Journal of Hydrology 509 (2014) 573–587

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Combining hydraulic knowledge and uncertain gaugings in the estimation of hydrometric rating curves: A Bayesian approach

J. Le Coz [a,*], B. Renard [a], L. Bonnifait [a,b], F. Branger [a], R. Le Boursicaud [a]

[a] Irstea, UR HHLY, Hydrology-Hydraulics, 5 rue de la Doua CS70077, 69626 Villeurbanne cedex, France
[b] CETE Ile-de-France, 12 rue Teisserenc de Bort, 78197 Trappes cedex, France

ARTICLE INFO

Article history:
Received 6 June 2013
Received in revised form 1 November 2013
Accepted 11 November 2013
Available online 21 November 2013
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Peter F. Rasmussen, Associate Editor

Keywords:
Stage-discharge relations
Rating curves
Hydrometry
Uncertainty analysis
Bayesian inference
Hydraulic controls

SUMMARY

Discharge time series in rivers and streams are usually based on simple stage-discharge relations calibrated using a set of direct stage-discharge measurements called gaugings. Bayesian inference recently emerged as a most promising framework to build such hydrometric rating curves accurately and to estimate the associated uncertainty. In addition to providing the rigorous statistical framework necessary to uncertainty analysis, the main advantage of the Bayesian analysis of rating curves arises from the quantitative assessment of (i) the hydraulic controls that govern the stage-discharge relation, and of (ii) the individual uncertainties of available gaugings, which often differ according to the discharge measurement procedure and the flow conditions. In this paper, we introduce the BaRatin method for the Bayesian analysis of stationary rating curves and we apply it to three typical cases of hydrometric stations with contrasted flow conditions and variable abundance of hydraulic knowledge and gauging data. The results exemplify that the thorough analysis of hydraulic controls and the quantification of gauging uncertainties are required to obtain reliable and physically sound results.

1. Introduction

1.1. Physical basis of stage-discharge relations

Most often, the discharges of water streams are monitored by converting continuous water level records using a stage-discharge relation (e.g., Rantz, 1982; Schmidt, 2002; WMO, 2010; ISO 1100, 2010). Such a hydrometric rating curve is usually calibrated using a set of direct stage-discharge measurements, which are called gaugings. McMillan et al. (2012) provide a comprehensive review of the uncertainty values for gaugings and rating curves that were reported in the literature. Due to technical constraints, the gaugings are often scarce, especially at extremely high or low discharge, and may be affected by large and variable uncertainty, typically 5–20% of the measured discharge. Note that in this document, by default uncertainty is expressed at 95% confidence level, which corresponds to the convention most often used in hydrometry, as recommended by the Hydrometry Uncertainty Guide (HUG, ISO/TS, 2007). Stage-discharge relations often have to be extrapolated beyond the range of available gaugings, which may produce systematic errors as high as 100% or even more, resulting in wide credibility intervals associated with flood quantile estimates (Lang et al., 2010) and obviously also with drought discharge values. According to the expertise of the hydrometer and to available information, establishing and updating rating curves involve analyzing the hydraulic conditions at the study site. Managing rating curves and assessing their uncertainty hence remain difficult tasks which are not fully standardized yet.

A simple rating curve is a monotonic function relating the discharge, Q, to the water level, h, which is assumed to prevail at a cross-section of the flow in the reference hydraulic conditions. This reference hydraulic regime is seldom explicitly defined. Most often, the reference regime refers to the hydraulic conditions which usually prevail in the considered flow (Schmidt, 2002), i.e. steady flow (negligible transient effects) and usual hydraulic controls (e.g. no variable backwater effects, no change in channel roughness or in the geometry of the cross-section). Nevertheless, any time the flow deviates from the reference regime, significant errors in the discharge estimate may appear. Such errors must be distinguished from the errors directly related to the reference stage-discharge relation.

When the reference regime is permanently changed, e.g., in case of changed channel geometry after a flood, the rating curve is no

* Corresponding author. Tel.: +33 472208786; fax: +33 478477875.
E-mail addresses: jerome.lecoz@irstea.fr (J. Le Coz), benjamin.renard@irstea.fr (B. Renard), laurent.bonnifait@developpement-durable.gouv.fr (L. Bonnifait), flora.branger@irstea.fr (F. Branger), raphael.le-boursicaud@irstea.fr (R. Le Boursicaud).

0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.11.016

longer valid, and a new one must be established corresponding to the new reference regime. Temporary changes of the reference regime may occur, due for instance to seasonal vegetation growth (WMO, 2010), variation of the downstream boundary condition (Petersen-Overleir and Reitan, 2009a), hysteresis due to transient flow effects (Le Coz et al., 2012), or dune-flat bed transitions during floods (Shimizu et al., 2009). Non-stationarity in the stage-discharge relation may impose the use of different rating curves according to time periods, or even of rating curves with time-varying parameters.

The physical characteristics of the channel which govern the relation between stage h and discharge Q at a section constitute the hydraulic control. Basically, two kinds of hydraulic controls may be distinguished: section vs. channel controls (WMO, 2010; ISO 1100, 2010). When section control holds, the flow is mainly regulated by the geometry of a cross-section or a hydraulic work where the flow becomes critical due to a water fall (e.g., riffle, weir, sill) or due to a constriction (e.g., Venturi, Parshall flumes). When channel control holds, usually for medium to high flows, the flow is mainly regulated by the geometry and roughness of a portion of the channel. In non-uniform flow cases, the downstream boundary condition may also influence the stage-discharge relation (backwater effects).

Depending on the discharge, hydraulic controls may change, with some controls disappearing and others appearing. Typically, the section control exerted by a sill will disappear when water stage exceeds a given level of submersion or when the backwater effect is repelled downstream of the station. Fig. 1 shows how the transition between different section and channel controls may occur at a typical hydrometric station without an artificial control. With increasing discharge, the stage at the station is successively controlled by a small natural riffle, then by a higher one, then by the main channel only, and eventually by the main channel and the floodplain. More complex hydraulic controls may be activated successively or simultaneously.

Based on simplifications acceptable for hydrometry purposes, the usual hydraulic formulas for uniform channel controls and for conventional section controls can be expressed as the following power function (ISO 1100, 2010; WMO, 2010):

$$Q = a\ (h - b)^c \tag{1}$$

where Q is the discharge, h ($h \geqslant b$) is the water level relative to a given datum (usually at the staff gauge), a is a scaling coefficient related to the characteristics of the control section or channel, b is a cease-to-flow reference level, and c is an exponent related to the type of hydraulic control.

Hydraulic theory provides nominal values for c such as 5/3 for a wide, uniform, rectangular channel control (derived from the Manning–Strickler equation), 3/2 for a rectangular weir control, 5/2 for a triangular weir control (derived from the critical flow equation). The value of the hydraulic exponent may also be determined experimentally for some control structures: $c \approx 1.55–1.60$ for commercial Parshall flumes, typically. The value of the exponent, c, may show some variability around the nominal value (say, ± 0.1) due to complex cross-sectional geometry or overbank flow processes. However, it is crucial to keep realistic values for c to allow for the physical derivation of coefficient a values, following the hydraulic formulas. Indeed, different values for the (a, c) couple with no physical meaning may better fit the observations, but yield very poor predictions in extrapolation.

1.2. Uncertainty analysis of stage-discharge relations

The methodology for assessing the uncertainty associated with stage-discharge relations is an important open scientific issue which received some attention in the recent literature. A first approach based mainly on hydraulic analysis of the stage-discharge relation can produce a valuable quantification of errors, since the physical basis of such errors is explicitly defined (Schmidt, 2002). Sensitivity analysis of the parameters of a hydraulic model provides a realistic and site-specific estimation of error bounds (Di Baldassarre and Montanari, 2009; Lang et al., 2010; Neppel et al., 2010; Di Baldassarre and Claps, 2011; Domeneghetti et al., 2012). However, translating these worst-case errors into probabilistic distributions from which uncertainty may be derived and combined is usually not a straightforward task.

The second family of approaches is based on the statistical analysis of gaugings. The work by Venetis (1970) seems to be the first published statistically sound method for computing the uncertainty associated with rating curves, based on nonlinear regression of a single segment power function (cf. Eq. (1)). In the same way, Dymond and Christian (1982) suggested a new method accounting not only for rating curve error and stage error, but also for errors caused by ignoring all physical parameters other than stage. In works by Herschy (1999); Clarke (1999); Clarke et al. (2000), the rating curve uncertainty analysis is based on the residual variance from regression of a power function like Eq. (1), and possibly on the standard error of the parameter estimates.

Petersen-Overleir (2004) proposed a heteroscedastic model to take into account the usually observed heteroscedasticity of stage-discharge relations, which is not captured by classical non-linear least squares methods. The same author extended the non-linear regression approach to more complex stage-discharge relation cases, including multi-segment (or piecewise) power functions (Petersen-Overleir and Reitan, 2005), hysteresis (Petersen-Overleir, 2006), and overbank flow in rivers with floodplains (Petersen-Overleir, 2008). While this seminal work constituted a significant advance in stage-discharge analysis, the physical basis of the assumptions seems too loose since unrealistic hydraulic exponents ($> 3, > 4$) were sometimes obtained.

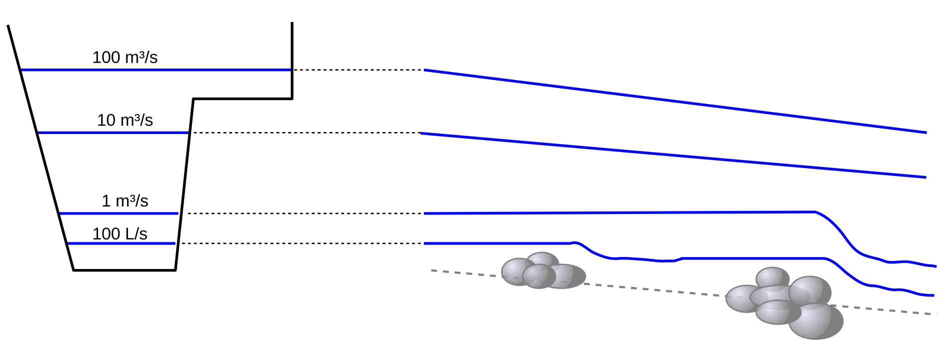

Fig. 1. Illustration of the succession of section and channel hydraulic controls for a typical hydrometric station without an artificial control: bottom and water lines for different discharge values (right); the water levels are plotted against the river cross-section at the station (left).