present at approximately 800 m upstream
 470 of the station and 3.6 km downstream of the station, respectively. The weir is too dis-
 471 tant from the station to control the flow. For in-stream flows ($h < 3$ m), a rectangular
 472 channel control is assumed. The main channel vegetation influence noticed by the field
 473 hydrologists is within this water depth range. No vegetation from the bank blocks the
 474 flow. When the flow reaches the floodplains (i.e. water depth above 3 m), the hydraulic
 475 control becomes more complex. The flow section changes radically and can be approx-
 476 imated by a combination of the main channel (represented by a wide and rectangular
 477 channel) and the two floodplains (represented by a single wide and rectangular channel).
 478 In this study, the focus is made only on flows for stages lower than 3 m.

479 The riverbed at the station is sand-dominated and flat with no large bedforms. In-
 480 stream vegetation is composed of flexible and filamentous macrophytes that are, most
 481 of the time, just-submerged or not deeply submerged. Plants are mainly *Ranunculus*.
 482 As they grow, they tend to concentrate near the water surface. The height of the deflected
 483 vegetation within the channel was never evaluated by the local staff, so no quantitative
 484 estimation of the relative submergence range at this station is available. According to
 485 the station managers, the plant species has not changed over the years and the riverbed
 486 stayed quite stable. The plant density at the station can nevertheless vary from year to
 487 year, but no quantitative estimation of these variations was provided by the hydromet-
 488 ric service. The macrophytes always die during winter or are washed out before the end
 489 of the year; no dormant vegetation is observed. Conditions are thus appropriate for ap-
 490 plying the temporal vegetation model.

491 4.2 Experimental set-up

492 4.2.1 Data

493 Hydraulic gaugings (measurements of h and Q) from January 1996 to August 2017
 494 were performed with a high frequency at the station (generally one gauging every 15 days).
 495 A total of 492 measurements of h and Q were carried out under the condition $h < 3$ m.
 496 The measurements were sometimes associated with comments about vegetation at the
 497 time of gauging. Typical comments were: no plant, few plants, many blooming plants.

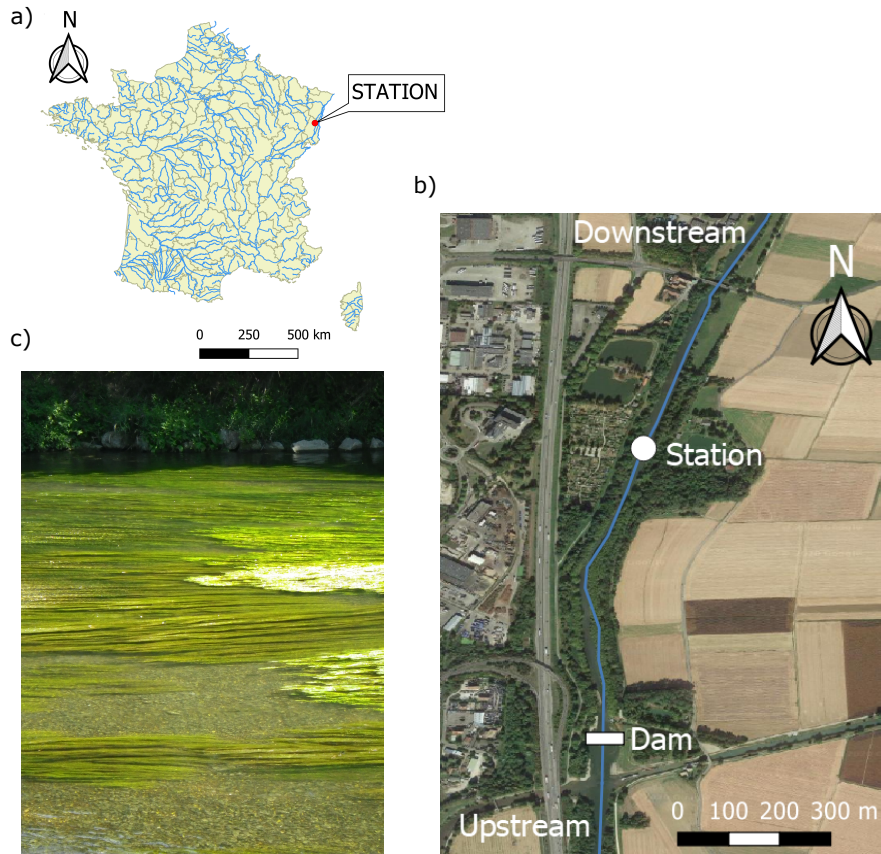


Figure 3: The Ill River at Ladhof hydrometric station: a) its location in France, b) aerial view of its surrounding environment and c) the type of aquatic vegetation (*Ranunculus*) present in the main channel.

498 A total of 293 comments are available among the 492 hydraulic gaugings. In the follow-
 499 ing, they are referred to as vegetation observations. We also have access to additional
 500 data such as water level from the French national hydrological database ([http://www](http://www.hydro.eaufrance.fr/)
 501 [.hydro.eaufrance.fr/](http://www.hydro.eaufrance.fr/)), air temperature and irradiance time series from the atmospheric
 502 Safran re-analysis over France (Vidal et al., 2010) and data collected from the station
 503 managers such as water temperature time series since 2009.

504 **4.2.2 Estimation**

505 Calculations are made over a 22-year data period, where sudden rating curve changes
 506 due to morphological evolution happened. The proposed rating curve model accounts
 507 for transient changes due to vegetation evolution only (i.e. deviations from the base rat-
 508 ing curve due to the presence of plants). Sudden changes due to bed evolution need to
 509 be dealt with using another approach (Mansanarez et al., 2019). The vegetation model
 510 should be used over stable periods, meaning periods where no significant changes in terms
 511 of river geometry are detected, i.e. no variations of S_0 , B , n_b , b or c . If the sudden change
 512 is not identified before using the vegetation model, interference with the estimation of
 513 plant-related parameters could happen, namely with χ , U_χ , d_{max} , t_b , t_m , t_e . The dataset
 514 is therefore divided into several stable periods following the method presented in Appendix
 515 B. Four stable periods are identified over the 22-year period. Only bed offset b is chang-

516 ing across these four periods, which reflects bed erosion and deposition at the station;
 517 the other parameters S_0 , B , n_b , c of the BRC do not change over the entire data-set pe-
 518 riod.

519 A 15% uncertainty is set for all the discharge measurements, which is fairly high
 520 but reflects the challenging conditions of measurements at this site (low flow velocity and
 521 water depth, presence of vegetation, soft surface riverbed). Uncertainty related to the
 522 water level measurement is neglected. The vegetation observations transcribed into a po-
 523 sition within the plant cycle (see Sections 3.1 and 3.2) are also affected with large un-
 524 certainty, since the interpretation of the station manager comments is subjective.

525 **4.2.3 Priors**

526 The prior distributions of the model parameters are given in Table 2. Our knowl-
 527 edge about the plant species at the station and their behaviour is limited, leading to wide
 528 priors for parameters related to plant development. The prior distribution for bed slope
 529 S_0 was chosen taking into account the difficulty to measure bed slopes in plains. In low-
 530 lands, bed slopes are quite low and it is often challenging to identify the right part of
 531 the channel for the measurement to have a representative value of the bed slope at the
 532 station. The same priors were given for series of parameters that need to be re-estimated
 533 for each new stable period (i.e. b) as well as for vegetation parameters that evolve ev-
 534 ery year (t_b , t_m , t_e and d_{max}). As the plant species was the same over the 22 years of
 535 data, parameter χ reflecting the plant flexibility is constant over the entire period. The
 536 prior for d_{max} is deliberately imprecise. It was chosen to represent values of d_{max} that
 537 can lead to a coefficient of resistance related to plant development, i.e. n_v considering
 538 no reconfiguration correction, twelve times higher than the coefficient of resistance re-
 539 lated to the bed without vegetation n_b .

540 **5 Results**

541 In this section, the performance of the temporal vegetation model is investigated
 542 using the data from Ladhof station. The model is evaluated in terms of parameter iden-
 543 tification and relative errors. We also explore the interest of accounting for the plant re-
 544 configuration effect. Using various tests derived from the Ladhof dataset, the importance
 545 of using various types of information for estimating the rating curve (i.e. gaugings and
 546 vegetation observation) is highlighted.

547 **5.1 Parameters estimation**

548 Figure 4 shows the prior and posterior distributions of the estimated parameters
 549 in the form of boxplots. The convergence of MCMC samples is verified visually for all
 550 the parameters. Most parameters are well-identified meaning that their posterior dis-
 551 tributions are more precise than their prior ones; this is the case for most BRC param-
 552 eters of each stable periods and for χ (i.e. posterior boxplots are three times narrower
 553 for n_b , S_0 , χ and up to 16 times narrower for b). Parameters related to plant-development
 554 show varying properties depending on the years. Except for a few years (e.g. 2001 and
 555 2017), posterior distributions of t_e are quite precise (14 narrower than prior distribution,
 556 on average). For the other three parameters (d_{max} , t_b and t_m), posterior boxplots stay
 557 rather wide (between 4 and 6 times narrower than prior boxplots, on average). Data for
 558 the year 2017 are only available for half of the year, which might partly explain the poor
 559 identification of those plant-development parameters. Their posterior distributions are
 560 nevertheless more precise than their prior ones, and would probably be even more pre-
 561 cise with additional information.

562 The parameters describing the timing of the vegetation cycle are always located
 563 at approximately the same time over the years (see Figure 4). It is important to recall

Table 2: Prior distributions of the temporal vegetation model parameters for the Ill at Ladhof study case.

| Parameter | Distribution |
|------------------------------------------|---------------------------------|
| Control channel | |
| B [m] | $\mathcal{LN}(\ln(25); 0.1)$ |
| S_0 [-] | $\mathcal{LN}(\ln(0.001); 0.5)$ |
| n_b [$\text{m}^{-1/3}\text{s}$] | $\mathcal{LN}(\ln(0.02); 0.2)$ |
| b_i [m] | $\mathcal{N}(0.8; 0.2)$ |
| c [-] | $\mathcal{N}(1.67; 0.025)$ |
| Vegetation parameters | |
| χ [-] | $\mathcal{N}(-1.4; 0.2)$ |
| U_χ [m/s] | = 0.1 (fixed) |
| $t_{b,j}$ [yr] | $\mathcal{U}(0; 1)$ |
| $t_{m,j}$ [yr] | $\mathcal{U}(0; 1)$ |
| $t_{e,j}$ [yr] | $\mathcal{U}(0; 1)$ |
| $d_{max,j}$ [-] | $\mathcal{U}(0; 5)$ |
| Structural uncertainty parameters | |
| $\gamma_{Q,1}$ [m^3/s] | $\mathcal{LN}(\ln(1); 1)$ |
| $\gamma_{Q,2}$ [-] | $\mathcal{LN}(\ln(0.5); 1)$ |
| γ_{cos} [-] | $\mathcal{U}(0; 1)$ |
| γ_{sin} [-] | $\mathcal{U}(0; 1)$ |

$1 \leq i \leq 4$ refers to the selected stable period; $1 \leq j \leq 22$ refers to the selected year within the data period; $\mathcal{LN}(m_{log}; s_{log})$ represents a lognormal variable whose logarithm has mean equal to m_{log} and standard deviation equal to s_{log} ; $\mathcal{N}(m_g; s_g)$ corresponds to a Gaussian distribution with a mean m_g and a standard deviation s_g ; $\mathcal{U}(a_u; b_u)$ corresponds to a uniform distribution defined by its lower (a_u) and upper (b_u) bounds.

564 that the plant growth in rivers is mostly driven by two key environmental factors, which
565 are the water temperature and the light intensity (Carr et al., 1997). At Ladhof station,
566 these factors evolve similarly over the years of the entire data-set period, which may ex-
567 plain why some plant-development parameters do not strongly vary over the years. As
568 a consequence, some of them could be fixed over the entire 22-year period to simplify
569 the model. This scenario will be investigated in section 5.3. Some exceptions are noticed
570 about the timing of the vegetation cycle in Figure 4, such as a delay at the beginning
571 of growth in 2016 (see t_b) and a late senescence in 2005 (see t_e). During those two years,
572 no specific anomalies in the water temperature or the irradiance time series were noted.

573 Maximal proxy biomass d_{max} is more variable from year to year than parameters
574 t_b , t_m , t_e . Remember that d_{max} is a key factor in the expression of n_v (see Equation 12).
575 A strong variation in d_{max} thus reflects a strong variation of flow resistance due to plants.
576 In 1998, the posterior distribution for d_{max} is quite close to the prior higher bound (see
577 Figure 4); this bound was set so that $n_v \approx 12 \times n_b$, which is quite strong for the sole
578 influence of in-stream plants but not unrealistic given the values found in the literature;
579 the Manning coefficient n_v can vary from around 0.025 to $0.4 \text{ m}^{-1/3}\text{s}$ (Chow, 1959; Coon,
580 1998; Wang & Zhang, 2019). In their review of flow resistance, Fisher & Dawson (2003)
581 categorize Ranunculus among the ‘Submerged fine-leaved’ vegetation type with reported
582 Mannings n values from 0.01 to more than 0.45 in some cases. The high values of d_{max}
583 reflecting high value of n_v may also include additional effects such as the possible reduction
584 in wetted area due to plants growing from banks, which were assumed negligible in
585 our case.

586 Correlations between t_b , t_m , t_e and d_{max} were checked for each year. Figure 5 shows
587 an example of the resulting correlation matrix for the year 2004. It looks similar for other
588 years. In general, a strong correlation between t_m and t_e is noticed; for some specific years
589 and to a lesser extent, correlations between t_b and t_m are also noted. We expect to bet-
590 ter identify model parameters by reducing the number of parameters varying per year,
591 for example by estimating a single t_m over the entire period of 22 years.

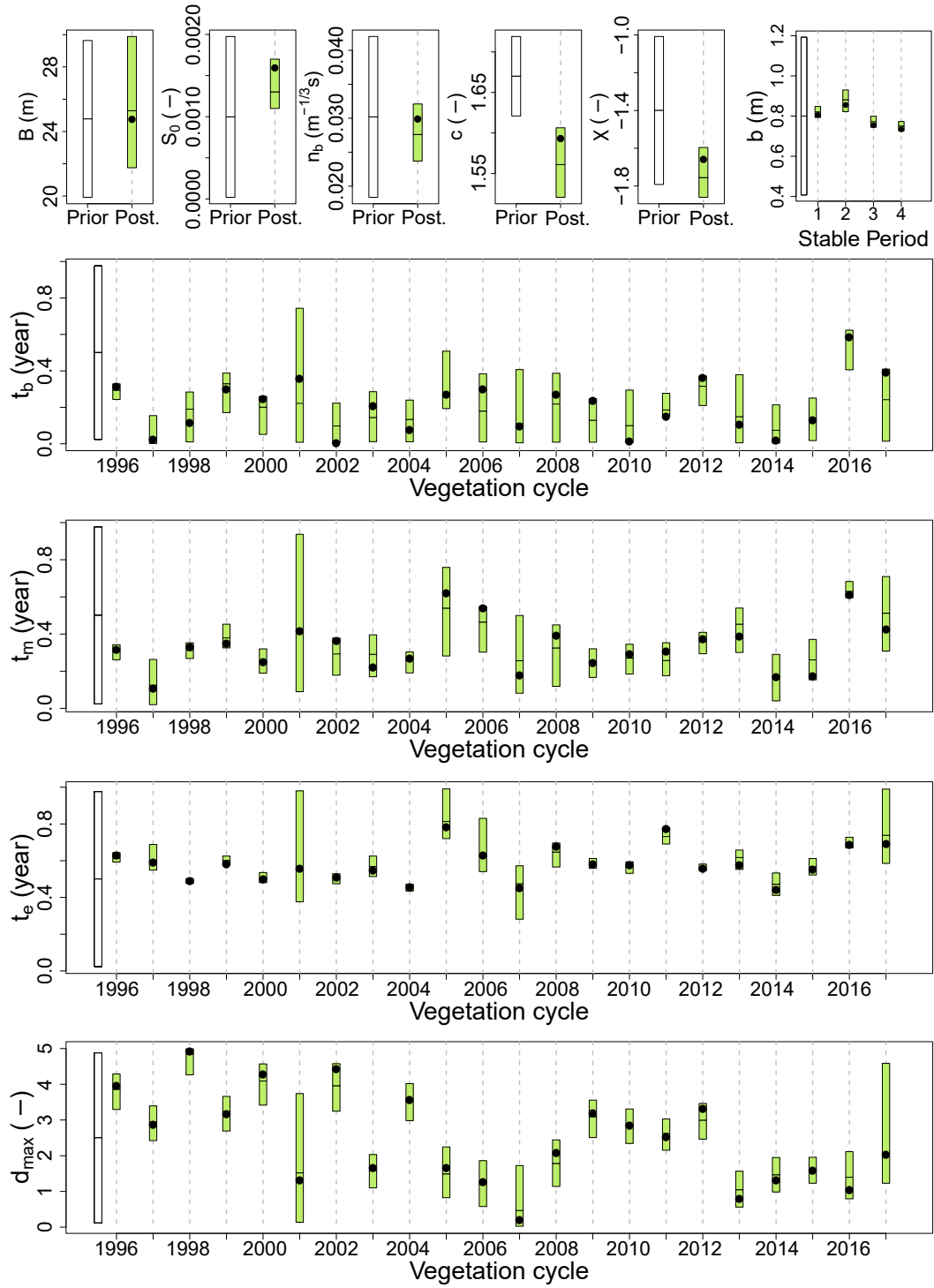


Figure 4: Prior and posterior distributions of the estimated parameters of the vegetation model in case of the Ladhof station over the 22 vegetation years from 1996 to 2017. White and green boxplots relate to the prior and posterior distributions, respectively. The boxes represent the 95% probability interval of the distribution with its median symbolized by a line. Black points refer to parameter values maximising the posterior pdf, also known as maximum a posteriori estimators (MAP).

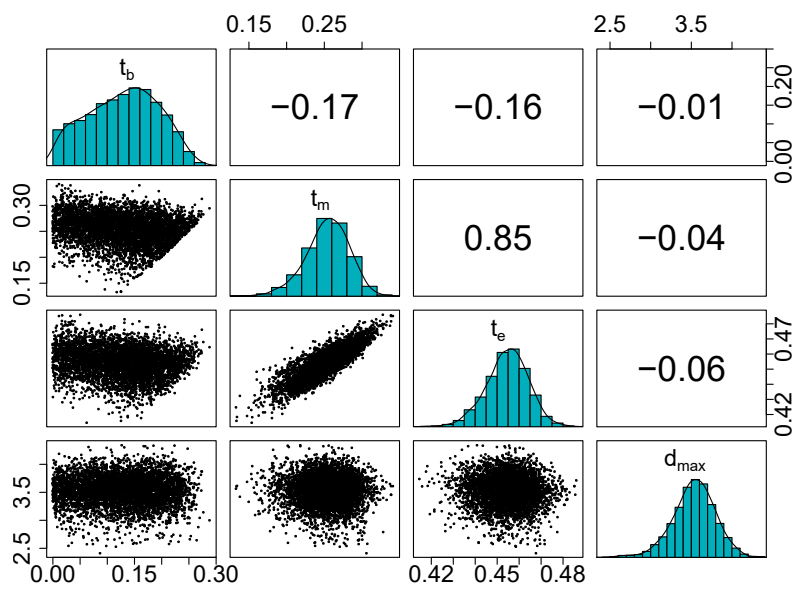


Figure 5: Example of posterior scatterplot correlation matrix between parameters of the plant development model for year 2004.

592

5.2 Time series reconstruction

593

594

595

596

597

598

599

600

601

602

603

604

605

606

607

608

609

610

611

612

Using the stage record at the station and the posterior distributions of the estimated parameters, it is possible to reconstruct the discharge time series $Q(\tau)$ with uncertainty as well as the plant development evolution $d(\tau)$ over the period of 22 years. Figure 6 shows these two time series with uncertainty. The 95% total uncertainty includes both the parametric (i.e. related to estimation errors of the parameters θ in Equation 18) and structural (i.e. related to structural errors in Equation 20) uncertainties. The “Maxpost” curves correspond to the results obtained using the maximum a posteriori estimates, i.e. parameter values maximising the posterior pdf. The uncertainty of $Q(\tau)$ is low and the measured and simulated water discharges are close, i.e. within the 20% error range (Figure 6a). For more clarity, a zoom on year 2015 is shown in Figure 6c. The effect of vegetation is generally well-described by the model. For comparison, the computed discharges obtained with a standard model with no vegetation module (see Q_0 in Equation 5) and their associated uncertainty are added to Figure 6c. Total uncertainty is higher when using the model with no vegetation module and observed discharges are better approximated by the vegetation temporal model. The temporal vegetation model is also able to simulate vegetation cycles that are strongly varying from year to year (see $d(\tau)$ in Figure 6b). It is thus possible to account for variable flow resistance induced by the plants. At the Ladhof station, plant cycles have different shapes and amplitudes, which shows that the analysis of the vegetation cycle on a yearly basis is essential even for a case where water temperature and light intensity conditions are similar over the years.

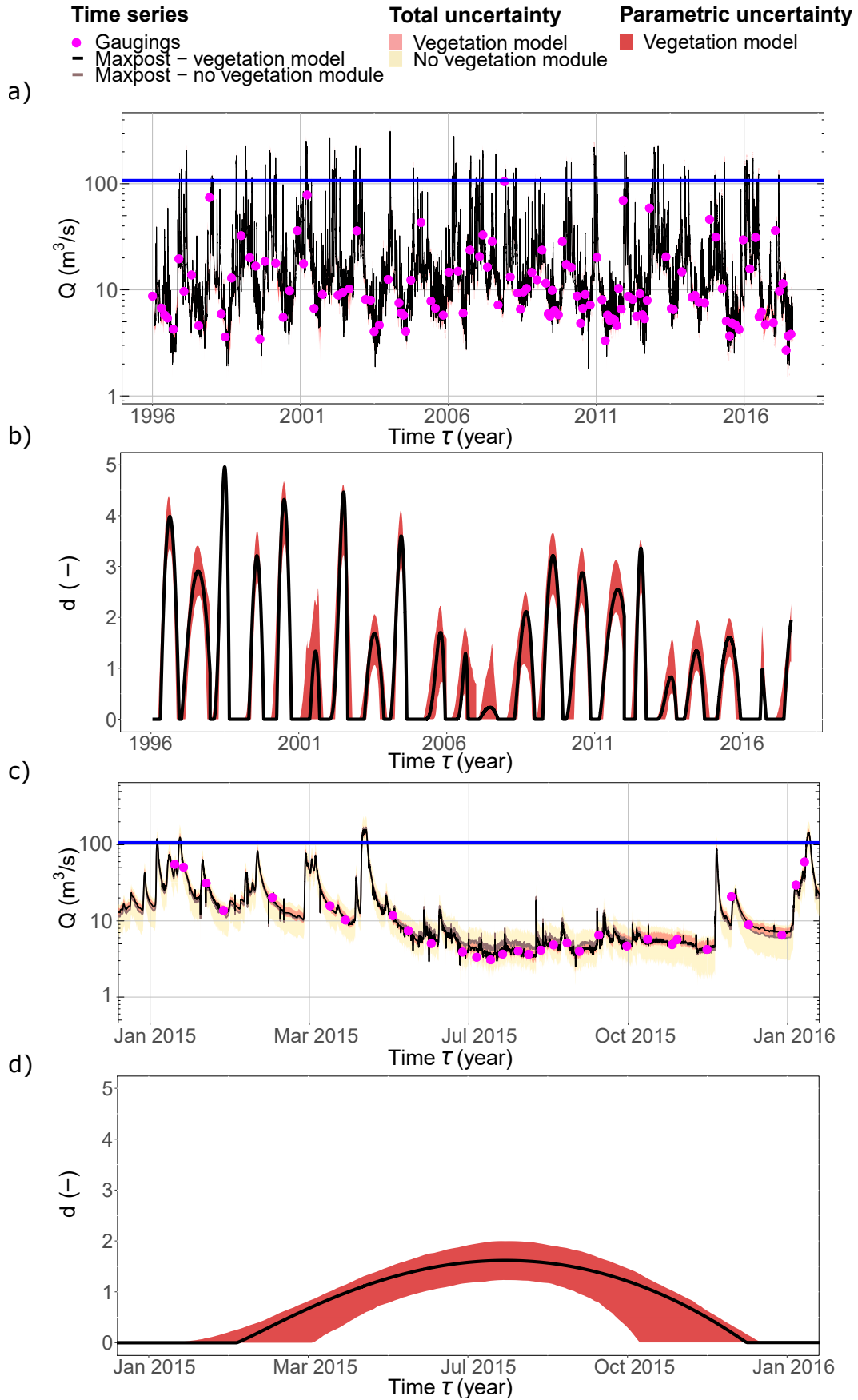


Figure 6: Results obtained with the temporal vegetation model over the 22 years of data at the Ladhof station : a) water discharge time series $Q(\tau)$ with uncertainties, b) time evolution of the plant biomass proxy $d(\tau)$ with parametric uncertainty over the entire period of study, c) water discharge evolution $Q(\tau)$ for year 2015 obtained with the temporal vegetation model and with a standard model with no vegetation module and d) plant evolution $d(\tau)$ for year 2015. Blue lines in b) and c) represent a change in hydraulic control occurring for $h > 3$ m: the vegetation model is not valid above this line (see Section 4.1).

613

5.3 Potential for reducing the number of time-varying parameters

614

615

616

617

Figure 7 shows the effect of fixing some of the yearly-varying parameters to a constant (but still unknown) value. It compares the relative errors E_r between the gauged discharge and the discharge predicted by the temporal vegetation model (using the MAP estimates).

618

619

620

621

622

623

624

625

626

627

Relative errors obtained with a standard model with a constant Manning coefficient (no vegetation module) are also added in Figure 7. In that case, E_r can exceed 50% and vary mostly between -28% and +81%. This result highlights the importance of using a rating curve model that accounts for the presence of plants when it is needed through a time-varying Manning coefficient $n_v(t)$. When all parameters related to the plant development vary, E_r values mostly range between $\pm 20\%$, which is a promising result considering the uncertainty applied to the measured water discharge (15%). Fixing either t_b or t_m does not result in any noticeable increase in relative errors. By contrast, fixing t_e or d_{max} leads to larger relative errors, suggesting that these parameters should be yearly-varying.

628

629

630

631

632

633

For the analyses described in the remainder of the paper, we decided to fix t_m based on the following rationale: a fixed t_m is expected to be very precisely estimated, and this might have the positive side-effect of improving the precision for parameter t_e through the correlation displayed in Figure 5. In these conditions, the model succeeds in identifying parameters and in predicting water discharge with relatively low errors ($\pm 20\%$, see Figure 7).

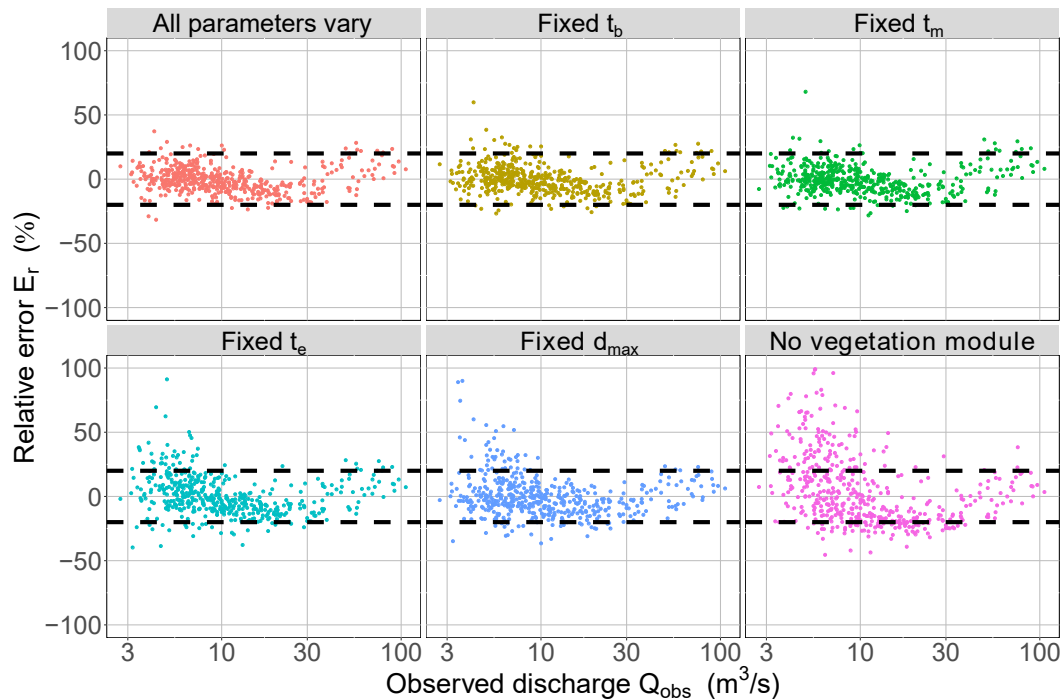


Figure 7: Relative discharge errors E_r for various computation configurations. Dashed lines delimit the $\pm 20\%$ range of errors.

634

5.4 Reconfiguration versus plant growth

635

636

637

638

In the rating curve model, it was assumed that the resistance due to aquatic plant was induced by the plant development (growth and decline) but also by the plant ability to reconfigure for high flow velocities. In this section, the relative importance of these two main effects is investigated.

639

640

641

642

643

644

645

646

647

When fixing the reconfiguration coefficient χ to zero, Equation 12 becomes only function of plant development $d(\tau)$. The reconfiguration correction is thus not activated. With $\chi = 0$, plants are assumed to be rigid and not to reconfigure under flow power. To evaluate the importance of the reconfiguration correction in the rating curve model, we compare the discharge obtained with the complete temporal vegetation model accounting for reconfiguration Q_R with the discharge obtained with no reconfiguration correction $Q_{\text{no-R}}$. The discharge $Q_{\text{no-R}}$ is computed using the same MAP estimators than those estimated for Q_R , except that χ is now fixed to 0 (i.e. the rating curve is not re-estimated). For more details, please refer to Perret et al. (2020).

648

649

650

651

652

653

654

655

656

Figure 8 shows the relative discharge differences due to deactivating the reconfiguration function in the estimated model. Only the data for which vegetation was present were selected and plotted in Figure 8. A large difference in discharge is observed, reaching more than 70%. The reconfiguration correction is larger when the quantity of plant is larger (i.e. $d(\tau)$ is high) and when the mean velocity is higher. The difference between $Q_{\text{no-R}}$ and Q_R is negative. Indeed, by contrast to flexible plants, rigid plants cannot bend or align in the flow direction to reduce their frontal areas impacted by the flow. The flow is therefore impeded by their presence. Rigid plants act as strong obstacles. Discharge is thus reduced in presence of rigid plants compared with flexible plants.

657

658

659

660

661

662

663

664

In Figure 8, measurements in presence of vegetation and for $U_m \leq 0.3$ m/s are barely available. Nevertheless, it is possible to predict that in this area the difference between $Q_{\text{no-R}}$ and Q_R will tend to 0 as we approach the threshold value of $U_m = U_\chi = 0.1$ m/s. For reminder, the critical flow velocity for which the plant is able to reconfigure U_χ was fixed to 0.1 m/s for all the calculations. When $U_m \leq U_\chi$ the plant reconfiguration is made not possible by definition in the model (i.e. the function characterizing the reconfiguration equals the value of 1 in Equation 9). The reconfiguration correction thus becomes inactive.

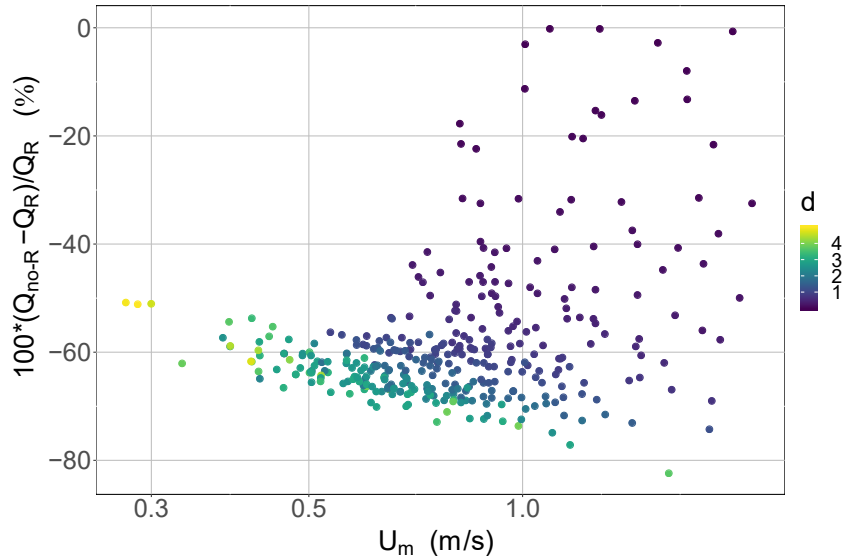


Figure 8: Impact of the reconfiguration correction in the estimated temporal vegetation model versus the gauged mean velocity U_m and the proxy biomass d at the station of the Ill at Ladhof.

665 5.5 Sensitivity to the number and type of gaugings

666 At many hydrometric stations, gaugings are less frequent than those performed at
 667 Ladhof station, and indications about vegetation are generally not available. From the
 668 perspective of testing the model in more realistic conditions, the Ladhof station is
 669 subdivided into different tests varying the number and type of available information (i.e.
 670 gaugings and vegetation observations) for the computation. These tests are described
 671 in Table 3. They were chosen to represent diverse kinds of stations : 1/research stations,
 672 where many data are available for estimating the water discharge; the original Ladhof
 673 station is considered as a research station; 2/operational stations, more common than
 674 research stations and used for surveillance and monitoring purposes; and 3/participa-
 675 tory stations, still rare nowadays, where gaugings are very rare and where most of the
 676 vegetation observation comes from the goodwill of outside actors or automatic devices
 677 (e.g. photographs of the river section).

678 The model performance is investigated comparing the test results in terms of pa-
 679 rameter identification and relative errors. Figure 9 shows posterior distributions of pa-
 680 rameters estimated for all the tests. Figure 10 shows the discharge relative errors obtained
 681 with the 283 validation data of tests O1, O2, P1 and P2. For information, discharge re-
 682 lative errors resulting from tests R1 and R2 at the same 283 validation points are added
 683 to Figure 10, but note that for these two cases, these points are estimation points too.

684 The main conclusion arising from these sensitivity tests are summarized in the fol-
 685 lowing:

- 686 1. With vegetation information only, estimating time parameters related to plant de-
 687 velopment is possible (see Figure 9, test P2 and parameters t_b , t_m , t_e). However,
 688 for the other parameters the posteriors remain very similar to the priors (see Fig-
 689 ure 9, test P2 and parameters d_{max} , B , S_0 , n_b , c , χ , b). Unless these priors are
 690 very accurate, this procedure leads to fairly large discharge errors (see Figure 10,
 691 test P2).

Table 3: Test configurations chosen to evaluate the temporal vegetation model.

| Test | Kind of station | Gaugings | | | Vegetation observations | |
|------|-----------------|----------------------------|----------------------------------------|-----------|----------------------------|-----------|
| | | Number of estimation data* | Number of validation data [†] | Frequency | Number of estimation data* | Frequency |
| R1 | Research | 492 | 0 | 2/month | 293 | 1/month |
| R2 | Research | 492 | 0 | 2/month | 0 | 0 |
| O1 | Operational | 209 | 283 | 10/year | 119 | 5/year |
| O2 | Operational | 209 | 283 | 10/year | 0 | 0 |
| P1 | Participatory | 88 | 283 | 4/year | 293 | 1/month |
| P2 | Participatory | 0 | 283 | 0 | 293 | 1/month |

*: Estimation data are those used for the estimation of the model parameters; they are different from the validation data.

†: Validation data are additional data used only for testing and validating our model; they are the same for tests O1, O2, P1 and P2 in order to compare their results.

- 692 2. Adding only a few gaugings per year allows a better estimation of the rating curve
693 parameters (see Figure 9 and compare improvements from tests P2 to P1 for all
694 parameters). While still large, discharge relative error E_r values are already smaller
695 than when using a well-gauged rating curve that ignores vegetation (compare test
696 P1 in Figure 10 versus test with no vegetation module in Figure 7).
- 697 3. At the other end of the spectrum, if plenty of gaugings are available and well-distributed
698 over the years, then this suffices to estimate the model (compare test R1 versus
699 test R2 in Figure 9 and 10). A large amount of information is included in the wa-
700 ter discharge measurements, including the resistance induced by the vegetation.
- 701 4. The operational case is more difficult to interpret as results seem to be parameter-
702 dependent and year-dependent (Figure 9, compare test O1 and test O2). The use
703 of vegetation observations improves the estimation of time parameters for some
704 years but does not have any positive effect on the estimation of the BRC param-
705 eters. For the operational cases, most errors are within $\pm 20\%$, with a few isolated
706 points showing larger errors (Figure 10).

707 To sum up, the model has a good performance as long as a few gaugings combined
708 with vegetation observations are available. Although vegetation observations are not es-
709 sential when many gaugings are available, it does help a lot when gaugings are scarce,
710 in particular for the identification of parameters related to plant development.

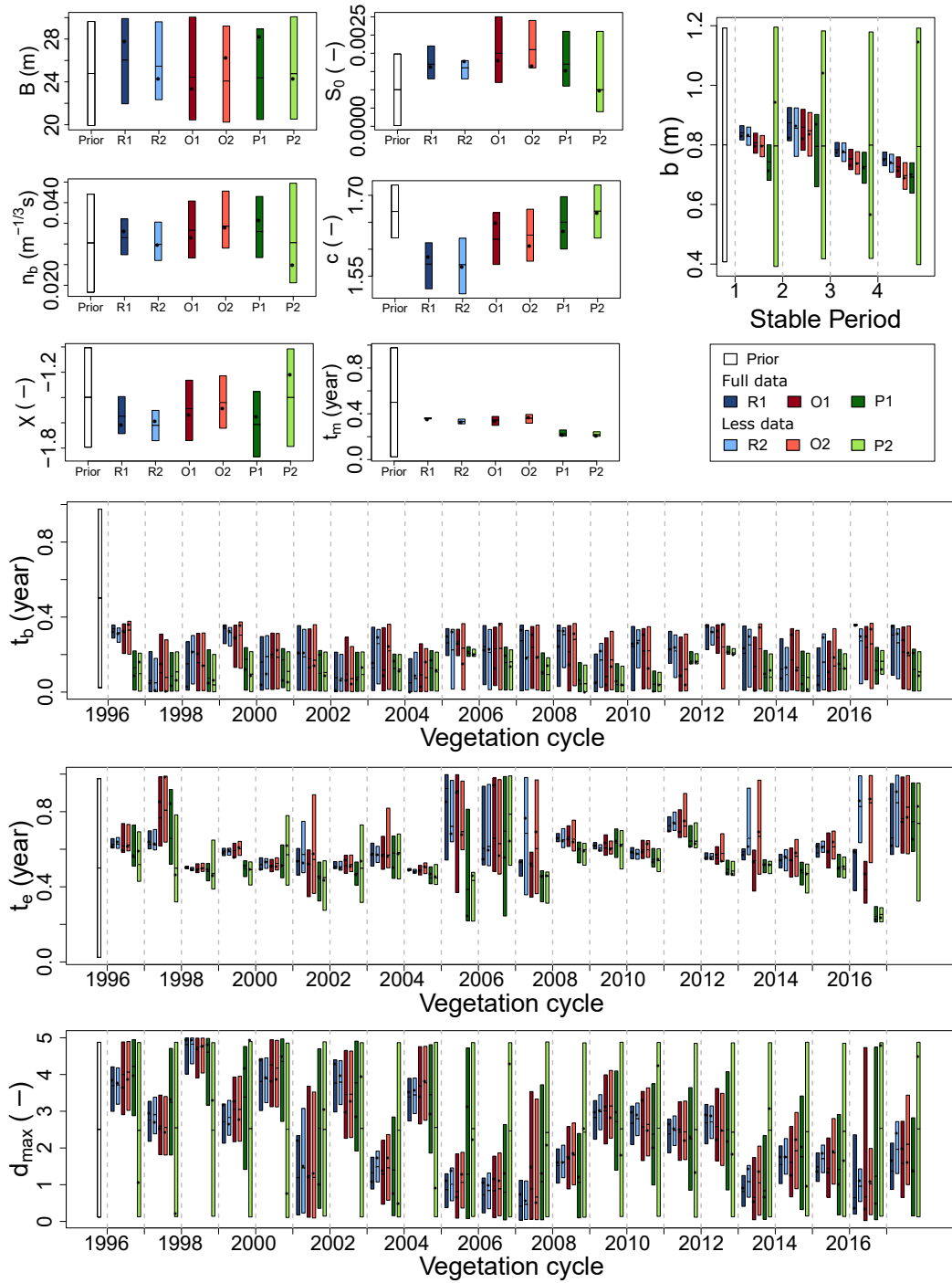


Figure 9: Model sensitivity to the type and number of gaugings or observations. Prior and posterior distributions (95% probability intervals) of the model parameters estimated for all cases presented in Table 3. Black points represent the MAP estimators.

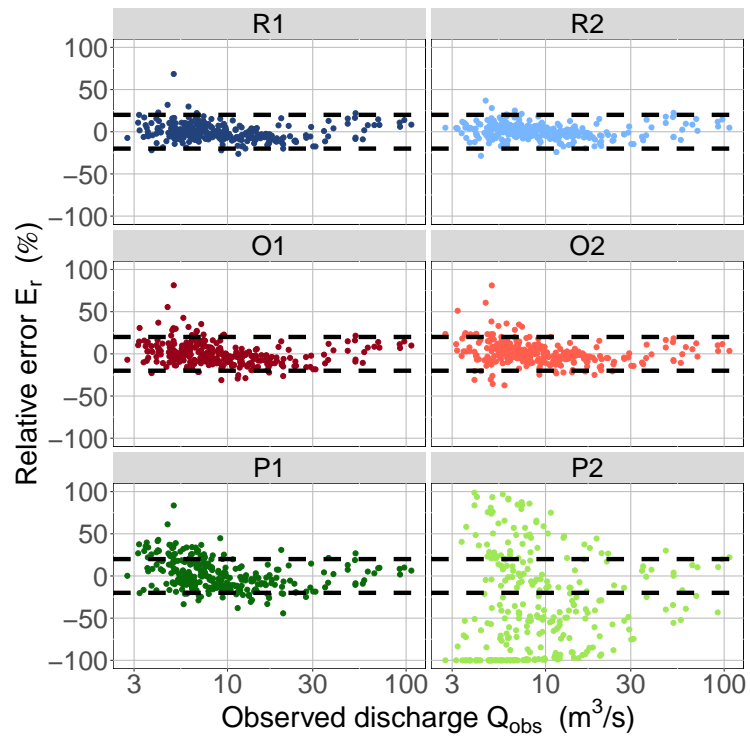


Figure 10: Discharge relative error as a function of observed water discharge obtained for the tests presented in Table 3.

6 Comments on model use and further developments

6.1 How to use the model?

One of the objective of this paper was to develop a rating curve model for operational use. In this part, we detail how the temporal rating curve model can be used in practice. Figure 11 formalizes its functioning. To predict discharge in vegetated flows, an operational user may use the computer implementation of the model that is freely available (see data availability statement). She/he will need to provide the following local information:

1. A data file containing two inputs (i.e. the time and the stage time series recorded at the hydrometric station) and observations (i.e. gaugings and vegetation observations converted into a position into the vegetation cycle using $\cos(\tilde{\eta}_i)$ and $\sin(\tilde{\eta}_i)$).
2. Prior specifications for parameters that define the channel control, namely for the channel width B , the channel slope S_0 , the base Manning coefficient n_b , and the bed level b .
3. Prior specification for plant-related parameters (i.e. the reconfiguration parameter χ , the reconfiguration velocity U_χ , the characteristic times of the plant cycle (t_b, t_m, t_e) and the maximal proxy biomass d_{max}).

In the model configuration files, non-informative priors can be specified in case no information can be provided a priori. After launching the model runner, the user can have access to the estimated parameters and to four outputs with their parametric and total uncertainty envelopes (see Figure 11), in particular to the discharge $Q(\tau)$ and the proxy biomass $d(\tau)$ time series.

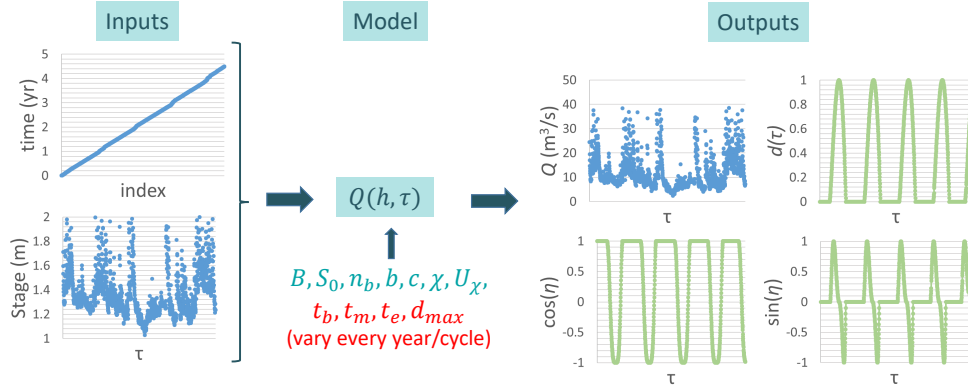


Figure 11: Diagram of the temporal rating curve model for vegetated flows: inputs, parameters and outputs.

6.2 Data collection strategy for vegetation-influenced rating curves

Some suggestions of data collection strategies are made based on our experience of modelling the Ladhof station. The first recommendation is to have information about the aquatic plants present at the station, namely about their nature, morphology and mechanical properties. We therefore advice the station managers to have opinions of experts in aquatic plants in order to improve the estimation of discharge, even if it is not a common practice at hydrometric station. Such information could be used to specify more precise priors for model parameters that are related to plant-development (i.e. t_b, t_m, t_e and d_{max}). Note that even if the plant properties are known specifically, there is

no means to deduce the parameters χ and U_χ precisely. For example, Järvelä (2004) identified the plant species in his study but used laboratory experiments anyway to evaluate empirically these parameters. Look-up tables with χ -values exist for few floodplain plants, but they are still missing for in-stream plants.

Secondly, the distribution of gaugings within the vegetation cycle (i.e. within the year) is likely to be an important factor for a good estimation of the model. Although this point was not explored in the paper, we suggest to have measurements amongst the various states of the vegetation cycle (no plants, growth, peak, decline). In this paper, the gauging measurements were performed about every two weeks and not necessarily scheduled according to the plant cycle.

Finally, this study highlights the importance of having data to characterize the plant development. The plant development is associated to the proxy biomass d in our model, but technically this parameter cannot be measured in the field because it is a proxy. In practice, the angle η is used in the rating curve model to provide information on the state of development of the plant. We thus suggest collecting information describing the position in the plant cycle, which would be used as observational data and would yield valuable information to estimate model parameters. Such information could take the form of simple explicit comments about plant development relative to previous visit at the station, such as *no / same amount of / more / less plants than before*. Comments such as *few plants, scarce plants, lots of plants*, should be avoided, because they are too vague to be translated into a plant cycle position. Some specific states of the plant cycle are easy to identify such as the vegetation peak, the period without vegetation and the periods of growth and decay. We also recommend collecting quantitative information such as the percentage of channel cross-section covered by vegetation, in order to directly assimilate information about d_0 in the model (i.e. the dimensionless proxy biomass).

As shown in this study, the model can be calibrated using simple observations on the amount of aquatic vegetation that can be made by non biologist observers, e.g. the field hydrologists in charge of streamflow measurement during their field visits. By contrast, post-processing vegetation observation, i.e. transforming them into angles in the development cycle, is generally more time-consuming and complex. For quantifying the plant development cycle, several inexpensive monitoring techniques can be considered such as direct observations (e.g. explicit comments or evaluation of the percentage of channel cross-section covered by vegetation), image analysis from frequent (and automatic) photography of the station or analysing satellite or drone images (Biggs et al., 2018). Indirect vegetation observations could also be deduced from other nearby hydrometric stations, since plant cycles are probably similar as long as the climate and the type of plants are the same at these other stations. Assimilating those data could be a promising development of our model. Thanks to the spatial coherence, these new data would help to better identify the plant parameters of the model and to reduce the uncertainty of the resulting discharge time series at the station.

6.3 Improvements of the rating curve model

The proposed temporal rating curve model is promising for the estimation of water discharge at hydrometric stations affected by aquatic plants. Nevertheless, the discharge relative errors are still high ($-20\% < E_r < +20\%$) even if acceptable compared with the uncertainty of the gaugings (15%). In this section, possible improvements of the temporal model proposed in this paper are discussed.

We anticipate that incorporating some biology concepts in the model might lead to better results. Using covariates controlling variations of the plant biomass could help predict the parameters of the vegetation model $d(\tau)$. For example, from their monitoring of the seasonal growth and decay of *Ranunculus* between 1971 and 1976 in an unshaded section of the River Lambourn at Bagnor, England, Ham et al. (1981) found that

793 the spatial expansion of *Ranunculus* in a given year tended to be greater as the mean
 794 discharge in spring of that year was greater. Therefore, cumulative discharge in the spring
 795 season might be a good candidate for modelling the maximum proxy biomass d_{max} of
 796 *Ranunculus* or similar vegetation. However, Ham et al. (1981) discuss several other in-
 797 fluencing factors and mention other sites where high discharge may limit the spatial ex-
 798 pansion of *Ranunculus*. Also, the water temperature (T) or its cumulative form (T_c) could
 799 help predict the characteristic times of the plant growth and decay. At hydrometric sta-
 800 tions, water temperature is arguably the most common continuously measured param-
 801 eter after the water level. A possible approach would be to relate t_b to the time where
 802 the degree-day had accumulated sufficiently for the plant to start growing ($t_b = t[T_c =$
 803 $T_{c,min}]$), t_m to the time where the water temperature reaches the optimal temperature
 804 T_{opt} for plant growth ($t_m = t[T = T_{opt}]$), and t_e to the time where the degree-day had
 805 accumulated too much, leading to the plant decay ($t_e = t[T_c = T_{c,max}]$). This method
 806 might work for t_b and t_m but less likely for t_e . Indeed, it often happens that the plant
 807 decline in natural rivers is driven by plant removal due to high velocities rather than by
 808 natural mortality. The optimal temperature T_{opt} and the minimal cumulative degree-
 809 day for plant growth $T_{c,min}$ would be estimated using the Bayesian framework in order
 810 to deduce t_b and t_m .

811 Ultimately, it could be judicious to use a dynamic model rather than a temporal
 812 model to predict the plant evolution at hydrometric stations. The evolution of the biomass
 813 proxy $d(\tau)$ is cyclic in our model. However, it does not always follow a bell-shaped curve
 814 in practice. Plant development can be sometimes subject to perturbations depending on
 815 external factors. For example, a brutal variation in water temperature, change in nutri-
 816 ent loads, human plant removal, or a large flood can strongly impact the typical evolu-
 817 tion of the plant. A dynamic model that would update the biomass as a function of such
 818 external drivers could increase the performance of the rating curve model. Compartment
 819 models are often used to describe dynamic behaviour, e.g. reservoir models in hydrol-
 820 ogy or crop growth compartment models in biology (Johnson & Thornley, 1983). By anal-
 821 ogy, the proxy of biomass $d(\tau)$ in rivers could be seen as a stock of biomass that evolves
 822 in time according to diverse external factors (Fovet et al., 2010). The production of biomass
 823 would be regulated by environmental factors that favor or limit the plant growth, such
 824 as the water temperature, the light intensity, the amount of nutrients, etc. The loss of
 825 biomass would be modelled by detachments of biomass (due to hydraulic variations, nat-
 826 ural senescence, external interventions, etc.). Using such model is promising for the fu-
 827 ture because these external factors are expected to change according to climate projec-
 828 tions (e.g. increase in water temperature, eutrophication). One of the main advantages
 829 of using this dynamic approach is that parameters would be estimated one time only for
 830 the entire data period and not every year as for the cyclic approach. In addition, more
 831 complex stations than Ladhof station could also be dealt with such a dynamic model,
 832 such as, for example, stations where plants do not die at the end of each year.

833 **6.4 Extension of the rating curve model to fully submerged or emer-** 834 **gent plants**

835 The applicability of the model is limited to specific conditions detailed in Section
 836 2.1. It could be extended by revising those conditions. However, limiting the model com-
 837 plexity is important to ensure that it is applicable for operational purposes.

838 Importantly, the model applicability is limited to a specific range of relative sub-
 839 mergence (close to 1), namely for just-submerged or not deeply submerged plants. To
 840 cover as many cases as possible, the model could be extended to emergent and fully sub-
 841 merged plants (i.e. $[h-b]/H_p \leq 1$ and $[h-b]/H_p > 1$, respectively). This would require
 842 modifying the flow resistance equation $n_v(\tau)$. Major changes in Equation 9 would be re-
 843 lated to the plant density parametrization (because emergent and submerged plants do

844 not have the same properties) and to the chosen characteristic velocity (because flow struc-
845 ture strongly changes from submerged to emergent plants).

846 In the case of submerged plants, the flow structure over the section would change
847 and the water volume located above the ground-plants should be accounted for. The flow
848 structure would be composed of two separate vertical layers: one for vegetation and one
849 for overflow. The mean velocity within the vegetated part of the cross-section U_v should
850 be retained as the new characteristic velocity for the computation of n_v , in replacement
851 of the depth-averaged velocity U_m used in our study. The velocity U_v is harder to es-
852 timate than U_m , but methods such as the common two-layer approach exist (Luhar &
853 Nepf, 2013; Västilä et al., 2016). The velocity U_v depends on the length of the submerged
854 plants, and hence on their evolution. Using U_v instead of U_m in Equation 9 will thus com-
855 plicate the flow resistance model, because (i) another proxy for plant development would
856 be needed and (ii) U_m would no longer be the characteristic velocity and its simple re-
857 lation with the total discharge Q (i.e. $U_m = Q/(B[h - b])$) would not hold anymore.

858 For emergent plants, no change of parametrization for the characteristic velocity
859 U_c would be needed in the flow resistance equation (i.e. $U_c = U_m$). Indeed, the flow
860 structure would still be composed of one layer. However, the plant density parameter
861 (i.e. $d(\tau)$, which simulates the proxy biomass of the entire vegetation) should be revis-
862 ited since only the submerged part of the plants needs to be accounted for. Järvelä (2004)
863 suggests that partially submerged plants generally have uniform distributions of LAI over
864 their height, and so adds the relative submergence $[h - b]/H_p$ as a correction in Equa-
865 tion 6. The same type of correction could be applied to Equation 9. It would imply the
866 addition of another time-varying model $H_p(\tau)$ to be able to predict the plant height evo-
867 lution in function of time.

868 In our opinion, extending the model to submerged plants should have priority be-
869 cause emergent plants are not often observed in main channels and are more relevant for
870 the study of floodplain flows.

871 7 Conclusion

872 This study is a first attempt at deriving a rating curve model for channel controls
873 to predict water discharge time series at hydrometric stations affected by seasonal in-
874 stream plants. A temporal rating curve model is developed based on the assumption that
875 vegetation induces a change in bed roughness mainly, which modifies the flow resistance.
876 In the model, the bed roughness is described using a time-varying resistance coefficient,
877 which combines the change in resistance due to plant growth and decay, and to the plant
878 ability to reconfigure with high flow velocity (i.e. streamlining and bending). A Bayesian
879 approach using prior knowledge on hydraulic controls at the station and observation data
880 (gaugings and comments about the amount of vegetation) is used for estimating the model
881 parameters and uncertainty. With such an approach, it is possible to compute the wa-
882 ter discharge time series over a given time-period along with the evolution of the proxy
883 biomass, which informs about the plant resistance potential.

884 Several tests are conducted to investigate the model performance using data from
885 a station affected by aquatic vegetation. The relative discharge errors and the param-
886 eter identification are analysed and discussed. The relative importance of the two main
887 effects that drive the time-varying resistance coefficient is investigated. Although plant
888 development is the main cause of flow resistance variation, the reconfiguration correc-
889 tion was found to be crucial for the discharge calculation. This correction is especially
890 important when the mean velocity and the plant biomass are large. The tests also sug-
891 gest that the complexity of the model can be reduced by fixing some year-to-year vary-
892 ing parameters related to plant growth and decay, without reducing the model perfor-
893 mance. Both gaugings and vegetation observations are valuable for a good calibration

894 of the model. Simple comments on the amount of aquatic vegetation yield valuable in-
 895 formation for the estimation of the parameters related to the plant growth and decay,
 896 especially when hydraulic gaugings are scarce. Finally, the temporal rating curve model
 897 accounting for aquatic vegetation can reduce the relative discharge errors to acceptable
 898 levels, from a range of $\pm 50\%$ to $\pm 20\%$ as found in the application case.

899 Obviously, further tests and the development of guidelines and procedures are needed
 900 to prepare the transfer of the proposed method to hydrological services. The main per-
 901 spective for model development are the extension to fully submerged plants and the im-
 902 plementation of a dynamic model instead of the temporal approach based on a param-
 903 eterized shape of the growth and decay cycle from year to year. A dynamic model would
 904 predict the biomass evolution based on external and environmental factors that enhance
 905 or limit the plant growth. Such an approach will certainly require a deeper knowledge
 906 of the plant species, distribution and dynamics at a given site. But again, a trade-off be-
 907 tween model complexity and performance should be sought to ensure its operational ap-
 908 plicability by field hydrologists.

909 Appendix A Temporal plant development model

910 The biomass model is obtained by integrating in time the growth rate model of Yin
 911 et al. (2003) (Equation 10):

$$912 \quad w(t) = \int \frac{dw}{dt} dt = \int GR_{max} \left(\frac{t_e - t}{t_e - t_m} \right) \left(\frac{t - t_b}{t_m - t_b} \right)^p dt \quad (A1)$$

913 with $p = (t_m - t_b)/(t_e - t_m)$, dw/dt the growth rate, $w(t)$ the biomass, t_b the time at
 914 which the plant starts to grow, t_m the time at which the growth rate is the greatest, t_e
 915 the end of the growth time and GR_{max} the maximal growth rate.

916 In the following, the integration of Yin et al. (2003) model is detailed step by step:

$$917 \quad \int \frac{dw}{dt} dt = \frac{GR_{max}}{t_e - t_m} \left[\int t_e \left(\frac{t - t_b}{t_m - t_b} \right)^p dt - \int t \left(\frac{t - t_b}{t_m - t_b} \right)^p dt \right] \quad (A2)$$

918 The second part of Equation A2 can be easily integrated by using the equality $t =$
 919 $t - t_b + t_b$:

$$\begin{aligned} \frac{1}{(t_m - t_b)^p} \int t(t - t_b)^p dt &= \frac{1}{(t_m - t_b)^p} \int (t - t_b + t_b)(t - t_b)^p dt \\ &= \frac{1}{(t_m - t_b)^p} \left(\int (t - t_b)(t - t_b)^p dt + \int t_b(t - t_b)^p dt \right) \\ &= \frac{1}{(t_m - t_b)^p} \left[\frac{(t - t_b)^{p+2}}{p+2} + t_b \frac{(t - t_b)^{p+1}}{p+1} \right] \\ &= \frac{1}{(t_m - t_b)^p} (t - t_b)^{p+1} \frac{pt + t + t_b}{(p+2)(p+1)} + C_0 \end{aligned} \quad (A3)$$

921 with C_0 a constant equal to zero since $w(t = t_b) = 0$.

922 Going back to the integration of the entire model, Equation A2 becomes:

$$\begin{aligned} 923 \quad w(t) &= \frac{GR_{max}}{t_e - t_m} \left[t_e \left(\frac{t - t_b}{t_m - t_b} \right)^p \frac{(t - t_b)}{(p+1)} - \frac{(t - t_b)^{p+1}}{(t_m - t_b)^p} \frac{(pt + t + t_b)}{(p+2)(p+1)} \right] \\ &= \frac{GR_{max}}{t_e - t_m} \left(\frac{t - t_b}{t_m - t_b} \right)^p (t - t_b) \left[\frac{(p+2)t_e - (p+1)t - t_b}{(p+2)(p+1)} \right] \end{aligned} \quad (A4)$$

924 We now assume that the maximum of biomass w_{max} is reached at $t = t_e$. To cal-
 925 culate w_{max} , t is replaced by t_e in Equation A4:

$$926 \quad w_{max} = \frac{GR_{max}}{t_e - t_m} \left(\frac{t_e - t_b}{t_m - t_b} \right)^p (t_e - t_b) \left[\frac{t_e - t_b}{(p+2)(p+1)} \right] \quad (A5)$$

The biomass model is deduced from the comparison between Equations A4 and A5, by forming the ratio $w(t)/w_{max}$:

$$\begin{aligned} \frac{w(t)}{w_{max}} &= \left(\frac{t - t_b}{t_e - t_b} \right)^p \frac{(t - t_b)}{(t_e - t_b)} \left[\frac{(p + 2)t_e - (p + 1)t - t_b}{t_e - t_b} \right] \\ &= \left(\frac{t - t_b}{t_e - t_b} \right)^{p+1} \left[\frac{(p + 2)t_e - (p + 1)t - t_b}{t_e - t_b} \right] \end{aligned} \quad (\text{A6})$$

Reminding that $p = (t_m - t_b)/(t_e - t_m)$, the final biomass model can be expressed as follows:

$$w(t) = w_{max} \left(\frac{t - t_b}{t_e - t_b} \right)^{\frac{t_e - t_b}{t_e - t_m}} \left[\frac{2t_e - t_m - t}{t_e - t_m} \right] \quad (\text{A7})$$

Appendix B Identification of stable periods

This appendix details the method used for identifying stable periods where no significant changes in terms of river geometry can be detected. Over a stable period, no sudden changes (due to bed evolution) in the rating curve should be observed.

We assume that significant change in riverbed happens after a morphogenic flood (Mansanarez et al., 2019). The date following the flood event marks the beginning of a new stable period. For convenience, morphogenic flood is arbitrarily defined as a flood exceeding the 2-year flood ($Q > Q_2$). For the Ladhof station, the possible changes after such a flood are overall bed erosion or deposition at the station according to station managers. In other words, it might induce a change in the offset of the main channel control b . No particular variations of channel slope S_0 , channel width B and bed roughness n_b have been previously noticed over the years. Note that at the Ladhof station, the vegetation disappears every winter and n_b depends on the type of sediments and bedforms present on the riverbed only. Consequently, only one parameter of the BRC needs to be re-estimated when a new stable period begins. Ten stable periods were identified based on $Q > Q_2$ for the Ladhof station over the 22 years of data. The stage time series (Figure B1a) show that even after floods the riverbed level does not obviously vary. The number of stable periods can thus be further reduced.

Base rating curves of the ten periods were estimated using the classical power-law model and the Bayesian method presented in Le Coz et al. (2014):

$$\begin{cases} Q(h, \tau) = \frac{1}{n_b} B \sqrt{S_0} [h(\tau) - b]^c \text{ for } h > b \\ Q(h, \tau) = 0 \text{ for } h \leq b \end{cases} \quad (\text{B1})$$

The base rating curves are shown in Figure B1b along with the posterior distributions of b in Figure B1c. The estimation of b is sometimes uncertain due to the small number of gaugings available over the considered periods (see gaugings from period 1 for example). Combining visual observations of the BRC (Figure B1b) and analysis of the riverbed level evolution (Figure B1c), the 22 years of data were divided into four periods. If two successive BRCs overlap and if the posterior distribution of b is in the same range, we assume that no changes have happened and that the two successive periods can be merged. The initial 10 stable periods are hence merged into four stable periods with this comparison technique. Figure B1d and Figure B1e show the characteristics of the BRCs for the new four periods.

Acknowledgments

This work was funded by SCHAPI, France's national hydrological service (SRNH 2018 and 2019 contracts between INRAE and the Ministry of Ecology). Data for the Ladhof

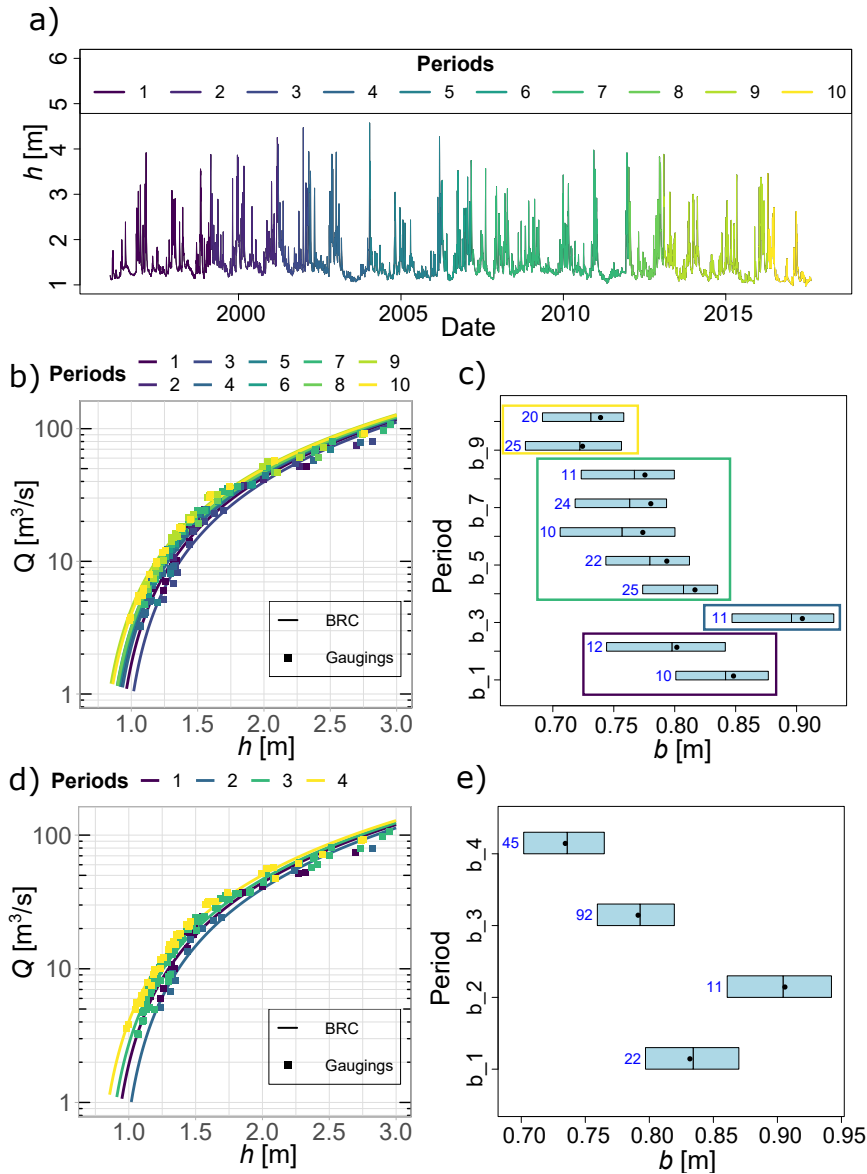


Figure B1: Identification of stable periods at the Ill at Ladhof hydrometric station over the 22-year of data available: a) stage time series of the ten periods defined by $Q > Q_2$ flood events, b) base rating curves (BRC) estimated using Bayesian method for the ten periods and c) distributions of the riverbed level b , and d) BRC estimated using Bayesian method for the four resulting periods and e) distributions of b . Blue numbers refer to the number of gaugings without vegetation used for computing the BRC over the considered period. Colored rectangles in b) highlight the four final periods.

967 station were provided by the DREAL Alsace/Grand-Est. Data were mostly collected by
 968 Daniel Moritz and his colleague Vincent Mossard. We gratefully thank them for their
 969 contribution. The authors would also like to thank Juha Järvelä, Sara Puijalon and El-
 970 lis Penning for the interesting discussions we had in the earlier stages of this work. We
 971 finally want to thank the two anonymous reviewers and Paul A. Carling, associate ed-
 972 itor and editor for their valuable and insightful comments, which have undoubtedly im-
 973 proved this paper.

974 **Competing interests.** The authors declare that they have no conflict of inter-
975 est.

976 **Data availability statement** The data set and the data processing algorithms
977 used in this study are available on request from the authors and are archived in [https://](https://forge.irstea.fr/projects/bam/files)
978 forge.irstea.fr/projects/bam/files (folder name: Perret_VegetationPaper_WRR.zip)..

979 References

- 980 Aberle, J., & Järvelä, J. (2013). Flow resistance of emergent rigid and flexible flood-
981 plain vegetation. *Journal of Hydraulic Research*, 51(1), 33-45.
- 982 Adams, M.-P., Collier, C., Uthicke, S., Ow, Y.-X., Langlois, L., & O'Brien., K.
983 (2017). Model fit versus biological relevance: Evaluating photosynthesis-
984 temperature models for three tropical seagrass species. *Scientific reports*,
985 7(39930), 1-12. doi: 10.1038/srep39930
- 986 Albayrak, I., Nikora, V., Miler, O., & O Hare, M. (2014). Flow-plant interactions at
987 leaf, stem and shoot scales: drag, turbulence, and biomechanics. *Aquatic Sciences*,
988 76(2), 269-294. doi: 10.1007/s00027-013-0335-2
- 989 Arcement, G.-J., & Schneider, V.-R. (1989). Guide for selecting Manning's rough-
990 ness coefficients for natural channels and flood plains. *U.S. Geological Survey Wa-*
991 *ter Supply, Paper 2339*, 1-67.
- 992 Asaeda, T., Trung, V., Manatunge, J., & Bon, T. (2001). Modelling macrophyte -
993 nutrient - phytoplankton interactions in shallow eutrophic lakes and the evalua-
994 tion of environmental impacts. *Ecological Engineering*, 16, 341-357.
- 995 Barnes, H.-H. (1967). Roughness characteristics of natural channels: color pho-
996 tographs and descriptive data for 50 stream channels for which roughness coeffi-
997 cients have been determined. *U.S. Geological Survey Water Supply, Paper 1849*.
- 998 Biggs, H., Nikora, V., Gibbins, C., Fraser, S., Green, D., Papadopoulos, K., & Hicks,
999 D. (2018). Coupling Unmanned Aerial Vehicle (UAV) and hydraulic surveys to
1000 study the geometry and spatial distribution of aquatic macrophytes. *Journal of*
1001 *Ecohydraulics*, 3(1), 45-58. doi: 10.1080/24705357.2018.1466666
- 1002 Brière, J.-F., Pracros, P., Roux, A.-Y.-L., & Pierre, J. (1999). A novel rate model of
1003 temperature-dependent development for arthropods. *Environmental Entomology*,
1004 28, 22-29.
- 1005 Carr, G.-M., Duthie, H.-C., & Taylor, W. (1997). Models of aquatic plant productiv-
1006 ity: a review of the factors that influence growth. *Aquatic Botany*, 59, 195-215.
- 1007 Chow, V.-T. (1959). *Open-channel hydraulics*. McGraw-Hill, NewYork.
- 1008 Coelho, D.-T., & Dale, R.-F. (1980). An energy-crop growth variable and temper-
1009 ature function for predicting maize growth and development: planting to silking.
1010 *Agronomy journal*, 72, 503-510.
- 1011 Coon, W. (1998). Estimation of roughness coefficients for natural stream channels
1012 with vegetated banks. *U.S. Geological Survey Water Supply, Paper 244*, 145.
- 1013 Cowan, W.-L. (1956). Estimating hydraulic roughness coefficients. *Agricultural En-*
1014 *gineering*, 37(7), 473-475.
- 1015 de Langre, E. (2008). Effect of wind on plants. *Annual Review of Fluid Mechanics*,
1016 40, 141-168. doi: 10.1146/annurev.fluid.40.111406.102135
- 1017 Fathi-Maghadam, M., & Kouwen, N. (1997). Nonrigid, nonsubmerged, vegetative
1018 roughness on floodplains. *Journal of Hydraulic Engineering*, 123(1), 51-57. doi:
1019 doi:10.1061/(ASCE)0733-9429(1997)123:1(51)
- 1020 Fisher, K., & Dawson, F. H. (2003). *Reducing uncertainty in river flood conveyance*
1021 *- Roughness review* (Tech. Rep.). London, UK: DEFRA / Environment Agency,
1022 Project W5A-057.
- 1023 Folkard, A.-M. (2011). Vegetated flows in their environmental context: a review.
1024 *Proceedings of the Institution of Civil Engineers - Engineering and Computational*

- 1025 *Mechanics*, 164(1), 3-24.
- 1026 Fovet, O., Belaud, G., Litrico, X., Charpentier, S., Bertrand, C., Dauta, A., &
1027 Hugodot, C. (2010). Modelling periphyton in irrigation canals. *Ecological Mod-*
1028 *elling*, 221, 1153-1161. doi: 10.1016/j.ecolmodel.2010.01.002
- 1029 Green, J. (2005). Comparison of blockage factors in modelling the resistance of
1030 channels containing submerged macrophytes. *Rivers Research and Applications*,
1031 21, 671-686. doi: 10.1002/rra.854
- 1032 Ham, S. F., Wright, J. F., & Berrie, A. D. (1981). Growth and recession of aquatic
1033 macrophytes on an unshaded section of the River Lambourn, England, from 1971
1034 to 1976. *Freshwater Biology*, 11, 381-390.
- 1035 Hicks, D.-M., & Mason, P.-D. (1999). *Roughness characteristics of New Zealand*
1036 *rivers*. NIWA, Christchurch.
- 1037 Hilton, J., O'Hare, M., Bowes, M., & Jones, J. (2006). How green is my river? a new
1038 paradigm of eutrophication in rivers. *Science of the Total Environment*, 365, 66-
1039 83.
- 1040 Horner, I., Renard, B., Le Coz, J., Branger, F., McMillan, H. K., & Pierrefeu, G.
1041 (2018). Impact of stage measurement errors on streamflow uncertainty. *Water*
1042 *Resources Research*, 54(1952-1976).
- 1043 Jalonen, J. (2015). *Hydraulics of vegetated flows: estimating riparian plant drag*
1044 *with a view on laser scanning applications* (PhD Thesis). Aalto University School
1045 of Engineering.
- 1046 Järvelä, J. (2004). Determination of flow resistance caused by non-submerged woody
1047 vegetation. *International Journal of River Basin Management*, 2(1), 61-70. doi:
1048 10.1080/15715124.2004.9635222
- 1049 Johnson, I., & Thornley, J. (1983). Vegetative crop growth model incorporating
1050 leaf area expansion and senescence, and applied to grass. *Plant, Cell and Environ-*
1051 *ment*, 6, 721-729.
- 1052 Kiang, J., Gazoorian, C., McMillan, H., Coxon, G., Le Coz, J., & Westerberg, I.
1053 (2018). A comparison of methods for streamflow uncertainty estimation. *Water*
1054 *Resources Research*, 54, 7149-7176. doi: <https://doi.org/10.1029/2018WR022708>
- 1055 Kouwen, N., & Fathi-Moghadam, M. (2000). Friction factors for coniferous trees
1056 along rivers. *Journal of Hydraulic Engineering*, 126(10), 732-740.
- 1057 Le Coz, J., Renard, B., Bonnifait, L., Branger, F., & Le Boursicaud, R. (2014).
1058 Combining hydraulic knowledge and uncertain gaugings in the estimation of
1059 hydrometric rating curves: A Bayesian approach. *Journal of Hydrology*, 509,
1060 573-587. doi: <https://doi.org/10.1016/j.jhydrol.2013.11.016>
- 1061 Limerinos, J.-T. (1970). Determination of the Manning coefficient from measured
1062 bed roughness in natural channels. *U.S. Geological Survey Water Supply, Paper*
1063 *1898-B*.
- 1064 Luhar, M., & Nepf, H. (2013). From the blade scale to the reach scale: a characteri-
1065 zation of aquatic vegetative drag. *Advances in Water Resources*, 51, 305-316. doi:
1066 10.1016/j.advwatres.2012.02.002
- 1067 Lundquist, J. D., Roche, J. W., Forrester, H., Moore, C., Keenan, E., Perry, G., ...
1068 Dettinger, M. D. (2016). Yosemite hydroclimate network: Distributed stream
1069 and atmospheric data for the tuolumne river watershed and surroundings. *Water*
1070 *Resources Research*, 52, 7478-7489.
- 1071 Mansanarez, V. (2016). *Non-unique stage-discharge relations: Bayesian analysis of*
1072 *complex rating curves and their uncertainties* (PhD Thesis). Université Grenoble
1073 Alpes.
- 1074 Mansanarez, V., Renard, B., Le Coz, J., Lang, M., & Darienzo, M. (2019). Shift
1075 happens! adjusting stage-discharge rating curves to morphological changes at
1076 known times. *Water Resources Research*, 55, 2876-2899. doi: <https://doi.org/10.1029/2018WR023389>
- 1077
1078 McMillan, H., Seibert, J., Petersen-Overleir, A., Lang, M., White, P., & Snelder, T.

- 1079 (2017). How uncertainty analysis of streamflow data can reduce costs and promote
 1080 robust decisions in water management applications. *Water Resources Research*,
 1081 *53*, 5220-5228. doi: <https://doi.org/10.1002/2016WR020328>
- 1082 Meyer-Peter, E., & Müller, R. (1948). Formulas for bed-load transport. In *Proceed-*
 1083 *ings of the 2nd iahr congress* (p. 39-64). Stockholm, Sweden.
- 1084 Morin, J., Leclerc, M., Secretan, Y., & Boudreau, P. (2000). Integrated two-
 1085 dimensional macrophytes-hydrodynamic modeling. *Journal of Hydraulic Research*,
 1086 *38*(3), 163-172. doi: [doi:10.1080/00221680009498334](https://doi.org/10.1080/00221680009498334)
- 1087 Neary, V., Constantinescu, S., Bennett, S., & Diplas, P. (2012). Effects of vegetation
 1088 on turbulence, sediment transport, and stream morphology. *Journal of Hydraulic*
 1089 *Engineering*, *138*(9), 765-776.
- 1090 Nepf, H.-M. (2012). Hydrodynamics of vegetated channels. *Journal of Hydraulic Re-*
 1091 *search*, *50*(3), 262-279.
- 1092 Nikora, V. (2010). Hydrodynamics of aquatic ecosystems: An interface between ecol-
 1093 ogy, biomechanics and environmental fluid mechanics. *River Research and Appli-*
 1094 *cations*, *26*, 367-384. doi: <https://doi.org/10.1002/rra.1291>
- 1095 Olsen, J., McMahon, C.-R., & Hammer, G.-L. (1993). Prediction of sweet maize
 1096 phenology in subtropical environments. *Agronomy journal*, *85*, 410-415.
- 1097 Pasche, E., & Rouvé, G. (1985). Overbank flow with vegetatively roughened flood
 1098 plains. *Journal of Hydraulic Engineering*, *111*(9), 1262-1278.
- 1099 Perret, E., Le Coz, J., & Renard, B. (2020). Estimating time-varying stage-discharge
 1100 relations in rivers with aquatic vegetation. In *10th Conference on Fluvial Hy-*
 1101 *draulics, IAHR-River Flow*. Delft, The Netherland.
- 1102 Petryk, S., & Bosmajian, G. (1975). Analysis of flow through vegetation. *Journal of*
 1103 *Hydraulic Division*, *101*(7), 871-884.
- 1104 Rantz, S. E. (1982). *Measurement and computation of streamflow : Volume 1. Mea-*
 1105 *surement of stage and discharge*. (Tech. Rep.). USGS.
- 1106 Rantz, S. E. (1982). *Measurement and computation of streamflow: Volume 2. Com-*
 1107 *putation of discharge*. (Tech. Rep.). USGS.
- 1108 Renard, B., Garreta, V., & Lang, M. (2006). An application of Bayesian anal-
 1109 ysis and Markov Chain Monte Carlo methods to the estimation of a regional
 1110 trend in annual maxima. *Water Resources Research*, *42*(W12422). doi:
 1111 [http://dx.doi.org/10.1029/2005WR004591?](http://dx.doi.org/10.1029/2005WR004591)
- 1112 Room, P.-M. (1986). Equations relating growth and uptake of nitrogen by salvinia
 1113 molesta to temperature and the availability of nitrogen. *Aquatic Botany*, *24*, 43-
 1114 59.
- 1115 Shields, F.-D., Coulton, K., & Nepf, H. (2017). Representation of vegetation in two-
 1116 dimensional hydrodynamic models. *Journal of Hydraulic Engineering*, *143*(8), 1-9.
 1117 doi: [10.1061/\(ASCE\)HY.1943-7900.0001320](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001320)
- 1118 Smart, G. M., Maurice, M. J., & Walsh, J. M. (2002). Relatively rough flow resis-
 1119 tance equations. *Journal of Hydraulic Engineering*, *128*(6), 568-578.
- 1120 Tollenaar, M., Daynard, T.-B., & Hunter, R.-B. (1979). Effect of temperature on
 1121 rate of leaf appearance and flowering date in maize. *Crop Science*, *19*, 363-366.
- 1122 van der Heide, T., Roijackers, R.-M.-M., van Nes, E.-H., & Peeters, E.-T.-H.-M.-.
 1123 (2006). A simple equation for describing the temperature dependent growth of
 1124 free-floating macrophytes. *Aquatic Botany*, *84*, 171-175.
- 1125 Vargas-Luna, A., Crosato, A., & Uijtewaal, W. (2015). Effects of vegetation on flow
 1126 and sediment transport: comparative analyses and validation of predicting models.
 1127 *Earth Surface Processes and Landforms*, *40*, 157-176. doi: [10.1002/esp.3633](https://doi.org/10.1002/esp.3633)
- 1128 Västilä, K., & Järvelä, J. (2014). Modeling the flow resistance of woody vegeta-
 1129 tion using physically based properties of the foliage and stem. *Water Resources*
 1130 *Research*, *50*, 229-245. doi: [10.1002/2013WR013819](https://doi.org/10.1002/2013WR013819)
- 1131 Västilä, K., & Järvelä, J. (2017). Characterizing natural riparian vegetation for
 1132 modeling of flow and suspended sediment transport. *Journal of Soils and Sedi-*

- 1133 *ments*, 1-17. doi: 10.1007/s11368-017-1776-3
- 1134 Västilä, K., Järvelä, J., & Aberle, J. (2013). Characteristic reference areas for es-
1135 timating flow resistance of natural foliated vegetation. *Journal of Hydrology*, 492,
1136 49-60. doi: <http://dx.doi.org/10.1016/j.jhydrol.2013.04.015>
- 1137 Västilä, K., Järvelä, J., & Koivusalo, H. (2016). Flow-vegetation-sediment interac-
1138 tion in a cohesive compound channel. *Journal of hydraulic Engineering*, 142(1).
- 1139 Vidal, J.-P., Martin, E., Franchistéguy, L., Baillon, M., & Soubeyroux, J.-M. (2010).
1140 A 50-year high-resolution atmospheric reanalysis over France with the Safran sys-
1141 tem. *International journal of climatology*, 30, 1627-1644. doi: 10.1002/joc.2003
- 1142 Vogel, S. (1994). *Life in moving fluids - the physical biology of flow* (P. University,
1143 Ed.). Princeton University Press.
- 1144 Wang, J., & Zhang, Z. (2019). Evaluating riparian vegetation roughness computa-
1145 tion methods integrated within hec-ras. *Journal of Hydraulic Engineering*, 145(6).
1146 doi: 10.1061/(ASCE)HY.1943-7900.0001597
- 1147 Whittaker, P., Wilson, C., Aberle, J., Rauch, H.-P., & Xavier, P. (2013). A drag
1148 force model to incorporate the reconfiguration of full-scale riparian trees under
1149 hydrodynamic loading. *Journal of Hydraulic Research*, 51(5), 569-580.
- 1150 World Meteorological Organization. (2010). *Manual on Stream Gauging. Computa-*
1151 *tion of discharge - Vol. II* (Tech. Rep. No. 1044). WMO.
- 1152 Wu, F., Shen, H., & Chou, Y. (1999). Variation of roughness coefficients for unsub-
1153 merged and submerged vegetation. *Journal of hydraulic Engineering*, 125(9), 934-
1154 942.
- 1155 Yan, W., & Hunt, L.-A. (1999). An equation for modelling the temperature response
1156 of plants using only the cardinal temperatures. *Annals of Botany*, 84, 607-614.
- 1157 Yin, X., Goudriaan, J., Lantinga, E.-A., Vos, J., & Spiertz, H.-J. (2003). A flexible
1158 sigmoid function of determinate growth. *Annals of Botany*, 91, 361-371. doi: 10
1159 .1093/aob/mcg029
- 1160 Yin, X., Kropff, M.-J., McLaren, G., & Visperas, R.-M. (1995). A nonlinear model
1161 for crop development as a function of temperature. *Agricultural and Forest Meteo-*
1162 *rology*, 77, 1-16.