Environmental Modelling & Software 55 (2014) 107–119

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

Development of discharge-stage curves affected by hysteresis using time varying models, model trees and neural networks

Vincent Wolfs*, Patrick Willems

KU Leuven – University of Leuven, Department of Civil Engineering, Hydraulics Section, Kasteelpark Arenberg 40, 3001 Leuven, Belgium

ARTICLE INFO

Article history:
Received 6 June 2013
Received in revised form
10 January 2014
Accepted 11 January 2014
Available online 7 February 2014

Keywords:
Hysteresis
Model tree
Neural network
Rating curve
Regression
State dependent parameter analysis

ABSTRACT

Flow data forms the base on which much of the edifice of water management is raised. However, flow measurements are expensive and difficult to conduct. Therefore, the more accessible stage measurements are employed in combination with stage–discharge relationships. Setting up such relationships is often infeasible using traditional regression techniques. Two case studies are examined that show hystereses using various approaches, namely (1) single rating curves, (2) rating curves with dynamic correction, (3) artificial neural networks (ANN) and (4) M5′ model trees. All methods outperform the traditional rating curve. The presented approach that uses a dynamically corrected rating curve delivers accurate results and allows for physical interpretation. The ANNs mimic the calibration data precisely, but suffer from overfitting when a small amount of data is applied for training. The rarely used M5′ model tree's architecture is easier to interpret than that of neural networks and delivers more accurate results.

1. Introduction

Rating curves play an essential role in hydrology. It is common practice to obtain discharge estimates using stage measurements in combination with river stage–discharge relationships. These stream flow data form, in turn, a key source of information in virtually all hydrological applications, such as calibration and validation of rainfall-runoff models, boundary conditions of flood inundation models, stochastic modelling of river flow time-series, river sediment studies, etc. Another application is the use of conceptual models that try to emulate results of detailed hydrodynamic models. They become more widely used in applications where calculation time is the limiting factor, such as long term simulations, uncertainty analyses and real time control (e.g. De Vleeschauwer et al., 2013; Wolfs and Willems, 2013). Simplified or conceptual river models often alter the flow at a specific location along the river into a flow at a more downstream position using a transfer function (e.g. Romanowicz et al., 2008). This flow can then be transferred in water levels at one or more locations along the river network. In that case, the stage–discharge relationship is utilized in the reverse way than described above for the common use of these relationships.

Modelling stage–discharge relationships (also called rating curves) is difficult due to the large number of influencing factors. Boyer (1964) composed a conclusive list of factors affecting a rating curve:

- Backwater effects – changes in the downstream conditions such as the effects of control constructions and confluence of downstream tributaries. Note that constant backwater, as caused by rigid section controls for instance, will not affect the simple stage–discharge relation detrimentally (Herschy, 1995);
- Unsteadiness of the river flow;
- Variable channel storage – overflow streams onto floodplains during high discharges, thereby resulting in different surface slopes and unsteadiness effects;
- Channel modifications due to dredging, construction works, etc;
- Sediment transport – growing and receding bed forms during floods alter bed roughness, which causes looped rating curves (see e.g. Simons and Richardson, 1962). In addition, sedimentation and erosion can change the cross-section and bed slope of the channel, hereby also affecting the rating curve;
- Vegetation – effect on the roughness and hence the stage–discharge relationship;
- Ice.

These factors can result in rating curves with looped trajectories, denoted as hysteretic behaviour. During flood events for instance,

---

* Corresponding author. Tel.: +32 16 321655; fax: +32 16 321989.
E-mail address: vincent.wolfs@bwk.kuleuven.be (V. Wolfs).

1364-8152/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.envsoft.2014.01.021

the water surface slope will depend on whether the discharge is increasing or decreasing. As the discharge increases, the surface slope becomes greater than the slope for steady flow at the same stage. Hence, the discharge in the river is greater than the steady rating curve would suggest. This is also illustrated in Fig. 1: a measured stage S_{measured} yields via a univocal rating curve a discharge value Q_{calc} that differs from the real values during a flood event ($Q1$ and $Q2$ in the rising and falling limbs respectively). Note that the size and form of a hysteresis is different for each flood (Fread, 1975). More details on the physical background of hystereses can be found in literature (e.g. Chow, 1959; Henderson, 1966; Fenton and Keller, 2001).

Since hystereses can have a significant influence on the rating curve, it is essential to include this behaviour in the mathematical models describing the stage–discharge relationship. Logically, all hydrologic investigations and practical operations that rely on rating curves can be affected by these hystereses. During highly dynamic floods for instance, the peak discharge could be significantly under- or overestimated. Di Baldassarre and Montanari (2009) showed in a numerical study on the River Po that the errors in discharge estimation when significant flood waves occur may exceed 15% when a flow rating curve is employed that does not take hysteresis into account. Moreover, the arrival time of the peak discharge could be in error and hence influence flood warning predictions, since maximum stage and maximum discharge do not necessarily coincide (Dottori et al., 2009; Fenton and Keller, 2001). Similarly, the calibration of unsteady flow models can be distorted because of incorrect discharge estimates obtained via univocal rating curves.

Numerous approaches can be found in literature that deal with rating curves, each with its own advantages and limitations. The simplest and at the same time most commonly used approach is the single (steady) curve methodology. This approach links the measured water level univocally to a discharge, thereby neglecting effects such as unsteadiness and backwater. The widely known rising and falling curves approach is highly similar to the single rating curve. Prior to the curve estimation, the data set is divided into two groups. One group represents the data for the rising branch, the other the data of the falling branch. By calibrating different curves to both data sets, hysteretic behaviour can be captured to some extent in contrast to the single rating curve approach. However in practice, the classification into the two sets is subjective and not always straightforward. Secondly, discharge estimates obtained via this approach can show sudden drops and rises when shifting between the rising and falling curves (Tawfik et al., 1997). To overcome this issue, most standard hydrometric literature (e.g. Boyer, 1964; Mander, 1978; Herschy, 1995; ISO, 1998) recommends the use of Jones' formula (Jones, 1916) to correct the single rating curve when unsteadiness effects are significant. This approach has been the subject of many investigations since its publication. Numerous elaborations and variations of the Jones' formula exist, each valid under different assumptions (e.g. Henderson, 1966; Di Silvio, 1969; Gergov, 1971; Birkhead and James, 1998; Fenton and Keller, 2001; Perumal et al., 2004; Petersen-Øverleir, 2006). However, these methods focus on unsteadiness effects solely, thereby disregarding variable backwater effects. To account for backwater effects, techniques involving two stage gauging stations at adjacent cross-sections were developed (Fenton and Keller, 2001; Arico et al., 2008; Dottori et al., 2009). However, the application of formulas using simultaneous water level measurements was criticised for lowland meandering rivers, where the water level gradient can be smaller than the measuring accuracy of the gauge (Koussis, 2010; Dottori and Todini, 2010). To overcome the practical concerns and limitations own to the twin level gauges approaches, Hidayat et al. (2011) proposed the use of velocity measurements in combination with only one stage measurement.

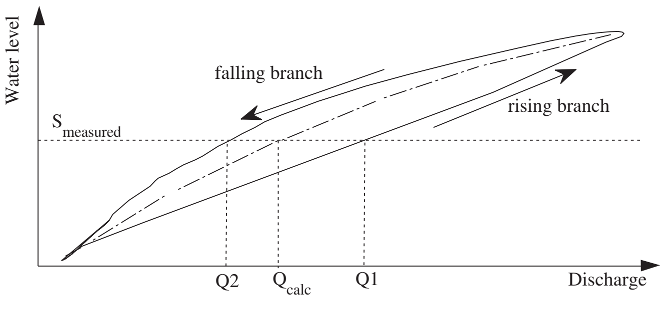

Fig. 1. Discharge-stage data couples affected by unsteadiness effects showing a looped trajectory (full line) versus the steady rating curve (dash dotted line).

Aside from the more theoretical methods originating from the dynamic flow equations, soft computing techniques have recently been applied for the modelling of rating curves. A significant advantage of these approaches is that they do not impose a rigid model structure for transforming the input into an output. The performance of different types of artificial neural networks and the more complex adaptive neuro fuzzy inference systems were examined and compared in multiple earlier studies that focus on rating curves (e.g. Deka and Chandramouli, 2003; Lohani et al., 2006). However, their "black box" nature and proneness to overfitting are two major disadvantages to be considered when applying these approaches, despite the satisfactory results they yielded in the reported case studies.

This paper focuses on several methods for discharge estimation based on a time-series of stage data, while allowing for the hysteretic behaviour of the relationship. Since in practice commonly only stage–discharge couples are available to set up rating curves, this research concentrates on the use of rating curves that rely solely on this information. Hence, approaches are investigated that try to emulate looped rating curves when twin stage or velocity measurements are unavailable. To restrain the problem's complexity and obviate measurement uncertainties, only data is used from numerical simulations with models that solve the complete de Saint-Venant equations. Two fundamentally different case studies are examined to assess the performance of the selected modelling methodologies. The stage and discharge data employed for the first case study are gathered at a specific location of a detailed InfoWorks RS model where variable channel storage, caused by modelled floodplains, and significant backwater result in a large looped rating curve. The data for the second case study comes from a detailed MIKE11 model. In contrast to the first case study, this rating curve is characterized by numerous smaller hystereses, caused by tidal influences downstream. This location is also affected by nearby floodplains during floods. Other influencing factors such as vegetation, sedimentation and erosion are not incorporated in the detailed hydrodynamic models and are therefore not taken into account in this research.

First, the performance of the simple and most commonly used single rating curve approach is evaluated. Next, a variant of the Jones' formula is presented, in which the conventional rating curve is corrected by a time varying parameter to acquire greater flexibility. This should allow the model to account for the unsteadiness, backwater and variable channel storage effects. A state dependent parameter (SDP) algorithm is used for the non-parametric identification of the dynamic parameter. In addition, two expert systems are employed, namely the rarely used M5′ model tree and artificial neural networks.