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Using unsteady-state water level data to estimate channel roughness and discharge hydrograph

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ABSTRACT

A novel methodology for simultaneous discharge and channel roughness estimation is developed and applied to data sets available at three experimental sites. The methodology is based on the synchronous measurement of water level data in two river sections far some kilometers from each other, as well as on the use of a diffusive flow routing solver and does not require any direct velocity measurement. The methodology is first analyzed for the simplest case of a channel with a large slope, where the kinematic assumption holds. A sensitivity and a model error analysis are carried out in this hypothesis in order to show the stability of the results with respect to the error in the input parameters in the case of homogeneous roughness and to analyze the effect of unknown roughness heterogeneity on the estimated discharges. The methodology is then extended to the more general case of channels with mild slope and validated using field data previously collected in three Italian rivers: the Arno (in Tuscany), the Tiber (in Latium) and the Vallo di Diana, a small tributary of the Tanagro river (in Southern Italy). The performance of the proposed algorithm has been investigated according to three performance criteria estimating the quality of the match between the measured and the computed stage and discharge hydrographs. Results of the field tests can be considered good, despite the uncertainties of the field data and of the measured values.

1. Introduction

Direct measurement of discharge in rivers is traditionally obtained through spatial integration of measured local velocities. The velocity values can be obtained with instruments like mechanical or electromagnetic probes, in full contact with the water at the measured point. More recently, the all velocity profile along a given radius starting from the instrument transducer can be obtained from Acoustic Doppler Current Profilers (ADCPs) [14,17,18,26], measuring the Doppler shift of the backscattered acoustic signal reflected by the solid particles moving within the stream flow. These and also other instruments fully immerged in the water are easily subject to damage and usually require direct personnel assistance.

The Large Scale Particle Image Velocity (LSPIV) is used to get a measurement of the 2D plane surface velocity field, applying image analysis to two subsequent natural images of the water surface around a given section [12]. Further information and analysis is obviously required in order to estimate the velocities at different depths from the water surface.

Because of the abovementioned difficulties for direct discharge measurements, gauged sections in natural rivers and artificial channels are usually equipped with water level sensors and the measured water levels are related to the discharges by means of so-called stage–discharge (SD) relation. This relation assumes a one-to-one relationship between water depth and discharge, an hypothesis that is strictly true only according to the kinematic assumption. This assumption holds in many gauged sections, located upstream of the urbanized areas; in this case the error in the discharge estimation, for given water depth, is a few percent units.

In spite of this, the use of the SD relation has several drawbacks. The SD is difficult to compute, because for almost all natural rivers it requires direct velocity measurements. The hydraulic resistance and the geometry sections are subject to frequent changes, due to erosion/deposition processes, as well as to seasonal vegetational changes [4,8]; this implies the need for a frequent reconstruction of the SD relation. Most importantly, direct velocity measurement is very unlikely to occur during significant hydrological events. For almost all the available SD relations, the higher stage–discharge points are obtained via simple extrapolation of real measured values.

To partially cope with this difficulty, the use of two water level sensors located in two different river sections has been proposed since about ten years ago. Most of the authors have proposed more or less simplified models to relate directly the downstream rating curve with the measured stage hydrograph in both sections and

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Nomenclature

A	flow cross-section, m^2	S_0	bottom slope, –
c	wave celerity, m/s	S_f	friction slope, –
C_H	covariance matrix	S_p	likelihood function
E	expected value	x	spatial coordinate, m
g	gravitational acceleration, m/s^2	t	time, s
h	water depth, m	σ_h	measurement error variance for the maximum water depths
L	free surface width, m	σ_c	measurement error variance for the maximum celerity
n	Manning friction coefficient, $s/m^{1/3}$	Σ_p	covariance matrix
q	flow discharge m^3/s		
$\Re$	hydraulic radius, m		

the upstream rating curve. Moramarco et al. [16] and Tayfur and Moramarco [27] use a "black box" model, including a set of parameters that have to be calibrated using known rating curves. The advantage of using a synthetic model is that the channel geometry does not have to be known. On the other hand, the use of such models requires the calibration of several parameters, with a potential error that can be limited only by using several events for calibration [7].

Birkhead and James [5] use the Muskingum algorithm to route a measured rating curve up to the downstream section; the use of the classical Muskingum algorithm, with respect to other diffusive or complete dynamic numerical models, simplifies the computation and avoids the need to specify the downstream boundary condition. Franchini and Ravagnani [11] use a diffusive model adopting a more general numerical scheme than the Muskingum algorithm, including two unknown parameters that have to be calibrated using known rating curves.

Todini in [3] uses two gauged sections to estimate both the water depth and the water level gradient and to compute the related discharge according to the zero local inertia assumption. The distance between the sections must be large enough to allow robust water level gradient estimation, but also has to be short enough to assume negligible lateral inflows between the two sections.

All the abovementioned algorithms require knowledge of at least one directly measured discharge for the calibration of the model parameters. The need for direct velocity measurements, for discharge measurement or stage–discharge relation reconstruction, derives basically from the quasi-stationarity hypothesis. If stationarity occurs, a single water level profile does not correspond to a single flow rate, as it is also a function of the channel roughness. This implies that water level data alone are not enough for discharge measurement.

In reality, the peak flows associated with even small time return periods are, in most western country climates, associated with quite unsteady discharge and stage hydrographs. In recent papers Perumal et al. [22], as well as Aricò et al. [1,3], applied their flow routing algorithms to directly relate the upstream stage hydrograph with the downstream rating curve, using the measured downstream stage hydrograph for the model calibration. The algorithm of Perumal et al. [22] deals with the case of a prismatic channel with simple cross-section geometry and constant bed slope. The algorithm is, like all the previous ones, "diffusive" in the sense that it includes the water depth gradient terms in the momentum equation but adopts a Muskingum numerical scheme. This results in the lack of a downstream boundary condition, which prevents the application of the methodology in the case of subcritical flow and occurring downstream perturbations.

The present paper is aimed to (1) assess the identifiability of the problem solved by Perumal et al. [22] and Aricò et al. [1,3] in the context of a roughness calibration problem, (2) show the advantages of using an hydraulic diffusive flow routing model in the context of the proposed calibration procedure, (3) show the application of a similar procedure for the roughness estimation using three water level transducers in the case of subcritical flow and an occurring strong downstream perturbation. The presentation is organized as follows.

In Section 2 the discharge and the channel roughness estimation are carried out according to the kinematic assumption, i.e. assuming both the inertia and the water depth gradient in the momentum equation to be negligible. In this case it is possible to get an estimation of the roughness coefficient and the rating curve by solving only a simple algebraic system. In the same section, a sensitivity analysis is carried out to evaluate the sensitivity of the sought after parameters (roughness coefficient and peak flow value) with respect to the error in the input data (stage hydrographs). In an other subsection, the effect of more general model errors, mainly the missing homogeneity of the roughness coefficient inside the channel, is investigated by means of numerical tests on synthetic examples.

In Section 3 the final procedure is presented, as further applied to the field tests in the next section. The use of an hydraulic diffusive model, with respect to more general complete models, is motivated and the chosen DORA numerical scheme is briefly presented. The same model error analysis previously carried out in Section 2 is repeated for the diffusive case. The likelihood criterion used for the roughness coefficient calibration is presented and motivated.

In Section 4 the application of the procedure to three field tests is presented. Field tests include comparison of the numerical results with historical discharge and water depth data available in the Tiber and Arno rivers (in Central Italy), as well as in a small tributary of the Tanagro river (in Southern Italy).

In Section 5 the idea of combining direct discharge estimation, based on velocity measurements, with the use of a diffusive flow routing code is finally presented and motivated with the results of the field tests described in the previous section.

2. Discharge and channel roughness estimation in rivers with large bed slope

Saint–Venant (SV) equations (or shallow water equations) are commonly applied for the simulation of unsteady shallow water flows [25]. The 1D SV equations in a channel with non-prismatic section can be written in the following form (see for example [2]):

$$\frac{\partial A}{\partial t}+\frac{\partial q}{\partial x}=0, \tag{1}$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{q^2}{A}\right)+gA\frac{\partial h}{\partial x}+gA(S_f-S_0)=0, \tag{2}$$

where x is the flow direction, t is the time, g is the gravitational acceleration, h is the water depth, A is the flow cross-section, q is