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Integration of 1D and 2D finite volume schemes for computations of water flow in natural channels

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ABSTRACT

A wide variety of flood simulation models are available nowadays. Some of them use a 1D approach and others a 2D one, but there are also some which allow the performance of integrated 1D–2D simulations. These latter models, which have important advantages in optimizing computational costs, commonly use the 1D approach in river channels and the 2D one in floodplains. The coupling of 1D and 2D flows usually ensures mass conservation and makes use of simplified weir-type or friction slope equations, but neglects momentum transfer between the two domains. This paper presents a fully conservative method for the coupling of 1D and 2D domains to be used in numerical schemes based on finite volumes. The method, based on a discretization of the numerical fluxes which ensures the conservation of mass and momentum, is verified with simple test cases. The proposed scheme is compared with the standard method based on the source term of the equations and is applied to the hydrodynamic characterization of a river-reservoir system situated in the River Ebro in Spain.

1. Introduction

Flood models have proven to be very useful tools for solving river dynamics problems and developing flood management strategies. Different approaches have been used for such modelling techniques. Presently there exists a broad diversity of modelling tools: commercial models, free models, open source models and research models. With respect to spatial discretization techniques, most modelling tools use either a one-dimensional or a two-dimensional approach.

In recent years, some developments have been presented in which the one and two-dimensional approaches are integrated into a single modelling tool. By means of a mixed approach, it is possible to use the more accurate flow description of a 2D scheme where needed, and use the 1D approach elsewhere. In this way, computer time and memory are saved, as the number of calculation points in a 1D scheme is radically lower than in a 2D scheme. When simulating large areas, the number of points involved in a 2D simulation will be proportional to the area of the study, while the number of cross sections in a 1D model will depend on the length of the river reach. Fully 2D models of large areas can involve millions of elements, whereas a 1D model of the same reach could be done with less than a thousand sections. This difference results in important savings in terms of computational time and computer memory requirements, which can be limiting factors for the application of 2D models. Computational time usually increases exponentially with the number of involved elements to the power of between 1.5 and 2. Time differences between approaches can range from a few seconds to a few minutes in 1D to several hours, days or even weeks in 2D. When using a mixed 1D–2D model, every kilometre of river that can be studied with the 1D approach can save a crucial amount of time and memory. Mixed 1D–2D models also have some advantages in terms of use, for example when refining floodplain flow simulations in an area where a 1D model of the river is already available, or when there is information regarding the geometry of a river's cross sections, but no global Digital Elevation Model. In cases where there is uncertainty regarding the boundary condition of a 2D model, a 1D model can be coupled to the 2D one to extend the domain and achieve a better approximation of the boundary conditions at a reasonable cost. Coupled 1D–2D models can also have advantages when using explicit schemes in which the time step is limited by the Courant condition. In a 2D model of a river and floodplain, the river is usually the time step limiting factor, as depths and velocities there are greater than in the floodplain. If the same area is modelled in 1D–2D, the value of the time step can be increased using a separation between cross sections larger than the size of the 2D elements.

The first integrated 1D–2D models were developed as extensions of already existing 1D models (the only method available at that time). A pioneering work in this respect was the model of the Mekong River Delta in 1975–1976 [1], where a one-dimensional

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model of looped channel flow, solving the Saint Venant equations with the Preissmann Scheme, was integrated with a storage cell algorithm using the mass conservation equation to link domains. This method was subsequently referred to as a 1D-quasi 2D model, and was soon adopted in the first versions of Mike-11. It was later used by others with slight variations, as is the case in [2], and in the present version of Hec-Ras. Quasi 2D schemes can be used in an uncoupled way [3] if the riverbed elevation is higher than the floodplain, or if there is a dike or embankment between them. In this case, backwater effects are not included [4]. When the influence of backwater effects cannot be neglected, the coupling of the 1D and the quasi-2D schemes is needed [5–7]. Quasi-2D schemes are always limited in determining the front wave advance and recession over the floodplain.

Several other approaches are possible for coupling a 1D model with a 2D model. The very first research integrating fully 1D with fully 2D schemes was developed to study the hydrodynamics of the Venice Lagoon [8] using finite element schemes. It used an original approach in which 1D channels would work as open channels for low water elevations, and as pressure conduits below 2D elements for high tide flows. Numerical results were compared with field data [9] and also with a fully two-dimensional model [10,11], with satisfactory agreement. Later, a sediment transport module in finite volumes was added to the model [12]. Integrated 1D and 2D numerical schemes were also used for flood modelling in the Netherlands, using implicit schemes with Sobek software [13]. Here, Sobek used two separate computational layers linked to each other via water level compatibility. Later, the same software incorporated the possibility of linking the two schematizations using discharge compatibility [14]. This method was used in the Sistan–Baluchistan river basin in Iran [15] and in the Bicol Basin in the Philippines [16].

Other combinations of 1D and 2D approaches have also been employed. Using LISFLOOD-FD software [17–19], the flow in the river main channel is solved in 1D and the overbank inundated areas are solved in 2D by means of the diffusive wave equation [4]. Also, finite volumes and Riemann solvers in the river have been combined with storage cells in the floodplain [20]. In other cases, a quasi-2D approach has been used to provide input hydrographs for a fully-2D module [21]. In [22] an innovative method was presented for steady flows, or for cases in which attenuation effects could be neglected. 1D–2D integration was achieved by means of the mass conservation equation, using the Parabolic Shallow Water Equations (PSWE), a simplified version of the SWE.

This paper presents a numerical method for coupling 1D and 2D finite volume schemes. In both 1D and 2D areas, the finite volume method has been used to solve the full Saint Venant equations, or Shallow Water Equations. The finite volume method is particularly suitable for irregular meshes and flows with shocks and discontinuities [23], such as those that occur in Mediterranean rivers. Recently, this technique has been used in a good number of research models, as well as in commercial software packages for flood analysis, such as Infoworks [24], Mike Flood [25] or Guad2D [26]. The method presented here originates from the CARPA modelling system, developed by the Flumen Research Group at the Universitat Politècnica de Catalunya [27]. More recently, CARPA has undergone various improvements. On the one hand, enhancements have been made to the numerical scheme, such as the one subject of this paper. On the other hand, a user-friendly interface has been developed based on GiD [28], a software for the pre-processing and post-processing of finite elements, finite differences, and finite volume schemes [29]. With this interface it is possible to read data from Digital Terrain Models in common GIS formats, discretize the geometry in cross sections and meshes, assign conditions, run the simulations and analyze the results. The developments of the integrated 1D–2D scheme presented here ensure mass and momentum conservation. The scheme is verified against simple test cases and is applied to a real case (the River Ebro between the Ribarroja and the Flix dams).

2. Equations and numerical schemes

Both the 1D and 2D numerical schemes use a High Resolution Godunov scheme with Roe's Riemman Solver and TVD functions [30]. A detailed description of the 1D numerical scheme used here can be found in [27] or [31]. In this last reference, some improvements were presented in order to ensure that the scheme provides solutions that satisfy the energy equation in the case of steady flows over irregular geometries, something that was not achieved by some of the previously existing schemes [32]. The following subsection outlines the basics of the 1D equations and the numerical scheme for a more complete understanding of the 1D–2D developments presented below.

2.1. One dimension

The one-dimensional Saint Venant equations in conservative form for irregular channels are:

$$\mathbf{U_{1D}}_{,t} + \mathbf{F_{1D}}(\mathbf{U})_x = \mathbf{H_{1D}} \tag{1}$$

$$\mathbf{U_{1D}} = \begin{pmatrix} A \\ Q \end{pmatrix}; \quad \mathbf{F_{1D}} = \begin{pmatrix} Q \\ \frac{Q^2}{A} + gI_1 \end{pmatrix}; \quad \mathbf{H_{1D}} = \begin{pmatrix} q_l \\ gI_2 + gA(S_0 - S_f) \end{pmatrix} \tag{2}$$

$$I_1 = \int_0^h (h-\eta) b(x,\eta) d\eta; \quad I_2 = \int_0^h (h-\eta) \frac{\partial b(x,\eta)}{\partial x} d\eta \tag{3}$$

where $\mathbf{U}_{1D}$ is the vector of conserved variables, $\mathbf{F}_{1d}$ is the flux vector and $\mathbf{H}_{1D}$ the source term, A represents the wetted cross-sectional area, Q the discharge, g gravity, S_0 the channel slope, S_f the friction slope, h the water depth, b the channel width and q_l the lateral discharge. A finite volume numerical scheme for these equations can be written as:

$$\mathbf{U}^{n+1}_{\mathbf{1D},i} = \mathbf{U}^{n}_{\mathbf{1D},i} - \frac{\Delta t}{\Delta x}\left(\mathbf{F}^*_{\mathbf{1D},i+1/2} - \mathbf{F}^*_{\mathbf{1D},i-1/2}\right) + \frac{\Delta t}{\Delta x}\mathbf{H}^*_{\mathbf{1D},i} \tag{4}$$

where $\mathbf{F}^*_{\mathbf{1D}}$ is the numerical flux and $\mathbf{H}^*_{\mathbf{1D}}$ is the numerical expression of the integral of the source term in the finite volume, in which the effects of bed slope and roughness are included. For the 1D approach, each finite volume corresponds to a segment or river reach of length Δx represented by one cross section, and $\mathbf{U_{1D}}$ are the conserved variables averaged in the finite volume, as shown in Fig. 1. In

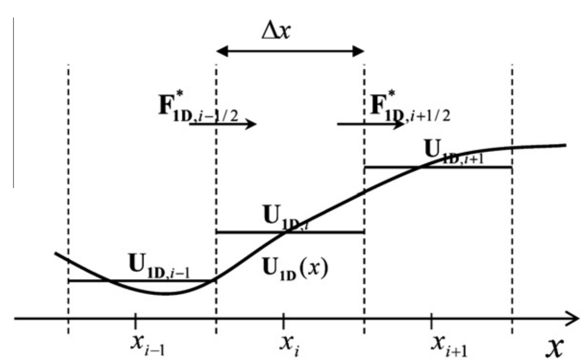

Fig. 1. Finite volume discretization in 1D. $\mathbf{U}_{1D,\,i-1}$, $\mathbf{U}_{1D,\,I}$ and $\mathbf{U}_{1D,\,i+1}$ are the vector of conserved variables at each finite volume which approximate the solution $\mathbf{U_{1D}}(x)$. $\mathbf{F}^*_{\mathbf{1D}}$ is the numerical flux at every intercell, and Δx is the distance between cross sections.