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Reconstruction of 2D river beds by appropriate interpolation of 1D cross-sectional information for flood simulation

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ABSTRACT

The 2D numerical simulation of river flow requires a large amount of topographic data to build an accurate Digital Terrain Model which must cover the main river channel and the area likely to be flooded. DTMs for large floodplains are often generated by LiDAR flights. However, it is often impossible to obtain LiDAR data of permanently inundated river beds. These areas are often surveyed and discrete cross-sections of the river channel are obtained. This work presents an algorithm to generate the missing information for the areas between cross-sections. The algorithm allows to generate a river bed which preserves important morphological features such as meanders and thalweg trajectory. Two benchmark cases are studied: a synthetic river-floodplain system and a real case application on a reach of the Ebro river in Spain. The cases are analyzed from a geometry and hydrodynamics perspective by performing 2D simulations with good results.

1. Introduction

Flood simulation is a crucial element for flood risk assesment and management (European Parliament, 2007). Because of such relevance, a large body of research exists seeking to improve and understand hydraulic models for flood simulation. Hydraulic simulation models offer the possibility to estimate the extension and duration of a flood event over a particular area, as well as obtaining quantitative information of relevant physical variables, such as water depth and velocity. Nevertheless, not only the numerical capabilities of models need to be addressed. It is also crucial to understand the needs for field data, the sensitivity of models to it, and to provide robust tools able to fill the gaps in data which are necessary for numerical modeling.

In many cases, 1D hydraulic models have been preferred (Chang, 1982; Burguete and García-Navarro, 2001; Yoshida and Dittrich, 2002; Helmio, 2002) due to their low computational cost as well as the relatively scarce field data that they require. In particular, they are computationally efficient when dealing with large river/channel systems and several other hydraulic structures. They are, however, unable to represent the actual meandering river shape, nor are they able to simulate the flow over the floodplain (Merwade et al., 2008a). This restriction can be avoided using 1D–2D coupled models (Morales-Hernández et al., 2013b), able to represent the river channel with a 1D model and the floodplain areas with a 2D model. Although they have been turning widely popular in the recent years, they need to represent adequately river-floodplain interaction and the exchanges between the models.

Depth averaged 2D hydrodynamic models of the shallow water type (Murillo and García-Navarro, 2010) provide reliable information on the values of the depth averaged velocity components as well as the water depth. This formulation, widely accepted as the basis for the development of fluvial hydrodynamic models (Wu, 2007) is governed by the friction forces, bed level elevation irregularities and strong advection effects. Nowadays, 2D models are the most accepted tool to simulate the behavior of meandering rivers as well as to reproduce the flooding extension in low-laying areas.

The strong influence of terrain irregularities on the response of 2D shallow water models requires a sufficiently fine topographic representation (Caviedes-Voullième et al., 2012a; Cook and Merwade, 2009; Horritt and Bates, 2001; Horritt et al., 2006) of the whole domain including both the river bed and floodplain extension. From the available data point-of-view, Digital Terrain Models (DTM) offer exhaustive spatial information which can be easily manipulated by the modeler. In order to generate such DTMs, LiDAR techniques are very useful and widely used to characterize the dry regions (Casas et al., 2006; Liu, 2008). However,

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conventional LiDAR techniques are unable to measure the terrain covered by water and Airborne LiDAR Bathymetry techniques still have limitations (Wang and Philpot, 2007). Alternative sources of information for those regions are SONAR techniques (Dal Cin et al., 2005) or the more traditional local bathymetry surveys in which cross-sections of the river bed are usually measured at distances ranging from tens to hundreds of meters but never provide a continuous 2D representation of the river.

The present work is motivated by the necessity to generate a complete DTM of the entire computational domain, including the wetted regions of the river channel which are likely to have no LiDAR generated DTM data. Since LiDAR data is often available for floodplains and other dry areas, and measured river cross-sections of the bathymetry are also usually available, an algorithm which can use both and generate a single DTM is a valuable tool.

This is a common issue when simulating floodplains with 2D models, and therefore, it has been previously addressed in the literature. Merwade et al. (2006) studied the importance of river channel anisotropy on 2D interpolation processes, testing algorithms on global Cartesian coordinates and local flow-oriented coordinates. Merwade et al. (2008b) proposed a linear interpolation for both the horizontal (x-y) and vertical (z) directions using a local reference system based on the longitudinal distance along the river bed and the normal distance to the banks. The method presented by Merwade et al. (2008b) also requires careful definition of the river banks by the modeler. Merwade (2009) studied the possible use of isotropic interpolation methods, working on a local flow-oriented coordinate system and treating cross-sectional trends. Schäppi et al. (2010) also implemented a linear interpolation, but with a global reference system that requires the modeler to input the breaklines which define the river bank. Flanagin et al. (2007) used Kochanek-Bartels splines to interpolate channel bathymetry from cross-sections.

Merging the measured or interpolated river bathymetry with the measured dry land topography is also a challenge. In the works by Merwade et al. (2008b) and Schäppi et al. (2010), river banks were purposely smeared to avoid large differences in elevation between the floodplain and the riverbed. Jha et al. (2013) studied a Direct Sampling geostatistical method to merge different bathymetry datasets from different sources and generate suitable 2D channels.

The algorithm proposed in this work interpolates twice on the cross-sectional data using global coordinates. First in the horizontal plane (x-y) and then in the vertical (z) direction to generate a surface mimicking the river bed morphology. The horizontal interpolation attempts to approximate the river trajectory and is based on cubic Hermite splines whereas in the vertical direction linear elevation interpolation is performed along the (interpolated) splines. The 2D point cloud generated from this interpolation allows to build a river bed which can then complement the LiDAR data of the dry areas to generate a complete DTM. Furthermore, in the proposed algorithm, smearing is avoided to preserve as much of the original data as possible.

In order to test the quality of the interpolated terrain, two benchmark tests of 2D river flow inundation are performed. First, a synthetic river and floodplain, in which both topography and simulated flows are studied. Second, a real floodplain for which a LiDAR generated DTM exists and a number of 1D cross-sections are available.

The text is structured as follows. Section 2 presents the mathematical model for shallow flows and a brief summary of the numerical techniques employed. Section 3 presents the concepts and algorithms proposed for the generation of 2D river bed surfaces from cross-sections. Section 4 presents a benchmark test on a synthetic, analytical river and floodplain used for verification of the algorithm. Section 5 discusses the application of the proposed algorithm on a real river reach on the Ebro river in Spain together with hydrodynamic results compared against field data. Finally, conclusions and future lines of research are discussed in section 6.

2. Shallow water model

The 2D Shallow Water equations, expressing water volume and momentum conservation in vector form are.

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}(\mathbf{U})}{\partial x}+\frac{\partial \mathbf{G}(\mathbf{U})}{\partial y}=\mathbf{S}+\mathbf{H} \tag{1}$$

with conserved variables

$$\mathbf{U}=\left(h,q_x,q_y\right)^T \tag{2}$$

with h representing depth (L) and $q_x = hu$ and $q_y = hv$ the unit discharges (L^2/T), with u and v (L/T) the depth averaged components of the velocity vector $\mathbf{u}$ along the x and y coordinates respectively. The fluxes are given by

$$\mathbf{F}=\left(q_x,\frac{q_x^2}{h}+\frac{1}{2}gh^2,\frac{q_xq_y}{h}\right)^T \quad \mathbf{G}=\left(q_y,\frac{q_xq_y}{h},\frac{q_y^2}{h}+\frac{1}{2}gh^2\right)^T \tag{3}$$

where g (L/T^2) is the acceleration of the gravity. The source term $\mathbf{S}$ represents friction effects and is defined as

$$\mathbf{S}=\left(0,\ -ghS_{fx},\ -ghS_{fy}\right)^T \tag{4}$$

where the friction slopes are written in terms of the Manning's roughness coefficient n ($TL^{-1/3}$):

$$S_{fx}=n^2u\sqrt{u^2+v^2}\Big/h^{4/3}\ S_{fy}=n^2v\sqrt{u^2+v^2}\Big/h^{4/3} \tag{5}$$

The source term $\mathbf{H}$ represents bed slope effects and expresses the pressure force variation along the bottom in the x and y direction, formulated in terms of the bed slopes of the bottom level z (L).

$$\mathbf{H}=\left(0,\ -gh\frac{\partial z}{\partial x},\ -gh\frac{\partial z}{\partial y}\right)^T \tag{6}$$

It is clear that the bed elevations are essential to the phenomena at hand. Therefore, it is very important for accurate bed elevation data to be available. This leads to the particular issue that, if no bed elevation data is available, it must be generated by some source, and most importantly, that the accuracy of such bed elevation directly influences the accuracy and quality of the simulated flow results.

An important property of the system is the existence of a normal Jacobian matrix $\mathbf{J_n}$ of the normal flux $\mathbf{E_n}=\mathbf{F}n_x+\mathbf{G}n_y$ where $\mathbf{n}$ is the unit normal vector to a given cell edge.

$$\mathbf{J_n}=\frac{\partial \mathbf{E_n}}{\partial \mathbf{U}}=\frac{\partial \mathbf{F}}{\partial \mathbf{U}}n_x+\frac{\partial \mathbf{G}}{\partial \mathbf{U}}n_y \tag{7}$$

This Jacobian can be diagonalized and has real eigenvalues/eigenvectors due to the hyperbolic nature of the equations. This property has been recently exploited to provide robust, conservative and efficient upwind finite volume schemes able to solve the system in complex situations with wet and dry fronts (Murillo et al., 2009; Murillo and García-Navarro, 2010, 2012) on structured and unstructured grids. Structured quadrilateral grids are generally preferred in hydraulic engineering practice because the