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DISCHARGE ESTIMATION IN NATURAL CHANNELS WITH SIGNIFICANT LATERAL INFLOW

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ABSTRACT

The indirect measurement technique for discharge estimation, based on water level data analysis in two different river sections, is extended to the case of existing significant tributary flow between the two sections. The methodology is based on the calibration of a numerical flow routing algorithm, solving the Saint-Venant equations in diffusive form along the main channel between the two measurement sections. The first calibration parameter is the average Manning's roughness coefficient holding in the main channel, the other ones are relative to the rating curve of each tributary channel, estimated per unit roughness coefficient and per unit slope immediately before the junction of the tributary with the main channel. The new methodology is tested against different flood events observed along one gauged river reach: the Alzette river basin, in Luxembourg. The applied MAST hydraulic model solves the diffusive wave equations using the observed stage hydrograph at the upstream section as boundary condition. The observed stage hydrograph at the downstream section is used as benchmark function for the computation of the objective function to be minimized trough calibration.
Field tests include comparison of the numerical results with historical discharge and water depth data available in the Alzette river.

Keywords: Discharge estimation, lateral inflow, shallow water, diffusive model

1. INTRODUCTION

Discharge monitoring in natural rivers is essential for many engineering applications, from water management to the design of hydraulic structures. Direct discharge measurement in rivers is traditionally obtained through spatial integration of measured local velocities. Direct measurement is expensive and usually requires scheduling much ahead in time, as well as the cooperation of several personnel units. An alternative choice is to carry on indirect measurements, by means of water level data collected in two sections far few kilometers from each other and the help of hydraulic modeling (Aricò et al., 2009). In the indirect approach the stage hydrograph measured in the upstream section is used as upstream boundary condition of the hydraulic model and the stage hydrograph measured in the second downstream section is compared with the computed one to provide the likelihood function, which is maximized by calibrating the hydraulic model parameters. Aricò et al. (2009) have shown that accurate and robust results can be obtained using only one parameter for calibration, which is the average Manning's coefficient along the reach, and that the proposed procedure is specifically useful for the estimation of the peak discharge during floods, when direct measurements are very difficult or even impossible.
The procedure has been up to now restricted to the case of missing unknown lateral inflows between the two measurement sections and this was a strong limit. For example, for a peak discharges of the order of one thousand cubic meters per second a distance of the order of 10 Km is required between the two sections in order to minimize, with the Manning's coefficient calibration, the temporal shift between the two stage hydrographs. In many cases one or more significant tributary flows can be found along such a distance.
On the other hand, the use of diffusive assumption in the hydraulic model allows its use according to an 'head driven' approach not only in the boundary sections, but also in intermediate sections matching the confluence with one or more tributaries. The MAST hydraulic model has then been specifically modified in order to compute an entering discharge, at each tributary section, proportional to a given rating curve according to an unknown k parameter. The water depth at the tributary section is computed assuming, according to the diffusive assumption, the same water level for both the main channel and the tributary section at their confluence and the likelihood function estimated at the downstream section is used for the calibration of the n Manning coefficient, as well as of all the other k parameters.

2. TRIBUTARY FLOW MODELING

MAST numerical scheme is able to route observed water levels from upstream to downstream sections according to the diffusive assumption, i.e. neglecting inertial terms in the momentum equation. The topography, as well as the Manning roughness coefficient, has to be known in each computational section along with possible lateral inflows. It is possible to evaluate these lateral inflows, from known water level data and according to simple algebraic relationship, only according to some restrictive hypothesis (Moramarco et al., 2005): 1) the wave celerity is constant, 2) kinematic approximation holds in the main channel, 3) the lateral inflow is homogeneous along the reach.

On the opposite, it is usually possible to derive the discharge hydrograph in all the river sections downstream of the upstream one, according to much more general hypothesis with the help of hydraulic modeling. Assume the lateral inflow between the hydraulic model boundary sections to be concentrated in a small number of confluences, and that each confluence matches a computational cell of the hydraulic model. Call $I_1, I_2, \ldots, I_N$ the corresponding sections of the hydraulic model along the main reach. Assume to know the topography of the final section T_j of each tributary channel j, ending in the confluence section I_j. Finally, assume the kinematic hypothesis to hold for the tributary channels. Observe that kinematic conditions are likely to hold more for the tributaries than for the main channel, because tributaries at the confluence section have usually a basin much smaller than the basin of the main channel, and their longitudinal slope is higher. According to the previous hypothesis, as well as to the diffusive approximation in the momentum equations of the main channel, discharge ${Q_j}^T$ of the tributary channel at the inlet section can be written as:

$$ {Q_j}^T = {Q_j}^S(H_j - {z_j}^T)\frac{\sqrt{S_j}}{n_j} \qquad [1] $$

where ${Q_j}^S(H_j - {z_j}^T)$ is the specific discharge, computed per unit energy gradient and per unit Manning's coefficient according to any chosen water depth – discharge relationship, H_j is the water level common to the main channel section I_j and to the tributary channel section T_j, and ${z_j}^T$ is the minimum topographic level of the section T_j. Observe that the hypothesis of constant water level at the confluence for both the tributary and the main channels is strictly related to the diffusive hypothesis holding in the main channel. If kinetic energy gradients in both the main and the tributary channels were consistent with respect to the other terms of the momentum equations this assumption would fail.

Also observe that, due to the kinematic assumption in the tributary channel, Eq. (1) can be written as:

$$ {Q_j}^T = {Q_j}^S(H_j - {z_j}^T)K_j \qquad [2] $$

where K_j can be seen as an unknown calibration parameter, along with the Manning coefficient n in the main channel.

2.1 Embedding the tributary flow in the MAST hydraulic model

The MAST hydraulic model (Aricò et al., 2007) splits the solution of the Saint Venant equations along the main channel, for each time step Δt, in two iterations. In the first iteration a prediction convective problem is solved, where the piezometric gradients are kept constant in time, and equal to the values computed at the end of the previous time step. In the second iteration a corrective diffusive problem is solved. All the forcing functions are discretized in each computational cell only in the prediction problem. Solution of cell i in the prediction problem is given by integration along Δt of the following ODE in the H_j unknown, carried out using Runge-Kutta methods with self-adapting time sub-steps:

$$ \frac{dH_j}{dt}A_j(h_j) = {\bar{Q}^k}_j - {Q_j}^u(h_j)\frac{{H_j}^k - {H_{j+1}}^k}{n\sqrt{|{H_j}^k - {H_{j+1}}^k|}} \qquad [3] $$

where A_j is the horizontal cross sectional area of cell j, h_j is the water depth of the main channel in section j ($h_j = H_j - z_j$) , z_j is the minimum topographic level in section j, k is the index of the last solved time step, ${\bar{Q}^k}_j$ is the average discharge entering in computational cell j along time step Δt, ${Q_j}^u(h_j)$ is the specific discharge in section j, per unit energy slope and Manning's coefficient, n is the average Manning's coefficient in the main channel. After solution of Eq. (3) for cell j, the average discharge entering in computational cell $j+1$ along time step Δt is computed as:

$$ {\bar{Q}^k}_{j+1} = {\bar{Q}^k}_j - \frac{{W_j}^{k+1/2} - {W_j}^k}{\Delta t} \qquad [4] $$

where W_j^k and $W_j^{k+1/2}$ are the water volumes inside computational cell j respectively at the beginning and at the end of the prediction problem. $W_j^{k+1/2}$ is computed as function of $H_j^{k+1/2}$, solution of problem (3) at the end of Δt. The tributary flow can be embedded in Eq. (3) by setting:

$$ \frac{dH_j}{dt}A_j(h_j) = {\bar{Q}^k}_j - {Q_j}^u(h_j)\frac{{H_j}^k - {H_{j+1}}^k}{n\sqrt{|{H_j}^k - {H_{j+1}}^k|}} + {Q_j}^S(H_j - {z_j}^T)K_j \qquad [5] $$

where the last term in Eq. (5) is the r.h.s. of Eq. [2].

The new problem has no more only one calibration parameter (*n*), but *N*+1 calibration parameters, if *N* is the number of the tributary channels, given by the Manning coefficient *n* of the main channel plus all the K_j coefficients of the tributary flows.

3. RESULTS

The methodology has been applied to a river reach 20 km long of the Alzette river, set between two instrumented sections, Pfaffenthal (upstream section) and Mersch (downstream section), in order to have significant lateral inflow between the two sections. Both Manning's roughness coefficient and k parameters were calibrated and validated by maximizing the Nash Sutcliffe index (Nash Suctliffe, 1987), computed using the available water level observed data at the Mersch gauged section for all events available for the rivers.

$$NS = \left[1 - \frac{\sum_{i=1,N}(h_i|_{obs} - h_i|_{sim})^2}{\sum_{i=1,N}(h_i|_{obs} - \bar{h}_{obs})^2}\right] \qquad [6]$$

where $h_i|_{sim}$ is the i^{th} data of the simulated water level hydrographs, $h_i|_{obs}$ is the i^{th} data of the benchmark water level hydrographs and $\bar{h}_{obs}$ is the average value of the benchmark water level hydrographs.

See, for one of the three available events: in Figure 1(a) the observed and the computed water level hydrographs in the downstream section and the observed one in the upstream section; in Figure 1(b) the observed and the computed discharge hydrographs in the upstream section.

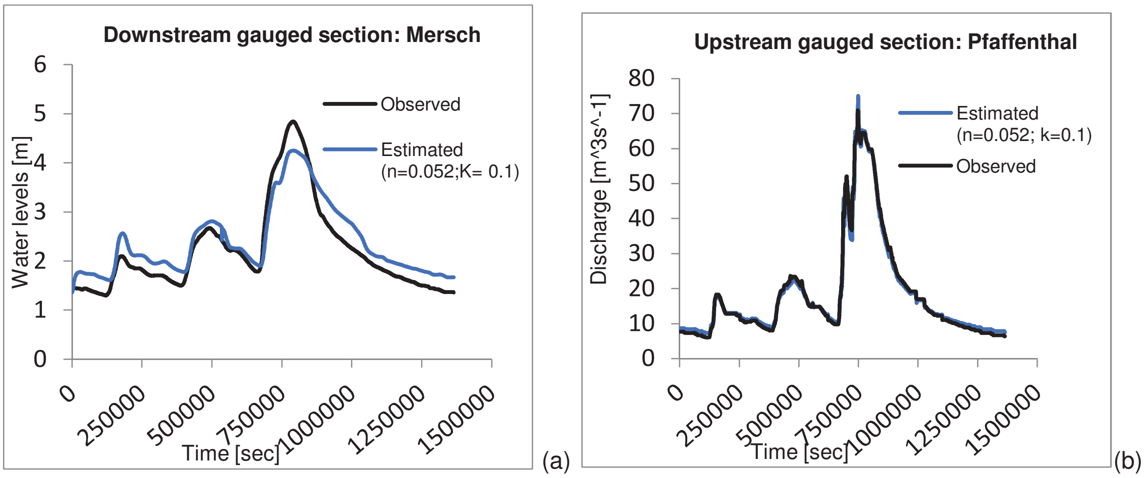

Figure 1: Observed and simulated stage hydrographs at Mersch gauged site (a) and observed and simulated discharge hydrographs at Pfaffenthal gauged site (b)

4. CONCLUSIONS

Preliminary results for the validation of the proposed methodology for indirect discharge estimation in sites with significant lateral inflows are quite encouraging. The computed error is, in fact, of the same order of the error given by the direct discharge measurement. Sensitivity analysis, not documented here, also shows robustness of both the estimated parameters and the computed discharge hydrographs in the upstream section with respect to the water level measurement error, as well as to the selection of the temporal interval adopted for the computation of the Likelihood function.

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