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A conservative strategy to couple 1D and 2D models for shallow water flow simulation

M. Morales-Hernández [a,*], P. García-Navarro [a], J. Burguete [b,c], P. Brufau [a]

[a] Fluid Mechanics, LIFTEC, EINA, Universidad Zaragoza, C/Maria de Luna, 3, 50018 Zaragoza, Spain
[b] Dept. Soil and Water, Aula Dei Experimental Stn., CSIC, P.O. Box 202, 50080 Zaragoza, Spain
[c] BIFI, Institute for Biocomputation and Physics of Complex Systems, Universidad Zaragoza Mariano Esquillor, Edificio I+D, 50080 Zaragoza, Spain

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ABSTRACT

A 1D–2D coupled numerical model is presented in this work. 1D and 2D models are formulated using a conservative upwind cell-centred finite volume scheme. The discretization is based on cross-sections for the 1D model and with triangular unstructured grid for the 2D model. The resulting element of discretization for the coupled model is analysed and two different coupling techniques based on mass conservation and mass and momentum conservation respectively are explored, considering both frontal and lateral configurations. The interaction with the boundaries in each model is highlighted and the necessity of using the appropriate strategy according to the flow regime is also justified. The coupled model is tested through academic test cases where the numerical results are compared with a fully 2D model as well as with experimental measurements in steady and unsteady scenarios. It is also applied to a real world configuration, where the flood wave propagation in the river bed is simulated by means of a 1D model and the inundation of the riverside is dealt with a 2D model. The computational gain is also analysed.

1. Introduction

Growing population and economic activities near rivers have caused an increased flood risk to many urban regions. Computers and modelization help assess and manage flood risk. One dimensional (1D) hydrodynamic models have been widely used in modelling flood flows [1–3]. This type of models are computationally efficient for dealing with large river/channel systems and several other hydraulic structures. However, when modelling floodplain flows, their accuracy and appropriateness decreases. Quasi 2D models have been developed for that situation, in which the floodplain is discretized into a network of virtual river branches and spills linked with main river channels [4–6]. Although this approach has been successfully used for many flood studies, it is generally time-consuming in setting up the initial model and the accuracy of predictions varies with the way in which the floodplain is discretized. Depth-integrated two dimensional (2D) hydrodynamic models have been used for many years for predicting free surface flows, but they are generally more computationally expensive when dealing with channel networks and hydraulic structures. The increasing availability of digital topographic data in recent years provides this type of models with a wider scope of application. 1D approximations require less information and are computationally time saving while 2D models when the real flow pattern does not correspond with a 1D domain, give more precise results but are time consuming and more topographical demanding. Therefore, with the need to improve modelling accuracy and to gain computational time, coupled modelling approaches of 1D and 2D shallow water models are increasingly used.

Coupled 1D–2D models have been developed in recent years and successfully applied to large and complex river systems [7–10]. Some authors [11,12] propose using only the 1D model to predict flow velocity and water level within the main river network. If large areas are inundated owing to a breach of a section of river embankment, it is likely that the flows would no longer be 1D. In such case the 2D model is used to predict the flow velocity and inundation levels in the flooded area. The models are linked by a weir equation, in which the volume of flow from the 1D domain to the 2D domain is determined by the water level difference. Another form to couple 1D–2D hydrodynamic models consists of a transformation of 2D quantities to 1D quantities just averaging the 2D terms along the cross-sections and imposing continuity at the interfaces. After that, a subdomain iterative procedure is carried out to solve the coupled 1D–2D problem [13]. This technique turns out to be a reliable strategy provided that a proper choice of the subdomain is performed, only for simple configurations (e.g. a straight channel or a river bifurcation). Some recent works propose

* Corresponding author. Tel.: +34 876 555052.
E-mail addresses: mmorales@unizar.es (M. Morales-Hernández), pigar@unizar.es (P. García-Navarro), jburguete@eead.csic.es (J. Burguete), brufau@unizar.es (P. Brufau).

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more sophisticated ways for 'stitching' both models. For example, they can be connected by internally coupling the 1D node with the centre of the 2D grid cell [14], by considering the numerical fluxes of each model [15] and also by introducing several corrections in the momentum quantity transfer due to the occurrence of swirls [16]. The concern of source terms and the possibility of linking both models in discontinuous topography is explored in [17].

Most of these coupled model approaches, developed from previous existing 1D and 2D models, require a deeply overview concerning how each model is perceiving the coupling by itself. The boundary conditions in each model play an important role within the modelization due to the fact that the end of the 2D domain is always interacting with the 1D model hence the boundary treatment should be continuously considered.

Bearing this in mind, two coupling strategies based on a mass conservation and a complete mass and momentum conservation will be proposed in order to cover all possible flow situations and to approximate faithfully the results given by a fully 2D model. The formulation is presented in a general expression, covering both frontal and lateral coupling configurations with respect to the 1D model. The bed slope and friction source terms relating to the 1D and the 2D models are included in the formulation of the coupled scheme. Emphasising the idea of a correct conservation philosophy and taking into account the information which leaves out the 1D or 2D domains, the adequate use of each strategy according to the flow conditions will be inherently justified and subsequently corroborated. Both models built using a conservative upwind cell-centred finite volume scheme based on Roe Riemann solver across the edges [18]. The topography is represented with cross-sections for the 1D model and with DTM (Digital Terrain Model) in a triangular unstructured grid for the 2D model.

The main objective of this manuscript is to enhance the correct formulation of coupled models based on existing 1D and 2D models. One test has been chosen for calibration corresponding to an extreme dam break in a channel propagating into a flood plain [19]. Being a test case without almost influence of source terms, the hydrodynamic of the system can be deeply analysed when coupling both models. Then, a trapezoidal channel connected laterally with a floodplain area is used as validation test case including steady and unsteady flow scenarios and comparing the numerical results with a fully 2D model in terms of time evolution of several probes located at the domain. The behaviour of this coupled model is also performed in a Y-shape junction problem, with two geometry configurations that have an impact on the flow regime. Finally, it is applied to the Ebro river, a real meandering river with complex topography where the numerical results of the coupled model in terms of flooding extension and longitudinal profiles are compared with those obtained with a fully 2D modelization. The computational gain achieved by the proposed 1D–2D coupled model is also estimated in all the test cases presented, analysing the results in terms of speed-up in comparison with a complete 2D model.

2. Governing equations

2.1. 1D model equations

Equations can be derived from mass and momentum control volume analysis:

$$\frac{\partial \mathbf{U}(x,t)}{\partial t} + \frac{d\mathbf{F}(x,\mathbf{U})}{dx} = \mathbf{H}(x,\mathbf{U}) \qquad (1)$$

$$\mathbf{U} = \begin{pmatrix} A \\ Q \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} Q \\ \frac{Q^2}{A} + gI_1 \end{pmatrix}, \quad \mathbf{H} = \begin{pmatrix} 0 \\ g[I_2 + A(S_0 - S_f)] \end{pmatrix} \qquad (2)$$

where Q is the discharge, A is the wetted cross-section area, $g$is the acceleration due to the gravity, S_0 is the bed slope

$$S_0 = -\frac{\partial z_b}{\partial x} \qquad (3)$$

where z_b is the bed level. S_f is the friction slope here represented by the empirical Manning law

$$S_f = \frac{Q^2 n^2}{A^2 R^{4/3}} \qquad (4)$$

being R the hydraulic radius and n the Manning's roughness coefficient. I_1 represents a hydrostatic pressure force term

$$I_1(x) = \int_0^h (h-\eta)\sigma(x,\eta)\, d\eta \qquad (5)$$

in a section of water depth $h = z_s - z_b$, water surface level z_s and width $\sigma(x, \eta)$ at a position η from the bottom (see Fig. 1). Therefore, the cross-sectional wet area can be expressed as follows:

$$A(x) = \int_0^h \sigma(x,\eta)\, d\eta \qquad (6)$$

On the other hand, I_2 accounts for the pressure force due to the longitudinal width variations:

$$I_2(x) = \int_0^h (h-\eta)\frac{\partial \sigma(x,\eta)}{\partial x}\, d\eta \qquad (7)$$

2.2. 2D model equations

The water flow volume and momentum conservation:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}_x(\mathbf{U})}{\partial x} + \frac{\partial \mathbf{F}_y(\mathbf{U})}{\partial y} = \mathbf{H}(\mathbf{U}) \qquad (8)$$

where the conserved variables:

$$\mathbf{U} = (h, q_x, q_y)^T \qquad (9)$$

$q_x = uh$ and $q_y = vh$, and the fluxes of these variables:

$$\mathbf{F}_x = \left(q_x, \frac{q_x^2}{h} + \frac{1}{2}gh^2, \frac{q_x q_y}{h}\right)^T, \quad \mathbf{F}_y = \left(q_y, \frac{q_x q_y}{h}, \frac{q_y^2}{h} + \frac{1}{2}gh^2\right)^T \qquad (10)$$

The source terms of the momentum are due to the bed slope and friction

$$\mathbf{H} = (0,\ gh(S_{0x} - S_{fx}),\ gh(S_{0y} - S_{fy}))^T \qquad (11)$$

where the bed slopes of the bottom level z_b are

$$S_{0x} = -\frac{\partial z_b}{\partial x}, \quad S_{0y} = -\frac{\partial z_b}{\partial y} \qquad (12)$$

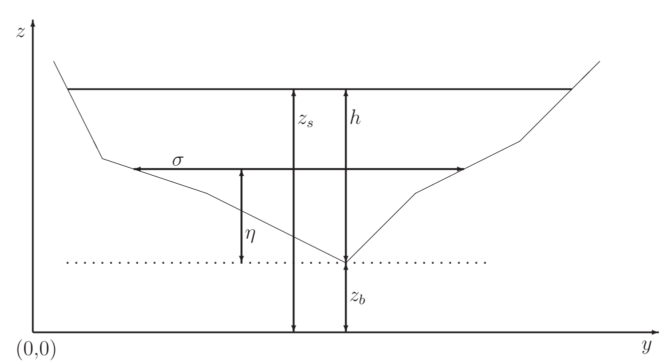

Fig. 1. Coordinate system in a cross-section as used in the 1D model.