Computers & Geosciences 62 (2014) 160–167

Contents lists available at ScienceDirect

Computers & Geosciences

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

Hydrodynamic model calibration from pattern recognition of non-orthorectified terrestrial photographs

N. Pasquale [a,c], P. Perona [a,*], A. Wombacher [b], P. Burlando [c]

[a] Group AHEAD, Institute of Environmental Engineering, EPFL – ENAC, Lausanne, Switzerland
[b] Database Group, Faculty of Computer Science, University of Twente, Netherlands
[c] Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland

ARTICLE INFO

Article history:
Received 3 January 2013
Received in revised form
11 June 2013
Accepted 19 June 2013
Available online 9 July 2013

Keywords:
Model calibration
Pattern recognition
Remote sensing
Non-orthorectified images
River restoration

ABSTRACT

This paper presents a remote sensing technique for calibrating hydrodynamics models, which is particularly useful when access to the riverbed for a direct measure of flow variables may be precluded. The proposed technique uses terrestrial photography and automatic pattern recognition analysis together with digital mapping and does not require image ortho-rectification. Compared to others invasive or remote sensing calibration, this method is relatively cheap and can be repeated over time, thus allowing calibration over multiple flow rates . We applied this technique to a sequence of high-resolution photographs of the restored reach of the river Thur, near Niederneunforn, Switzerland.

In order to calibrate the roughness coefficient, the actual exposed areas of the gravel bar are first computed using the pattern recognition algorithm, and then compared to the ones obtained from numerical hydrodynamic simulations over the entire range of observed flows. Analysis of the minimum error between the observed and the computed exposed areas show that the optimum roughness coefficient is discharge dependent; particularly it decreases as flow rate increases, as expected. The study is completed with an analysis of the root mean square error (RMSE) and mean absolute error (MEA), which allow finding the best fitting roughness coefficient that can be used over a wide range of flow rates, including large floods.

1. Introduction

The need for hydraulic simulations of river systems is important to explore the ecological role of low flows (e.g. Diez-Hernandez, 2008), to verify the inundation hazard in the floodplain at intermediate flows (e.g. Girard et al., 2010), as well as the hazard and the impact of flood waves (e.g. Junk et al., 1989, Di Baldassarre et al., 2009) and how to mitigate them (e.g. Bernardara et al., 2010).

The reliability of numerical hydraulic models depends on several factors and among them on how calibration is performed (e.g., Chow, 1973; Aronica, 1998; Horritt, 2004) ideally would require the use of flow-dependent roughness coefficients in order to adequately account for the role of submergence. However, the ability of finding a single roughness coefficient that works over multiple discharges is also important because it simplifies numerical operations. Recently, many authors have investigated the use of automatic techniques for calibrating hydrodynamic models. Such techniques are also often implemented for watershed models (e.g., Fabio et al., 2010).

Calibration methods can be classified in two main groups: traditional methods relying on field measurements (e.g., water depth, velocity and flooded area), and techniques based on remote sensing imagery. Both methods are based on an output error criterion, used to determine river bed roughness parameters.

Traditional methods (e.g., Beker and Yeh, 1972; Fread and Smith, 1978; Wasantha Lal, 1995; and Wohl, 1998), although very effective and still largely used to calibrate hydrodynamic models, are expensive, time consuming and often not practical. First, such measures represent only discrete information of the flow conditions for selected sections. Therefore, an accurate calibration requires as many observations as possible. In order to be representative of the flow conditions, the number of measures should increases in case of complex river sections such as braided rivers. Second, measuring flow depth or water surface elevation may be not practical, especially during high flow conditions, when the access to the river is difficult or even precluded for safety reasons.

More recently, non-invasive techniques based on remote sensing have tackled the problem by using aerial and satellite pictures. In recent studies, hydrodynamic models were calibrated by using either topographic information obtained from airborne laser altimetry (e.g., Cobby et al., 2001; Castellarin et al., 2009),

* Corresponding author. Tel.: +41 216933803
E-mail addresses: pasquale@ifu.baug.ethz.ch (N. Pasquale), paolo.perona@epfl.ch (P. Perona).

0098-3004/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cageo.2013.06.014

from satellite synthetic aperture radar (SAR) sensors (e.g., Horritt et al., 2007), or from inundation maps (e.g, Dung et al., 2011). However, inundation maps generated from a single observation often produce uncertain prediction (Aronica, 1998; Romanowicz and Beven, 1998, 2003; Aronica et al., 2002; Hall et al., 2005; Pappenberger et al., 2005). The use of aerial georeferenced images is another popular non-invasive technique, which usually relies on just one shot for economic reasons. Hence, no information about varying flow condition is available. Forzieri et al. (2010) calibrated a 1-D numerical hydraulic model on the basis of Quickbird images of a river reach riparian area and LIDAR data, showing the effect of different type of vegetation classes and patterns on the hydraulic roughness parameter. Other works combined velocity measurement using LS-PIV (e.g., Muste et al., 2008; Hauet et al., 2008, 2009; Jodeau et al., 2008; LeCoz et al., 2010), and ortho-rectification of ground-based images (often with very flat shooting angle) using photogrammetric equations in order to link reference points of known coordinates in both image and real world systems.

In order to have a reliable control of the calibration process, field measurements, at different spatial and time scales, are always recommended. Field work and remote sensing techniques are two methodologies that efficiently complete each other in field scale numerical hydrodynamic modeling studies.

This study addresses a terrestrial photography technique, which uses low cost digital images of the investigated river reach and obtains from them flow rate versus inundated area relationship. By comparing the simulation of the inundated area to that visible in the pictures taken at a known flow rate, the calibration of the riverbed roughness, expressed as flow-dependent Manning's roughness coefficient (e.g., Aronica, 1998) is performed. Moreover, an error statistical analysis allows highlighting a single roughness coefficient that can be used over a wide range of flow rates. This method is not expensive since the photographs used for the calibration are taken from a high resolution, but common digital camera. Moreover, the fact that no image orthorectification is needed, offers a new perspective of calibration and validation of 2-D numerical hydraulic models, which can be applied to several flow conditions, including flood events.

2. Material and methods

2.1. Study site and monitoring devices

The Thur is a perennial river in the north-eastern part of Switzerland (Fig. 1a) characterized by a nivo-pluvial hydrological regime. The catchment area (Fig. 1b) is about 1750 km^2 and the river has a length of about 127 km. It is the longest river in Switzerland that flows continuously without any regulation by artificial reservoirs or natural lakes (Pasquale et al., 2011).

The hydrologic regime of the Thur shows the presence of rapid floods particularly during springtime and autumn, when flood pulses are generated as a combination of snow melt and intense precipitation. Discharge may increase dramatically within a few hours and trig both bed load and suspended sediment transport. The mean annual discharge is 47 m^3/s. Observed low flows can be as low as 2.2 m^3/s. Flows with return period of 2, 10 and 100 years, at the gauging station located 15 km downstream the restored reach, are estimated respectively 570 m^3/s, 820 m^3/s and 1070 m^3/s[1] .

The Thur River was channelized in the past century to improve flood protection, to increase agriculture areas and to reduce spreading of disease. Since the '90 s several corrections equally promoted river restoration and flood protection measures. In 2002, a 2 km long reach near Niederneunforn was modified by removing lateral bank protections (Fig. 1c). As a consequence, an active alternate bar system developed as the river locally widened (Pasquale, 2012). The mean river bed slope in the non-restored reach is in the order of 0.16%. Fig. 1d shows an aerial view of the restored reach in 2009, and two representative cross section of the restored reach (Fig. 1e, f) to compare with a regular section of the straight channel upstream (Fig. 1g). River bathymetry is manually measured along river cross sections located at maximum 25 m distance to each other and one point each 50 cm approximately. High resolution Digital Terrain Model (DTM) are also produced from LIDAR flights once a year under autumn low flow conditions. The original planimetric accuracy of the DTM is ± 5 cm while the vertical precision is in the order of ± 10 cm.

In order to produce a continuous time series of terrestrial photographs of the bar shown in Fig. 1d, we installed one digital camera (NIKON D300) within a box on the top of a monitoring tower located 16 m above the levee level on the left side of the river (Fig. 1d, see also Pasquale et al., 2011). The digital camera is connected to a remote computer, from which it is possible to change the shooting frequency in order to better capture the evolution of floods events . Three representative photographs are shown in Fig. 2a, b, c. Such images show that only few flexible vegetation spots colonize the emerging bedforms, thus not contributing too much to the equivalent mean riverbed roughness.

Two gauging stations located few kilometers upstream and downstream of the restored reach record hourly discharge. Discharge data as well as rating curves, topographic information of the measuring site as well as hydrological data are also available via the Federal Office for the Environment (FOEN) webpage (http://www.hydrodaten.admin.ch/en/2044.html).

In order to characterize the grain size distribution of river bed of the restored reach, analyses of the grain size distribution were carried out in 2009. Results, also published by Pasquale et al. (2011) show a strong vertical sorting with higher percent of coarse sediment on the bedform surface (Fig. 3). Moreover, also in accordance with other experimental observations (Lisle et al., 1991; Diplas and Parker, 1992; Lisle and Madej, 1992 and Ashworth et al., 1992), the island is characterized by a longitudinal sorting. From coarse particle deposition upstream (d_{50}=1.0–5.0 cm) we move to fine sand deposition downstream (d_{50}=0.2 cm), where stratification also is not anymore evident (Pasquale et al., 2011).

2.2. Numerical hydrodynamic model

We used the freely available 2-D numerical hydrodynamic model BASEMENT (Faeh et al, 2010) developed at ETH Zurich (http://www.basement.ethz.ch/) which numerically integrates the shallow water equations using the finite volume method, and has extensively been tested for scientific and professional purposes (Beffa and Cornell, 2001a, b; Schäppi et al., 2010; Schneider et al., 2011; Pasquale et al., 2011, 2012; Pasquale, 2012).

Simulations were run on an unstructured irregular mesh built on the yearly recorded DTM, and corrected to include actual river cross sections as described by Schäppi et al. (2010). Recorded hourly discharge data were used as input together with suitable boundary and initial conditions (Pasquale et al., 2011; Pasquale, 2012).

Flow dynamics is modeled using the shallow water equations approximation:

$$\frac{\partial h}{\partial t}+\frac{\partial(\overline{u}h)}{\partial x}+\frac{\partial(\overline{v}h)}{\partial y}=0 \tag{1a}$$

[1] Federal Office for the Environment, http://www.hydrodaten.admin.ch/en/2044.html.