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A physically-based approach to predict input hydrographs in managed reservoirs

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ABSTRACT : Recently, the modelling of hydrology has experienced considerable activity, with a relatively new trend of direct modelization of the thin water layer flowing on the ground. The physical reasoning in hydrological modelisations presents many advantage of improving and hastening the calibration stage and of reflecting easily any change of land use. As simplified representation of a complex system, the model requires a large amount of datas leading to uncertainties in the parameters values. However, sensitivity tests including data variations in realistic limits can be easily examined in order to quantify the corresponding error scope of the output hydrographs. Besides, the superiority of a numerical code based on non-linear formulations can lead to substantial errors, mainly by neglecting the presence of potential discontinuities. A finite element approach is therefore suggested, overcoming all these difficulties. Applications demonstrate accurate and encouraging results and prove that this kind of software can assist the manager in the design stages as well as in the optimisation of a daily management.

1. INTRODUCTION

The reliable determination of usual and extreme inputs in a reservoir is a fundamental concern for dam safety and daily management. The hydrological stage on a watershed can be understood and simulated as the transformation processes arising after the fall of the raindrop on the ground up to the flows that induces at the outlet of the catchment.

In order to sum up the most complex processes acting upon the input variable (the rainfalls) to convert it into an ouptut variable (the flows they induce at the outlet of the catchment), we will refer to physical considerations in searching direct modelization of the thin water layer flowing on the ground.

With the physical interpretation of the parameters, the impact of any change of catchment features can be predicted with confidence by modifying their value. Sensitivity tests can be performed with data variation in realistic limits to quantify the corresponding error scope of the output hydrographs. Besides, physically based distributed models easily handle every topographic characteristics and soil types.

2. THEORETICAL MODEL

We focus here on the thin water layer propagating on natural tridimensional slopes in order to compute the lateral discharge for each element river. This additional inflow that propagates in the main drainage path is then computed in a final stage with the specific software applied this Symposium in the scope of dam-break flood wave propagation..

It is generally assumed that a dynamic equilibrium exists between friction and gravity components in the direction of flow. Resulting from the scale difference between the characteristic spatial dimension and water layer thickness, dynamic equations reduce to biunivoque relationships between the speed components and the water depth.

$$\bar{u} = \sqrt[4]{\sin\theta_j \sin\theta_j}\; c_f \sqrt{h} \cos\theta_s = a' h^m \cos\theta_s \tag{1}$$

$$\bar{v} = \sqrt[4]{\sin\theta_j \sin\theta_j}\; c_f \sqrt{h} \sin\theta_s = a' h^m \sin\theta_s \tag{2}$$

with x, t = the time and space variables; h(x,t) =the height of water; u, v(x,t) = components of the average speed along respectively the axes x, y; r(x,t) = the speed of the rainfalls; i(x,t) = the infiltration speed into the soil; θ_i = the opposite of the angle between local topography and the axis i; θ_S = the angle between the local flow direction and the axis x;a', c_f = parameters including surface and flow characteristics

They convert the continuity equation, expressed in terms of water layer thickness, into the following fully non-linear quasi-tridimensional system :

$$\frac{\partial h}{\partial t} + \frac{\partial\,(a_i h^{m+1})}{\partial x_i} + B\,(h) = 0 \tag{3}$$

with B(h) = the general function including the infiltration speed into the soil, the intensity of rainfalls and other effects of exchanges and losses, a_i = parameters including topographical data, surface and flow characteristics.

This kinematic wave approximation was proposed for the first time in the hydrologic field by Woolhizer and Ligett. They assessed the conditions of validity referring to two adimensional numbers and proved that overland flows conform to the fit range of these adimensional values.

Besides, several experiments confirmed that laminar and turbulent flows arise for each covering, depending on soil properties, fluctuations in depth and roughness and raindrop impact. A reasonable agreement can be assumed with the biunique relation between depth and discharge proposed by Manning.

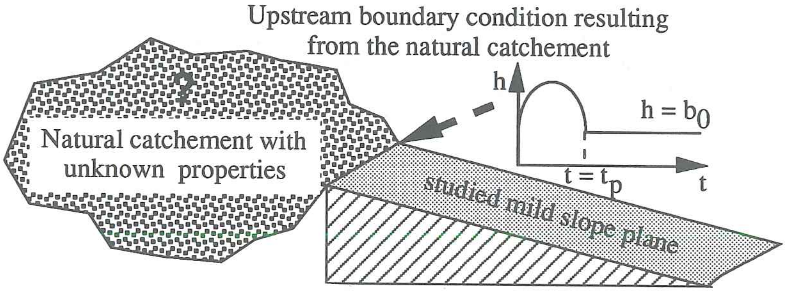

Figure 1. - Symbolic description of the studied catchement

3. SPURIOUS OSCILLATIONS IN OVERLAND FLOWS COMPUTATIONS

The first theoretical example shows that models built on the kinematic hypothesis are confined to work on "equivalent" catchment elements of simple shape, instead of the original quasi-tridimensional topography, whenever the presence of potential discontinuities is neglected.

We suppose that a natural catchment ends downstream in a constant slope plane. We provide no information about physical, topographical and morphological properties of the natural upstream part of the studied basin. Nevertheless, we describe the temporal evolution of the water depth at the upstream boundary of the ending slope. Due to the transformation processes on the unknown catchment, it takes the shape of half a sinusoïdal period, followed by a constant value. We leave the system evolve freely in the time and we investigate the impervious plane submitted to a constant rainfall intensity.

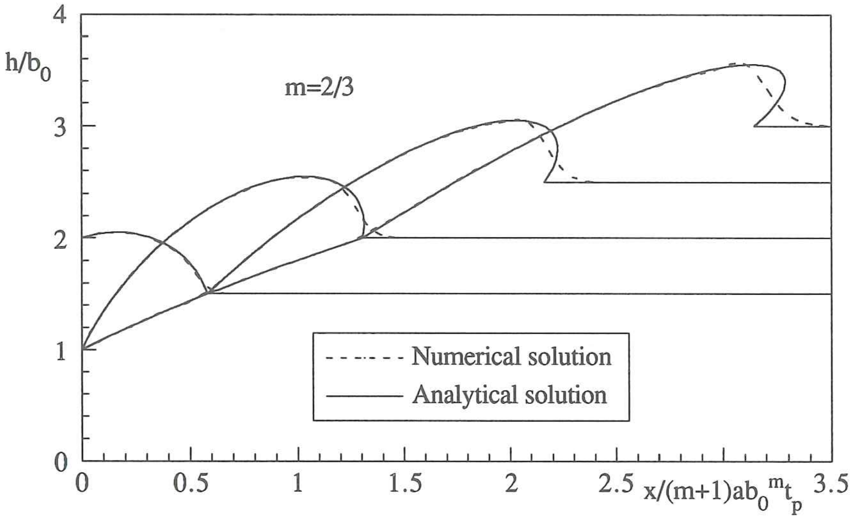

Figure 2. - Free surface flow on the mild slope plane for different times

Since the celerity is an increasing function of water depth, the higher points of the wave will overtake and crowd the lower portions in front of them. The wave becomes steep and the analytical free surface flow takes the breaking profile illustrated on figure 2. This solution brings fundamental contradictions referring to kinematic hypothesis, which ensures a biunivoque relation between depth and discharge. A theoretical approach of overland flow dynamics proves that a fit approximation consists, at this scale of modelization, to introduce moving bores satisfying the continuity requirement. Despite these shocks that are physically relevant, the kinematic wave approximation is theoretically confirmed to describe the continuous part of the solution.

4. NUMERICAL CONSIDERATIONS

It can be stressed that the classical Galerkin formulation used with the finite element method fails to predict and track with confidence shocks that occur in the correct solution. It induces parasitic effects highlighted by significant errors in the global volume balance.

The proposed shock capturing approach introduces discontinuous weighting functions in order to selectively dissipate the parasitic waves. The application of the Petrov-Galerkin

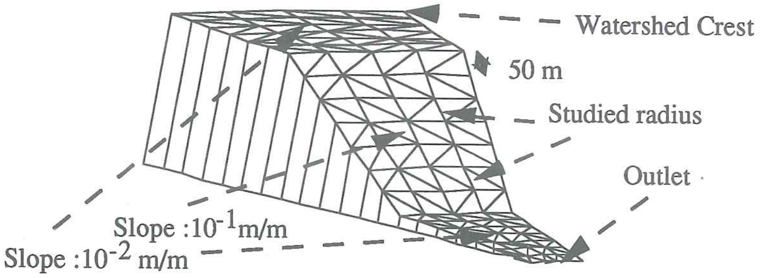

Figure 3 - Discretization of the studied catchment

technique to the basic equations leads to an orthogonal projection of the residual error due to discretization approximation to a set of linearly independent functions included in a vector P. We suggest the following test function components for P :

$$P_i = N_i + \alpha'_{ux}\frac{\partial N_i}{\partial x} + \alpha'_{uy}\frac{\partial N_i}{\partial y} \qquad (4)$$

with n = the number of discretization points; $h = N^T . H$, with H the approximate unknowns vector; $N^T = < N_1, N_2,..., N_n >$, with N_i the classical interpolation functions; $P^T = < P_1, P_2,..., P_n >$, with P_i the original shape functions; α'_{ux} , α'_{uy} = the dissipation parameters

Moreover, a second variant of the code, including the features to handle any natural topography and landuse was built with explicit upwind first order and second order finite volume methods. The temporal discretisation is based on explicit Runge Kutta schemes. Non-limear limiters are introduced in order to ensure monotone transitions of the water depths in shocks regions while maintaining high order of precision in smooth regions.

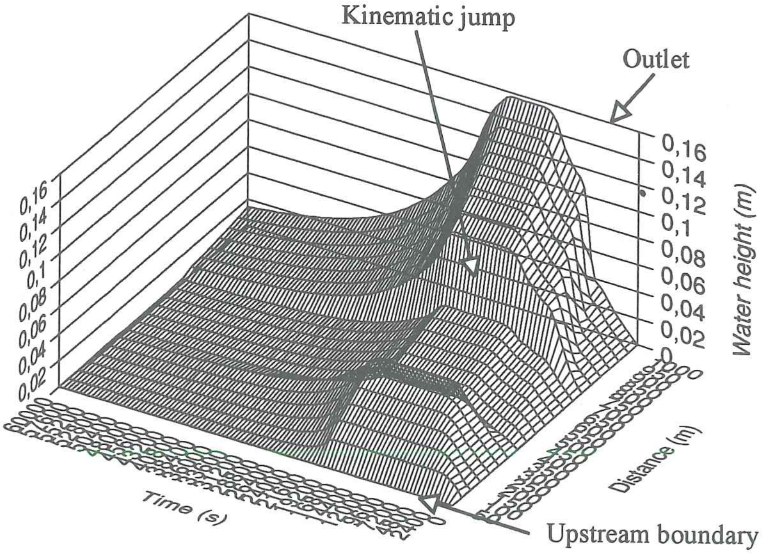

Figure 4 - Temporal evolution of water height on the studied radius

This second approach, reducing computation costs, is presently tested on basic applications to compare its behaviour with the first variant.

The computation of the previously described example was carried out with the finite element method in order to reveal the highly dissipative character of the method. This comparison (see figure 2) conforts the choice of the weak formulation of the problem, which ensures continuity through any kinematic jump.

5. COMPUTATION OF HYDROLOGICAL JUMPS

This example suggests in practice the occurence of this kind of shocks when we are dealing with a succession of natural slopes. The converging watershed area described in figure 3 is impervious but its morphological parameters values correspond to natural properties.

Theoretical considerations assess that if the first upstream transition of slopes introduces no hydraulic singularity, on the other hand the downstream one generates a transient shock because of the sudden decrease of discharge capabilities for a given water thickness. The code first produces a rising undisturbed shock, then a steady stage exhibiting the equilibrium for constant rainfalls of 5.10^{-6} m/s and finally the falling stage of the thin water layer after the end of this rainfall event (see figure 4).

6. INFLUENCES OF LANDUSE CHANGES

Each version of the proposed non-linear package works on a general digital terrain model, and handles spatial and temporal variations of rainfall and soil properties. Partially dried elements deal with the effects of infiltration, acting as a withdrawal for the free surface flows.

This approach is actually comforted by comparison with experimental data on natural watersheds.

The physical meaning of each parameter of the modelization and the much more realistic mathematical approach in terms of understanding the physics of overland flow processes allow to reflect easily the impact of any change of catchment features, as highlighted in fugure 5, with a small 34-ha natural catchment of submitted to a constant rainfall of 15.10^{-6} m/s during 1200 s.

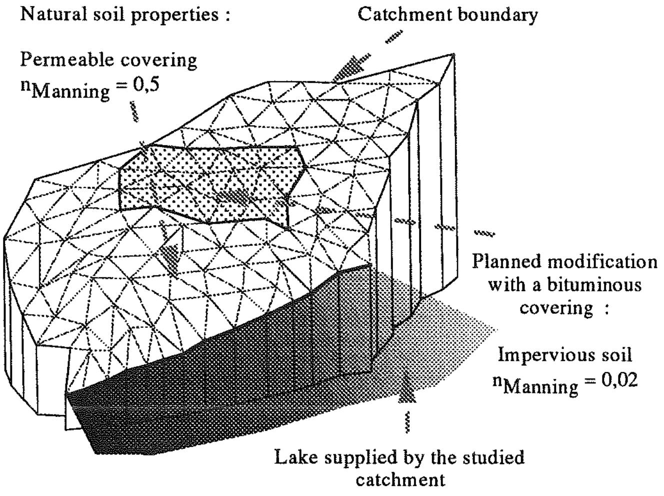

Figure 5 - Discretisation of the studied geometry

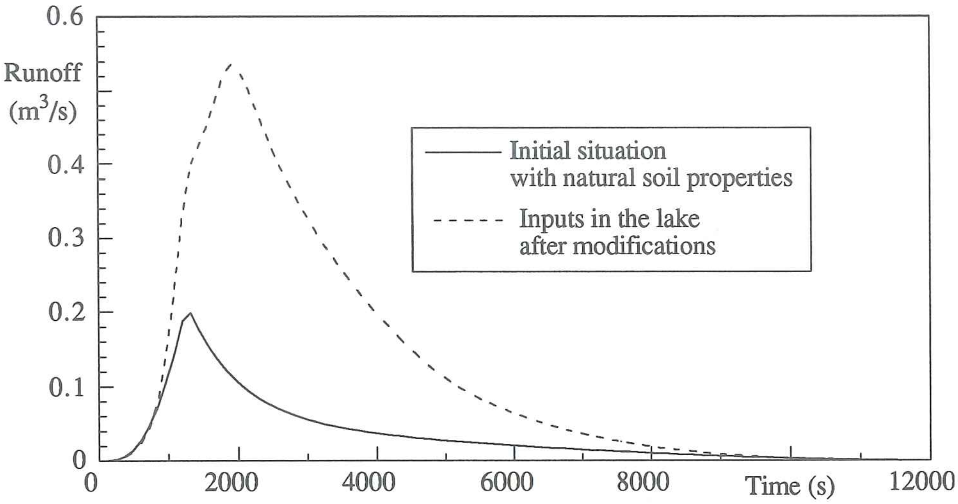

Figure 6. - Flood hydrographs poured in the lake before and after soil covering changes

This example analyses the effects on the hydrograph poured in a lake resulting from a covering modification. The first simulation is carried out with natural soil parameters while the curve of modified inputs reflects the effects of a planned bituminous surface (figure 6).

7. CONCLUSION

A global understanding of the physics of surface flows, in the fields of hydrology and hydrodynamics, leads to very large prospects of applications, especially in the scope of water resources management. However, reliable numerical resolutions have to be found, which apply for a wide range of hydrodynamic processes including problems of shocks.

In the field of hydrology, physically based models can follow the thin water layer flowing on the ground. However, the potential presence of discontinuities is demonstrated for runoffs computed on three-dimensional digital terrain models. Shock capturing approaches are therefore to be applied in accordance with the physical meaning.

Globally, the theoretical and numerical study of the physics of the unsteady free surface flows passes beyond all characteristic scale differences. Numerous benefits of this point of view can be found in considering first common physical features of the flows, then in discerning numerical shortcomings also as cautions aimed to ensure the best numerical efficiency.

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