Environmental Hydraulics
Environmental impact and risk assessment

Impact studies and water management with WolfHydro : a new physically based hydrological solver

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1 INTRODUCTION

The integrated suite of software WOLF has been entirely developed in the Department of Applied Hydrodynamics and Hydraulic Constructions (HACH) of the University of Liege (http://www.ulg.ac.be/hach/).

A spatial finite volume scheme was coupled with an explicit temporal discretisation for each model integrated in the Wolf package. This adaptation to the hydraulic equations is ideal for the numerical treatment and implementation. It provides a complete mass conservation of the propagated volumes and a great reliability for the momentum balance. A second order precision is assumed for both spatial and temporal discretisation. An original splitting of the convective terms was developed in order to treat any transient free surface flow discontinuities.

2 WOLFHYDRO

WOLFHYDRO is a physically based hydrological model. The first advantage of this method is that it allows the fitting of parameters to any catchment. In fact, the physical meaning of the parameters limits the range of potential values. Besides, the approach is useful for impact studies since all modifications of soil use have a direct impact on the value of the different coefficients.

With the tremendous increase of hardware and storage capabilities, it seems obvious to capitalize the potentiality of digital elevation model (DEM) and general satellite information. In fact, for several years, the HACH has developed some numerical hydrological software[8]. Each model resolves a partial or the full set of Euler or Navier Stokes equations.

The actual version of the hydrological software, WOLFHYDRO, resolves the conservative equations of 2-D diffusive wave model with a finite volume method for three specific vertically distributed layers. Different roughness law (Manning, Darcy-Weissbach, Bathurst,…)[2][3][4] are implemented to take into account the macroscopic roughness of the hydrological propagation and various flow regimes.

Originating from the well-known Saint Venant equations describing the flows :

$$\frac{\partial h}{\partial t}+\frac{\partial (uh)}{\partial x}+\frac{\partial (vh)}{\partial y}=q \tag{1.1}$$

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$$\frac{\partial(uh)}{\partial t}+\frac{\partial(u^2h)}{\partial x}+\frac{\partial(uvh)}{\partial y}+gh\left(S_{fx}+\frac{\partial H}{\partial x}\right)=0 \tag{1.2}$$

$$\frac{\partial(vh)}{\partial t}+\frac{\partial(uvh)}{\partial y}+\frac{\partial(v^2h)}{\partial y}+gh\left(S_{fy}+\frac{\partial H}{\partial y}\right)=0 \tag{1.3}$$

where H(x,y,t) is the water surface elevation above an horizontal datum, h(x,y,t) is the local water depth, t is the time, x, y are horizontal Cartesian coordinates, u(x,y,t), v(x,y,t) are depth averaged flows velocities in x and y directions, S_{fx}(x,y,t), S_{fy}(x,y,t) are friction slopes in x and y directions and g is acceleration due to gravity.

The diffusion approach can be obtained by ignoring the inertial terms compared with the gravitational terms, friction and pressure heads. Eqs (1.2) and (1.3) can then be replaced by the following system of parabolic differential equations:

$$\left(S_{fx}+\frac{\partial H}{\partial x}\right)=0,\left(S_{fy}+\frac{\partial H}{\partial y}\right)=0 \qquad (1.4),(1.5)$$

In addition and for example, applying the Manning-Strickler law to the description of the friction slopes that appears in the preceding equations, the relation between the velocity and water depth components can be obtained as

$$S_{fx}=\frac{n_x^2}{h^{\frac{4}{3}}}|w|\,w\ \mathrm{x}\ i=\frac{n_x^2}{h^{\frac{4}{3}}}u\sqrt{(u^2+v^2)}\,,S_{fy}=\frac{n_y^2}{h^{\frac{4}{3}}}|w|\,w\ \mathrm{x}\ j=\frac{n_y^2}{h^{\frac{4}{3}}}v\sqrt{(u^2+v^2)} \qquad (1.6),(1.7)$$

where $w=u_i+v_j$ is the velocity vector, n_x, n_y are the Manning roughness coefficients in the directions x and y, respectively, and therefore

$$|w|^2=u^2+v^2=h^{\frac{4}{3}}\sqrt{\frac{S_{fx}^2}{n_x^4}+\frac{S_{fy}^2}{n_y^4}} \tag{1.8}$$

Lastly, the replacement of the preceding relation in the expression for S_{fx} (1.6) and S_{fy} (1.7) determines the following expressions for the components of the velocity vector :

$$u=-\frac{\partial H}{\partial x}\frac{h^{\frac{2}{3}}}{n_x^2}\frac{1}{\left[\left(\frac{\partial H}{\partial x}\right)^2\frac{1}{n_x^4}+\left(\frac{\partial H}{\partial y}\right)^2\frac{1}{n_y^4}\right]^{\frac{1}{4}}},\ v=-\frac{\partial H}{\partial y}\frac{h^{\frac{2}{3}}}{n_y^2}\frac{1}{\left[\left(\frac{\partial H}{\partial x}\right)^2\frac{1}{n_x^4}+\left(\frac{\partial H}{\partial y}\right)^2\frac{1}{n_y^4}\right]^{\frac{1}{4}}} \qquad (1.9),(1.10)$$

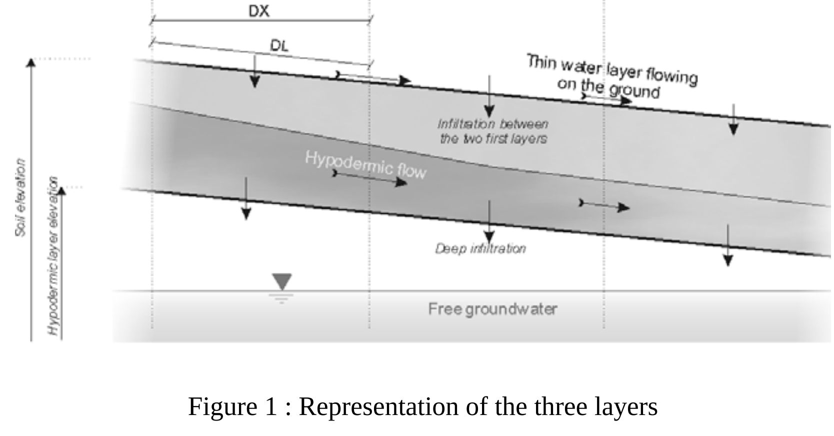

Figure 1 : Representation of the three layers

A 2D multilayers model handles the rainfall propagation, spatially and temporally variable according to the cloudy fronts, on the DEM and a complete 1D model propagates the lateral floods components in the drainage path.

The model has three bunk layers to simulate respectively the thin runoff, the hypodermic propagation and the transfer to the groundwater (see Figure 1). The unsteady infiltration law permits the reforming of the soil capacity after the rain stopping. The calculation of long periods is possible without stopping the software.

3 INVERSE MODELING

Inverse fitting methods are actually used to bound the physical parameters that characterize volume (roughness, permeability, porosity, …). Among others methods, genetic algorithms are developed in the HACH to solve general problems of optimization in hydrodynamics. Based on the natural selection and genetic mechanisms, these algorithms are working with a set of N chains, called a population, formed by coding of parameter values (generally 0 and 1) which evolve through generations to reach the optimum. Efficiency of chains is evaluate with an objective function to maximize. The better is the objective function value of a chain, the greater is its chance to participate in building the population of a new generation.

Genetic algorithms are so located between classical and purely random or systematic exploration methods of optimization. Indeed, first ones apply locally in the space to investigate, and second ones explore the entire parameters variation intervals. Genetic algorithms, as for them, intelligently conduct a pseudo-random investigation of the parameters spaces of variation.

Fundamental differences between genetic algorithms (GA) and classical optimization methods are summarized in four points (Goldberg [9]):

- GA use a parameters coding and not the parameters themselves,
- GA work with a population of points instead of a single one,
- GA only need to know the value of the function to optimize, not its derivative or auxiliary value,
- GA use probabilistic transition rules instead of deterministic ones.

Greater advantages of GA are in their simplicity, robustness and abilities to study discontinuous and disjointed functions.

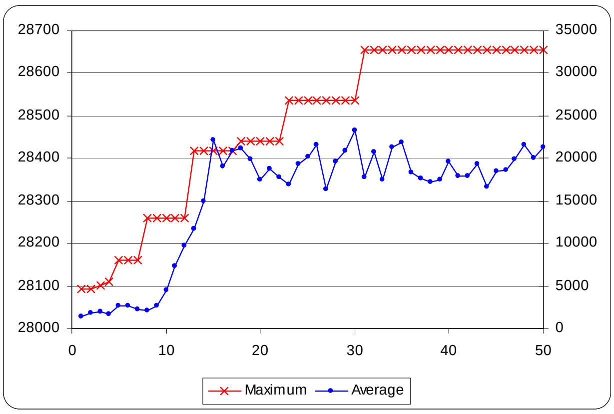

Figure 2: Optimization of roughness coefficient and outflow - Evolution of a 60 chains population through 50 generations

4 SOME EXAMPLES ON REAL CATCHMENTS

From any Digital Elevation Model, WOLFHYDRO ensures a suitable modification of this information to fit with the hypotheses of the hydrological propagation code. It induces slight local topographic modifications to prevent local depressions or flat areas and to create continuous slope paths.

After this fundamental and interactive stage, the hydrographic network is automatically delineated. A click on a point of this net induces an iterative automatic process to determine the limits of the catchment. River network propagation brings out to an other specific hydrodynamic process ensured with WOLF1D, presented in others publications [5][6][7].

The next example is the Ambleve watershed that covers a global surface of 976 km² at the Targnon outlet. The total number of nodes is 1'085'000 and the river network contains 9'000 segments of discretisation. The hydrologic modelisation permits to determine the discharge evolutions into the river network and the management optimization of two relevant dams present in the catchment (see Figures 3 and 4).

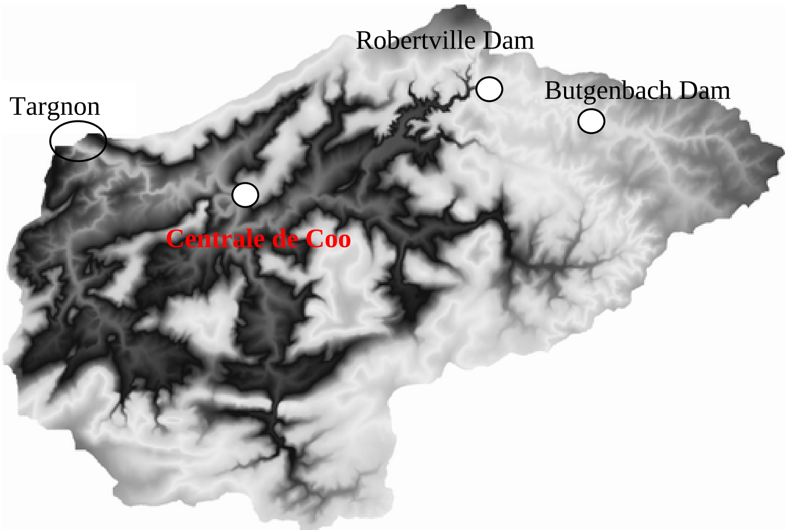

Figure 3 : Topography of Amblève watershed (Belgium)

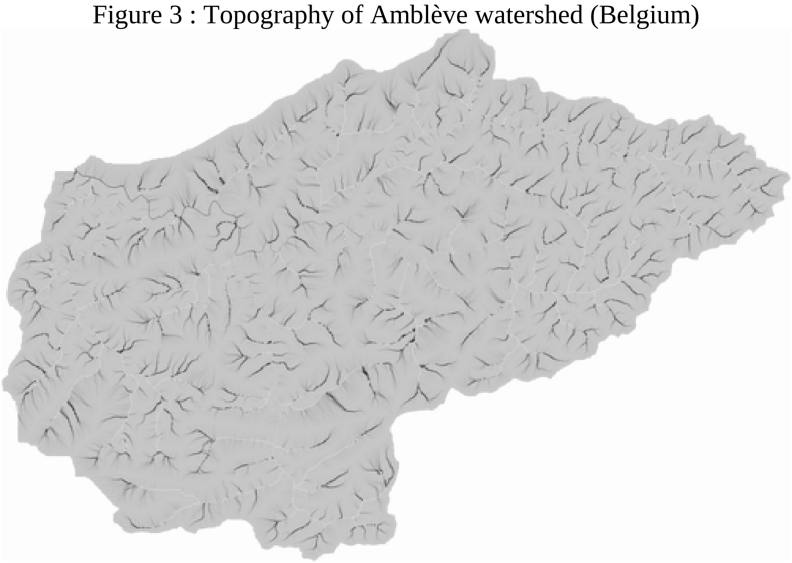

Figure 4 : Hydraulic convergences

An other application is the verification of the discharge capacity of large hydraulic constructions around the world due to likely climatic evolution and availability of hydrological numerical data on the concerned sites. In this way and to prevent extreme events, Switzerland is interested in the development and application of distributed physically based models.

Switzerland has a digital elevation model on all its territory. In the case of Mattmark watershed, the part of general map (Fig. 6) represents a global surface of 150 km² (raster of +- 200.000 nodes). A shading view of this topography can be easily obtained by the end-user interface of Wolf. The dam and the reservoir clearly appears at the centre of the Figure 7.

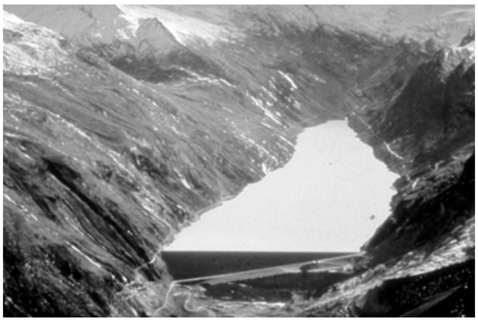

Figure 5 : Dam of Mattmark

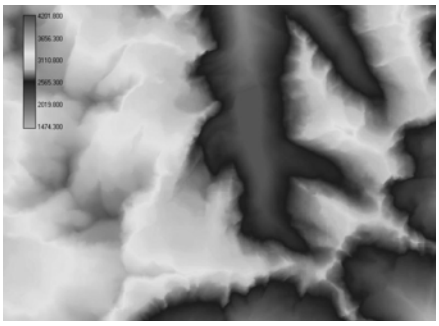

Figure 6 : DEM of Mattmark at 25m

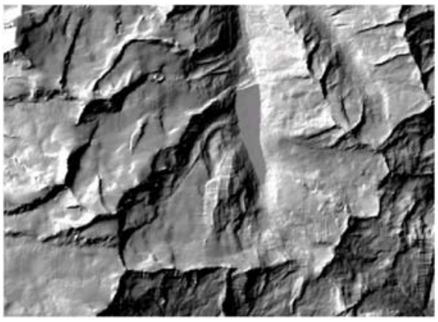

Figure 7 : Shading view of the DEM

Complete modelisation of an extreme event consists in a first hydrological computation. After automatic topographic corrections, catchment and river network determination, the results of the hydrological stage are temporally and spatially distributed lateral flows poured into the river network. The second stage consists in the propagation of these discharges right down the outlet with WOLF1D.

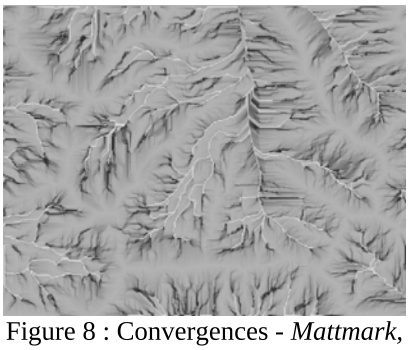

Figure 8 : Convergences - *Mattmark*, Switzerland

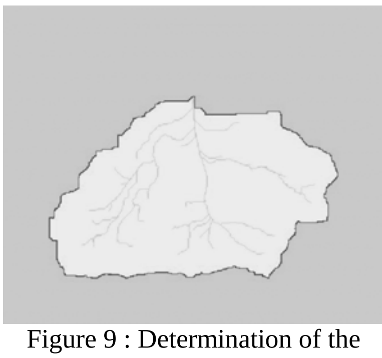

Figure 9 : Determination of the Mattmark's watershed, Switzerland

The result of this sequence is represented below (Fig. 10) for an extreme uniform rain, temporally variable, with safety saturated soil properties. A comparison with an observed hydrograph completes the validation of the simulation.

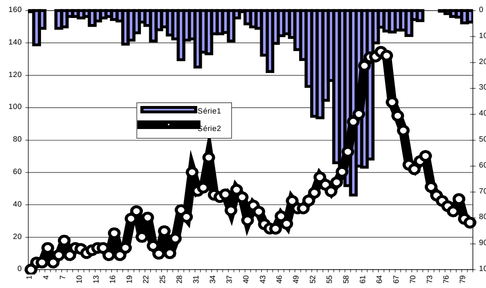

Figure 10 : Extreme rain and observed hydrograph

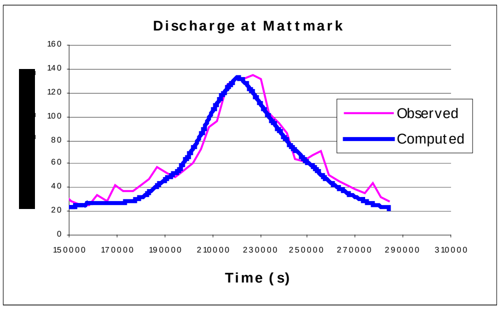

Figure 11 : Comparison between observed and computed hydrograph

5 CONCLUSIONS

Development of physically based models is a relatively new trend in free-surface hydrological modeling. The original approach used in WOLFHYDRO to adjust the topography and the determination of the catchment and river path are completely defined in accordance with the diffusive equations. It ensures a good transmission of the flux between hydrological and hydrodynamic stages. The diffusive equations are demonstrated to be suitable for such modelisation on any topography. Besides, a complete hydrodynamic software WOLF1D propagates the resulting hydrograms trough the network of rivers.

In WOLFHYDRO, the multilayers discretisation with temporal evolutive exchanges between surrounding layers and finite volumes is useful for the simulation on long periods. Different friction laws have been tested in order to ensure the reliability of all the phases. To ensure an objective tuning of parameters, inverse fitting methods are actually successfully used. Genetic Algorithms provide significative results and the HACH gains growing hope for the future in such approaches with the development of computer’s capacity and speed calculation.

The finite volumes method, used in all the softwares of the WOLF package, work on very large discretisation in short CPU times with the presence of potential discontinuities with reasonable computer’s resources (Personal Computer).

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