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MODELLING FLOOD EVENTS USING HIGH RESOLUTION DIGITAL ELEVATION MODELS AND CONSIDERING THE SEDIMENT INTERACTION WITH CONSTRUCTIONS IN FLOODPLAINS

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The main objective of the present paper is a description of two effective numerical 2D models to be used as strategic tools in the process of flood risks assessment and mitigation. The first one is a model for hydrodynamics simplified according to the diffusive assumption while the second one is a complete model based on the shallow water equations. Each of them is solved with an efficient numerical technique (including implicit time integration schemes and GMRES linear solvers) maximizing the convergence rate towards a steady state. A practical case study, for which a high resolution Digital Elevation Model exists, will be presented. The study shows the consequences on structures of a new construction in the floodplain in terms of inundation and erosion.

INTRODUCTION

Floods mitigation, inundation mapping and floodplain management are issues of continuously growing interest for a wide range of practitioners. At the same time reliable and efficient modelling of the corresponding flows remains a challenging task for hydroengineers and modellers. Moreover, the perspectives of improvements in the near future have to include the complete analysis of sediment transport effects to reliably assess deposition and erosion processes among others.

The present paper covers a detailed description and the comparison of two state-of-the-art 2D numerical models to be used as strategic tools in the process of flood risk assessment and mitigation. The first one is a model for hydrodynamics, simplified according to the diffusive assumption (DM), quickly generating initial flow fields for the second one, a complete model based on the shallow water equations (SWE).

Those two models are integrated in the software package WOLF, which has been developed for almost ten years at the University of Liege. WOLF includes a complete set of numerical models for simulating free surface flows (process-oriented and spatially distributed hydrology [3], 1D and 2D hydrodynamics [1, 2, 3], sediment transport, air entrainment…) as well as optimisation algorithms. This optimisation tool, based on the innovative Genetic Algorithms technique, allows an objective calibration of friction coefficients for example [3].

A user-friendly GIS interface, entirely designed and implemented by the authors, makes the pre- and post-processing operations very convenient. Import and export operations are easily feasible from and to various classical GIS tools. Different layers of maps can be handled to analyse information related to the topography, the ground characteristics, the vegetation density and the hydrodynamic fields.

A practical case study, for which a high resolution Digital Elevation Model has been used, will be presented. The study shows the consequences of a new building in the floodplain of the river Ourthe in Belgium in terms of inundation and erosion. In a second time, remediation solutions are presented.

MATHEMATICAL MODEL DESCRIPTION

The SWE model simulates any steady or unsteady situation, possibly taking into consideration air transport or sediment-laden flows, in Cartesian or curvilinear coordinates [1, 2]. It is in addition coupled to different turbulence models, based on mixing length concept or additional equations for kinetic energy and dissipation rate transport. The DM model is restricted to a specific range of Froude and cinematic wave numbers, but requires significantly less CPU resources.

In the shallow-water approach (SWE) the only assumption states that velocities normal to a main flow direction are smaller than those in the main flow plane. As a consequence, the pressure field is found to be almost hydrostatic everywhere. In the diffusive model (DM), a similar depth-averaging operation is combined to the assumption that the purely advective terms can be neglected. As a consequence the free surface slope is simply balanced by the friction term.

The divergence form of the SWE includes the mass balance:

$$\frac{\partial H}{\partial t}+\frac{\partial q_i}{\partial x_i}=0 \tag{1}$$

and the momentum balance:

$$\underbrace{\left[\frac{\partial q_i}{\partial t}+\frac{\partial}{\partial x_i}\left(\frac{q_i q_j}{h}\right)\right]}_{\text{inertia terms}}+gh\left(S_{fi}+\frac{\partial H}{\partial x_i}\right)=0; \quad j=1,2 \tag{2}$$

where Einstein's convention of summation over repeated subscripts has been used. H represents the free surface elevation, h is the water height, q_i the specific discharge in direction i and S_{fi} the friction slope.

The diffusive assumption leads to an important simplification of the momentum equations:

$$S_{fi}=-\frac{\partial H}{\partial x_i}\,. \tag{3}$$

A friction law is needed to close both the SWE and the DM models. Its general formulation can be stated as a relation between the discharge, the water height and the slope, such as in Manning's law for example. For the DM formulation, the generic form of the roughness law is:

$$q=\alpha h^{\chi} S_f^{\gamma}=\alpha h^{\chi}\left(\frac{\partial H}{\partial s}\right)^{\gamma}, \tag{4}$$

where α, γ and χ are coefficients suitable for the description of floodplain flows.

A more detailed description of these mathematical formulations can be found in Archambeau & al [1].

NUMERICAL IMPLEMENTATION

Space discretization and boundary conditions

A finite volume scheme is used in all the models to ensure exact conservation of the advected flow properties.

An original upwind scheme is exploited for space discretization of the complete set of SWE. The stability of this second order upwind scheme has been demonstrated through a theoretical study of the mathematical system as well as a von Neumann stability analysis. Much care has been taken to handle correctly the source terms representing topography gradients.

For the DM models, the same original upwind scheme is used with some specific modifications [1].

The models allow the user to specify any inflow discharge as an upstream boundary condition. The downstream boundary condition can be stated as a free surface elevation, a water height, a Froude number or even no specified condition if the outflow regime is supercritical (SWE only).

Time integration for the SWE model

An implicit pseudo-time integration scheme, suitable for solving steady-state problems, is implemented in the SWE model. This technique allows larger time steps than those acceptable for explicit time integration. On the other hand the resolution procedure is more intricate. A Newton method is exploited to solve the large non-linear system. Successive linearized systems are solved using the powerful GMRES algorithm, which is advantageously coupled to a preconditioner. For this purpose incomplete LU factorization is applied. The Switched Evolution-Relaxation technique by Van Leer has been used to continuously evaluate the time step value.

Resolution of the DM model

The primary goal of the diffusive formulation is the quick computation of steady-state approximate solutions. Those first estimations of the flow fields are used as fairly good initial condition for the complete SWE model.

A first approach for solving the DM might be a pseudo-time evolution, starting from a user-defined initial condition. In order to allow the possibility of using large time steps, this pseudo-time integration should be performed implicitly.

A second approach is to disregard the time derivative term and to solve a non-linear system of time independent equations. Various iterative techniques are available to solve such huge sparse systems. Among them are the methods « by point », such as Jacobi, Gaus-Seidel… or full implicit such as ADI, GMRES or CG. In the DM model, the GMRES or CG algorithms are used to evaluate iteratively the solution of the sparse symmetric linearized system. In both cases the resolution procedure represents a very challenging step because of the complexity of a cost-effective evaluation of the Jacobian matrix. WOLF performs this job effectively, by storing only non-zero elements and their location in the large sparse matrix.

Both these methods for steady state calculation become similar if the time step is very large.

Friction modelling

River and floodplain flows are mainly governed by topography gradients and by friction effects. The total friction includes three components: bottom friction (drag and roughness), wall friction and internal friction.

The bottom friction is classically modelled thanks to an empirical law, such as the Manning formula. The DM and SWE models allow the definition of a spatially non-uniform roughness coefficient. This parameter can thus easily be distributed as a function of soil properties, vegetation and sub-grid bed forms.

The friction along vertical boundaries, such as bank walls, is introduced thanks to a physically based model developed by the authors. This modification of the classical friction law presents the advantage of leading to a correct hydraulic radius evaluation of the 2D cross-section in case of sufficiently shallow flows.

Adapted turbulence models properly reproduce the internal friction.

Additional features of the numerical codes

In addition to the previous main characteristics of the numerical models, an automatic mesh refinement technique is used to enhance the convergence rate towards accurate steady-state solutions [1]. The computations are performed on several successive grids, starting from a very coarse one gradually refined up to the finest one. When the hydrodynamic fields are almost stabilized, the solver automatically jumps onto the next grid. The successive "initial solutions" are interpolated from the coarser towards the finer grid in terms of both water heights and discharges. This fully automatic method considerably reduces the number of cells in the first grids and then substantially decreases computation time, despite extra computation time for meshing and interpolation operations.

LASER DEM

Very recently, the Belgian Ministry of Facilities and Transport (MET), and in particular the Service of Hydrology Studies (SETHY), acquired an accurate DEM on the floodplains in the whole Walloon Region.

An airborne laser has been used for the data regarding the inundation zones of the main rivers network. An echo-sonar has been applied to measure the bathymetry of the main channel, exclusively on navigable rivers.

Consequently, the poor and inaccurate 3D information available for many years (30 meters of plan resolution with a precision of several meters in altitude) has been replaced by an exceptional DEM since the precision in altitude is 15 cm and the information density one point per square meter.

To illustrate the accuracy of the new DEM, a comparison of the different data on the same area is illustrated for the town of Eupen in Belgium (Fig. 1).

Generally, specific features of flows in urban area (such as blockage by buildings, slowing down of the wave front propagation, etc…) are taken into account in hydraulic numerical models by a local modification of the roughness coefficient. With the new set of topographic data, irregularities of the topography influence directly the inundation flows. This allows focusing on the roughness coefficient to proper physical values.

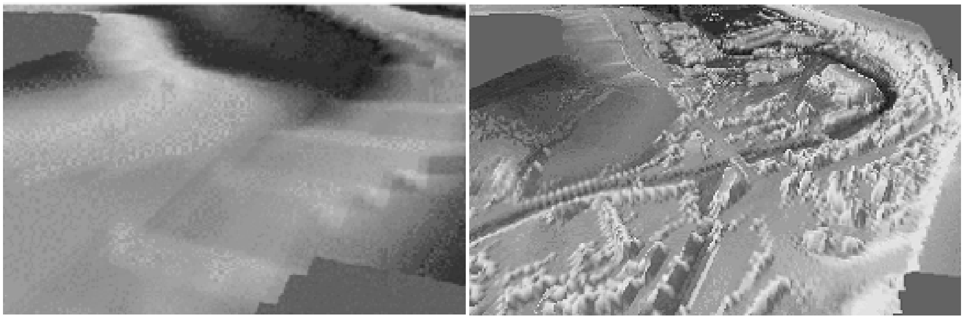

Figure 1. Town of Eupen: IGN topography (left) and laser data (right)

GIS ENVIRONMENT

Management and using of such a large set of data requires robust and efficient pre- and post-processing tools. A GIS environment, entirely designed and implemented by the authors, performs the operations necessary to the preparation of the data and their subsequent use in the numerical models, as well as the results visualization and exploitation. Several databases containing topographic data, pictures of historic floods, characteristics of structures along the rivers (dams, bridges, weirs,…) are stored on a single data server with their geographic coordinates to be easily downloaded by any modeller.

A last difficult task is also performed by the WOLF user interface. In non-navigable rivers, the only bathymetry available data are irregularly spaced cross sections of the minor bed. Specific interpolation of this source of information to generate a distributed topography is realized thanks to original methods specifically developed and implemented in the software to fulfil this job.

APPLICATION

Both the models presented in this paper have been applied to a practical case study concerning a sewage treatment plant built in the floodplain of the river Ourthe (Belgium).

After several flood events, as damages and degradations to the soil near the plant have been observed, the owner of the building entrusted the HACH with the task to study a posteriori the negative impacts on the flood plain of the structure and to suggest solutions to minimize them.

The laser DEM described above has been used in combination with cross section data to provide the basic information needed by the flow solvers (Fig. 2). In a first time, the flow fields have been modelled (Fig. 3) for reference extreme events in order to validate the model on the basis of photos. These simulations allow pointing out preferential flow paths in the flood plain, obstructed by the plant building and the bridge.

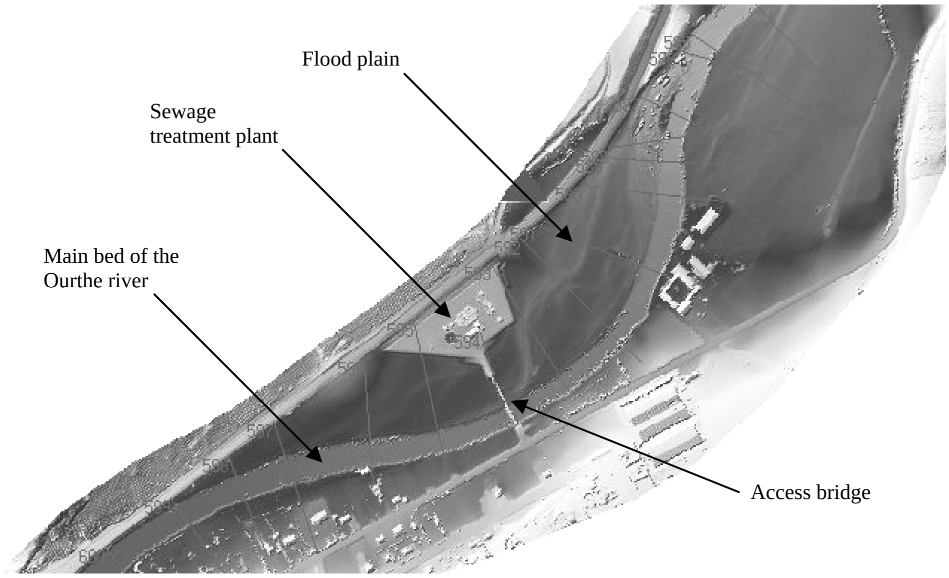

Figure 2. DEM of the study area on the river Ourthe

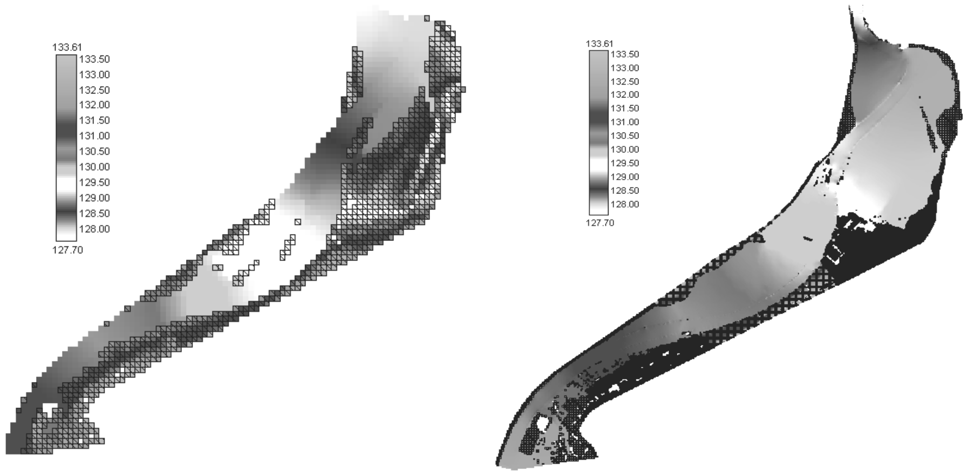

Figure 3. Intermediate results of the DM before the water treatment plant building – Free surface water levels (m) on a grid with 16 m meshes (left) and 1 m ones (right)

The obstruction of the preferential flow paths and the section contraction near the bridge create flow velocities higher than 2 m/s nearly everywhere near the plant. Before the plant building, the simulations show such high flow velocities were restricted to small localized areas. This increase in the velocities intensity caused the observed damages and local erosions. Moreover, the water levels also increase upstream of the plant, and thus the flood risks in the neighbouring town of Bomal.

The proposed solutions, developed on the basis of several numerical simulations, consist in topography and geometry modifications near the treatment plant in order to decrease the flow velocities. The river cross section under the bridge has also to by lengthen by creating a new channel (Fig. 4). These modifications should be coupled with adapted cultural methods in the concerned areas to decrease the risk of erosion.

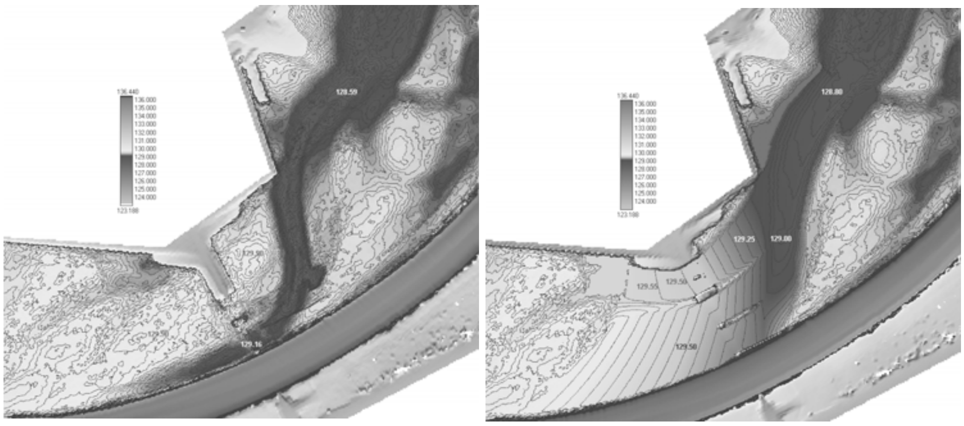

Figure 4. Initial (left) and final (right) topography of the river near the plant

CONCLUSION

The paper comprehensively details two numerical models developed in the very practical view of investigating flow fields in floodplains. It constitutes thus a genuine bridge linking highly sophisticated considerations in applied mathematics with major concerns of practitioners and decision makers in the field of flood control. The application of the models to a real case study shows their practical applicability and their ability to reproduce observed phenomena as well as to set up reliable remediation solutions.

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