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Calibration of Numerical Modelling of Hydrological and Hydraulic Processes in Arnas Experimental Basin

CALIBRATION OF NUMERICAL MODELLING OF HYDROLOGICAL AND HYDRAULIC PROCESSES IN ARNÁS EXPERIMENTAL BASIN

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ABSTRACT

Three quick and robust numerical models of hydrological and hydraulic processes are presented in this work applied to the simulation of the Arnás experimental basin: one semi-distributed model –combining SCS unit hydrograph method and a 1D hydraulic model- and two fully distributed ones. The distributed models combine rainfall and infiltration with an overland hydraulic model, a 2D unsteady flow shallow water model in the so called complete model, and a 2D unsteady kinematic-wave model in the simplified model. In both cases the hydrological model uses features based in simple but physically-based laws to calculate the evapotranspiration and the infiltration.

The first model, the semi-distributed one, combines the SCS unit hydrograph method for the main part of the catchment with a one-dimensional unsteady flow hydraulic model for the channel flow.

The two fully distributed numerical schemes are based on a methodology that works on unstructured meshes solved with an explicit finite volume upwind scheme able to solve the advance over dry bed.

The solutions are compared not only with the field measurements available but with the simulations carried out by means of the SCS unit hydrograph method alone.

Keywords: Hydrological calibration. Hydrological and hydraulic simulation. Shallow water. Overland flow. Finite volumes.

1. INTRODUCTION

Three numerical models of hydrological and hydraulic processes are presented in this work applied to the simulation of the Arnás experimental basin. The development of this type of connected hydrological-hydraulic models is justified since they can be a useful tool to achieve a plan of integral management of basins from the point of view of water resources. Once the complexity of designing an integrated model with such characteristics is known it is clear that the computational time and the confidence on the results must be fundamental aims.

The first model is based in the full two-dimensional transient shallow water equations combined with evapotranspiration (Heargraves) and infiltration (Horton) laws. It works on unstructured (triangular) or structured (quadrilateral and triangular) meshes. The equations are solved with an explicit finite volume upwind scheme able to solve the advance over dry bed and wetting/drying fronts. This model has been calibrated during the last years in a wide range of real and academic cases giving an efficient result (Brufau 2000, Brufau et al. 2004, Murillo 2006, Murillo et al 2006).

The second model combines a 2D kinematic-wave model with the same evapotranspiration and infiltration laws used in the first model.

The third model, the semi-distributed one, combines the aggregated SCS curve number abstraction method and the SCS unit hydrograph method for modelling the rainfall-runoff processes in the main part of the catchment with a one-dimensional unsteady flow hydraulic model for the channel flow. The latter is based on the 1D shallow water equations on irregular cross sections solved with an explicit finite volume upwind scheme able to deal with the advance over dry bed. This hydraulic model has also been calibrated during the last years in a wide range of real and academic cases giving an efficient result (Burguete and Garcia-Navarro 2001). The hydrograph provided by the hydrological model depending on the runoff serves as an entry condition to the 1D hydraulic model in terms of a boundary condition and that is the form the coupling goes on in this case.

The solutions obtained by means of these three models are compared not only with the data available but with the simulations carried out by means of a fully aggregated SCS unit hydrograph method.

2. ARNAS DESCRIPTION

Arnás is a well-instrumented basin -2.84 km^2 in area- located at the Spanish Pyrenees "Figure 1". The elevation of the highest elevation is 1340 m.a.s.l. (meters above sea level), and the outlet is at 910 m.a.s.l. The bedrock is Eocene flysch that consists of alternating sandstone and marl layers that dip northward and the dominant vegetation are brushes. The E–W orientation of the stream results in a strong contrast in slope between the steep south-facing slope (average value 0.5 m/m) and the gentle north-facing slope (average value 0.28 m/m). Most of the valley floor has a slope of less than 0.09 m/m, being made up of small fluvial terraces (Lana-Renault 2007, Lana-Renault et al. 2007). Several maps have been used to run out the simulations, those that describe the kind of vegetation and soil types in the catchment and a DTM (Digital Terrain Model) within 5 meters resolution. The main channel is 1136 meters long and there are field measurements of twenty seven cross sections to provide information to the one-dimensional model "Figure 2". Experimental data of water discharge from different rainfall events, together with precipitation, temperature, atmosphere and soil humidity and solar radiation have been used in order to calibrate the numerical model. The data are available since 1996 so different characteristics of soil and precipitation are observed.

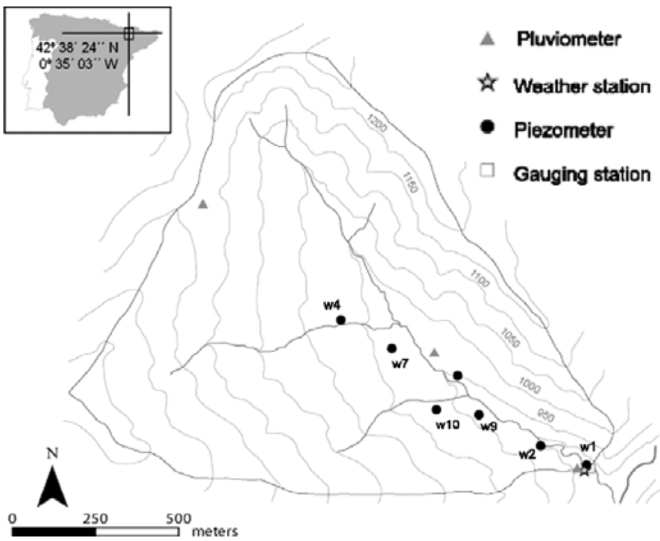

Figure 1: Map of the Arnás catchment showing the sites of the main monitoring instruments.

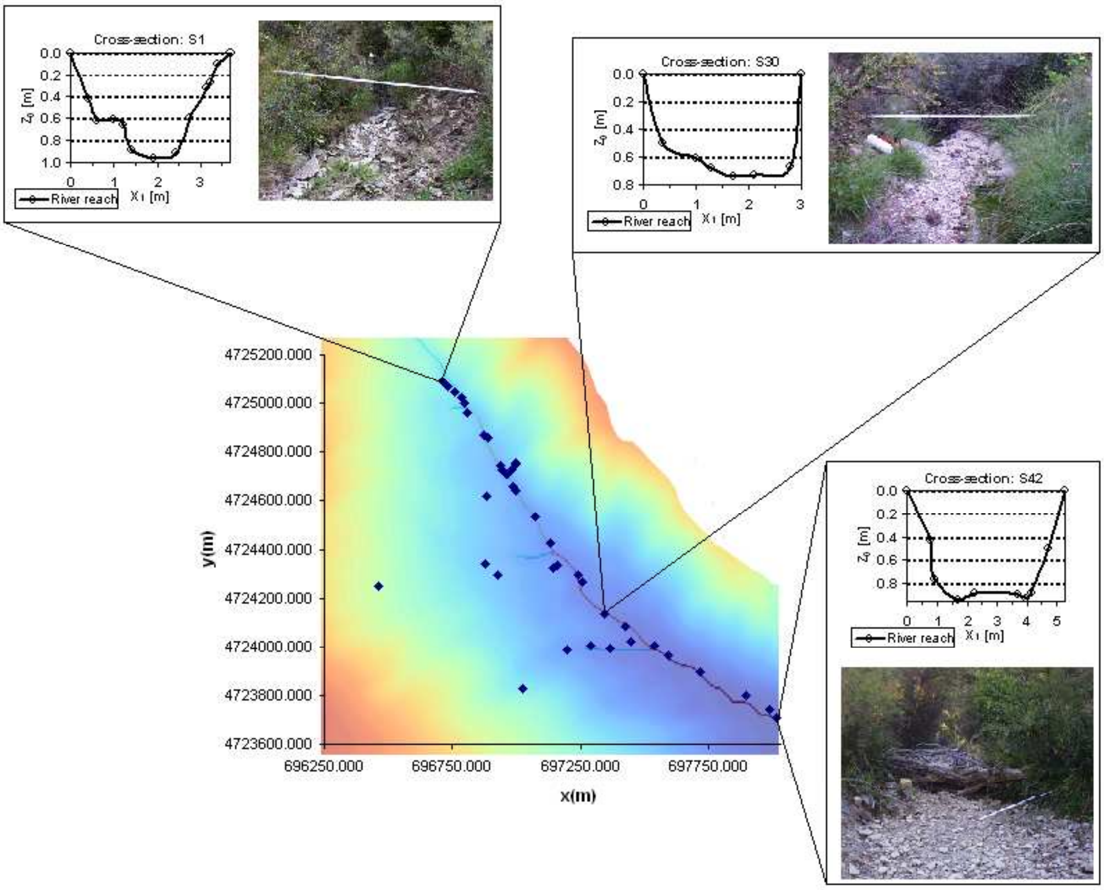

Figure 2: Map of the Arnás catchment showing the location of the 27 cross sections in the main channel and those from the secondary reaches.

3. COMPLETE AND KINEMATIC-WAVE MODELS DESCRIPTION

3.1 Hydraulic models

The surface motion of the water is simulated by the two-dimensional shallow water equations in the complete model and by the two-dimensional kinematic approach in the kinematic wave model. The two models are able to deal with different kind of grids. An explicit first order in space and time finite volume scheme was used to solve both systems of equations (Murillo 2006).

Shallow water models are based in the Saint Venant equations that, assuming incompressible flow and governed by hydrostatic pressure, can be written in a conservative form:

$$\frac{\partial}{\partial t}\mathbf{U}(\mathrm{x},\mathrm{y},\mathrm{t})+\nabla\mathbf{F}(\mathbf{U})=\mathbf{H}(\mathbf{U}) \tag{1}$$

with:

$$\mathbf{U}=\begin{pmatrix}h\\hu\\hv\end{pmatrix};\mathbf{F}=\begin{pmatrix}hu & hv\\ hu^2+g\frac{h^2}{2} & huv\\ huv & hu^2+g\frac{h^2}{2}\end{pmatrix};\mathbf{H}=\begin{pmatrix}0\\ gh(S_{0x}-S_{fx})\\ gh(S_{0y}-S_{fy})\end{pmatrix}$$

where h is the water depth, u, v are the depth averaged velocity components in the x and y directions respectively, g is the acceleration of gravity, S_{fx} and S_{fy} are the bed energy line slopes in the in the x and y directions respectively (defined here by the Manning Formula),

$$S_{fx}=\frac{n^2h^2u\sqrt{u^2+v^2}}{h^{10/3}} \qquad S_{fy}=\frac{n^2h^2v\sqrt{u^2+v^2}}{h^{10/3}} \tag{2}$$

and S_{0x} and S_{0y} are the bed slopes also in the coordinate directions.

$$S_{0y}=-\frac{\partial z}{\partial y} \qquad S_{0x}=-\frac{\partial z}{\partial x} \tag{3}$$

being z the magnitude that describes the bed topography elevation and n the Manning roughness coefficient.

A mathematical model using the full set Eq. 1 is what the authors call a complete model. There exist different kind of approximations for the modelling of these equations by considering negligible some terms of the momentum equations. Some of these models are based on the assumption that the first two terms of both momentum equations are much smaller than the rest so that they may be neglected thus reducing the system. The Kinematic-Wave model goes further and neglects all the left terms in the momentum equations what forces the equality between the friction and the gravitational terms reducing the system to three simple equations.

Having used the Manning formula (Chow 1959) to model the friction term, the kinematic model is formed by

$$\frac{\partial h}{\partial t}+\nabla\boldsymbol{q}=0 \quad , \quad \boldsymbol{q}=(hu,hv)$$

$$hu=sign(S_{0x})\cdot\frac{h^{5/3}\sqrt{S_{0x}}}{n\sqrt[4]{1+\left(\frac{S_{0yk}}{S_{0xk}}\right)^2}} \qquad hv=sign(S_{0y})\cdot\frac{h^{5/3}\sqrt{S_{0y}}}{n\sqrt[4]{1+\left(\frac{S_{0xk}}{S_{0yk}}\right)^2}} \tag{4}$$

One of the objectives of the present study was to compare the relative performance of a complete and a simplified two-dimensional overland flow model in order to produce a simulation tool as robust, accurate and efficient as possible to serve a AHIS (Automatic Hydrological Information System).

3.2 Hydrological model

According with the available data, the evapotranspiration processes were estimated by Heargraves model (Heargraves 1985)

$$ET0 = 0{,}0135\ (tmed + 17{,}78)\ Rs \quad (5)$$

where: *ET0* is the daily potential evapotranspiration in mm/day, *tmed* is the mean temperature in °C and *Rs* is the incoming solar radiation, converted into mm/day.

The incoming solar radiation, *Rs*, is evaluated from the extraterrestrial solar radiation (Sanami 2000).

$$R_s = R_0 \cdot KT\ (t_{\max} - t_{\min})^{0,5} \quad (6)$$

where: *Rs* is the incoming solar radiation, R_0 the extraterrestrial solar radiation, *KT* is an empirical coefficient (*KT*=0.162 for interior regions and *KT*=0.19 for coastal regions), $t_{\max}$ is the maximum daily temperature and $t_{\min}$ is the minimum daily temperature. There exist several tables to evaluate the extraterrestrial solar radiation (R_0), all of them as a function of the latitude and month.

It is important to remark that Eq. 5 provides only the soil potential evapotranspiration. The real evapotranspiration capacity of the subbasin is calculated by multiplying the potential evapotranspiration times the square root of the relative humidity of the soil. (Michel 1989).

Infiltration has been modelled using Horton formula (ASCE, 1996)

$$i = i_c + (i_0 - ic)e^{-k \cdot t} \quad (7)$$

where *i* is the infiltration rate, i_c is the constant infiltration rate where the value tends to, i_0 is the initial infiltration rate and *k* is an empirical constant. The hydrological models described here have been used together with the hydraulic models described in the above subsection.

4. SCS-1D MODEL DESCRIPTION

The semi-distributed Hydrological-Hydraulic scheme is a quick and robust tool combining a rainfall-runoff model with a 1D unsteady flow hydraulic model (Burguete and Garcia-Navarro, 2001).

The SCS unit hydrograph method is an aggregated hydrological model which calculates the response given by the basin to a rainfall event of one millimetre with a duration *dt.* Only four parameters are needed for this model: the subbasin area, the hydraulic length, the slope and the curve number. The latter parameter can be found in tables as a function of the soil and vegetation types and that must be corrected according to the previous soil humidity state (Mays 2001).

$$q_p = \frac{2.08A}{T_p}$$

$$T_p = 0.67T_c$$

$$Tb = Tp + t \quad (8)$$

$$Tc = \frac{L^{0.8}(S+1)^{0.7}}{1900Y^{0.5}}$$

where: q_p is the peak discharge of the unit hydrograph (m^2/s), A is the subbasin area (km^2), L is the hydraulic length (feet), Y the subbasin mean slope (m/m), Tc is the subbasin concentration time (hr), Tb is the base time of the UH (h), Tp is the time to peak of the UH (hr), and S is a function of the curve number (inches).

$$S = \frac{1000}{CN} - 10 \tag{9}$$

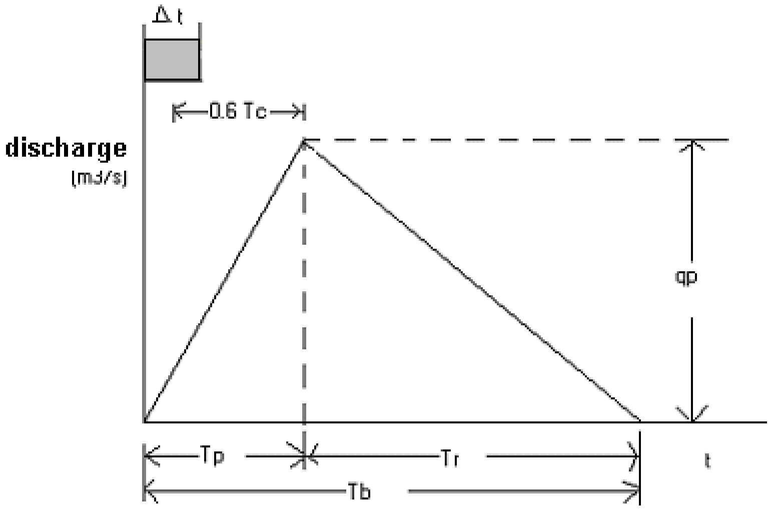

Figure 3 SCS unit hydrograph scheme.

Once the unit hydrograph is calculated the response of the basin to a specific rainfall event is just the convolution of the effective rain times the unit hydrograph. That effective rain is calculated by subtracting the infiltration losses calculated by the SCS curve number method (Mays 2001).

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{10}$$

Where P_e is the effective accumulated rain –excess of precipitation- and P the accumulated rain.

The 1D numerical model is a second order (TVD) explicit numerical scheme that results from a limited combination of the Lax-Wendroff method and second order upwind to solve the one-dimensional hyperbolic shallow water system with source terms.

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

$$\boldsymbol{U} = \begin{pmatrix} A \\ Q \end{pmatrix}, \quad \boldsymbol{F} = \begin{pmatrix} Q \\ \dfrac{Q^2}{A} + gI_1 \end{pmatrix}, \quad \boldsymbol{H} = \begin{pmatrix} 0 \\ g\left[I_2 + A\left(S_0 - S_f\right)\right] \end{pmatrix} \tag{11}$$

where Q is the discharge, A is the wetted cross section, g is the acceleration of gravity and S_0 is the bed slope. I_1 and I_2 account for pressure forces

$$I_1(x,A) = \int_0^{h(x,A)} [h(x,A) - z]\sigma(x,z)dz \qquad I_2(x,A) = \int_0^{h(x,A)} [h(x,A) - z]\frac{\partial \sigma(x,z)}{\partial x} dz$$

where h is the water depth and σ the channel width at a position z from the bottom, S_f is associated with bed friction and represented by the empirical Manning law

$$S_f = \frac{n^2 Q^2 P^{4/3}}{A^{10/3}}$$

where n is the coefficient of bed roughness and P the wetted perimeter.

The hydrographs obtained for each subbasin by the SCS unit hydrograph method are transferred to the 1D model as an additional contribution to the spilling section of each subbasin. So the hydrograph provided by the SCS unit hydrograph method serves as an entry condition in terms of a boundary condition and that is the form the coupling goes on. For this application the Arnás basin has been divided in seven different subbasins "Figure 4" and transporting the hydrographs by means of the 1D numerical model (semi-distributed method) and applying the SCS unit hydrograph method to the whole basin (aggregated method).

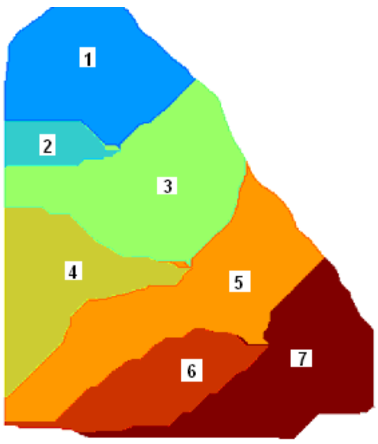

Figure 4: Division of Arnas basin in seven subbasins.

Table 1 Calculated values for Arnas basin and the seven subbasins used in the simulations.

Subbasin	Curve number	Area (km^2)	Hydraulic length (m)	slope (%)
Arnás	43.8	2.270	1136.5	18.8
1	49.5	0.350	444.1	28.8
2	43.8	0.774	253.0	18.8
3	43.8	0.460	581.7	26.9
4	43.8	0.288	731.6	17.0
5	43.8	0.490	706.2	21.0
6	33.0	0.227	601.2	21.2
7	43.8	0.377	539.7	23.7

5. RESULTS AND DISCUSSION

Experimental field data corresponding to five different rainfall-runoff events with different previous soil humidity states are available. Only the solutions obtained for one of them with the complete model, the kinematic-wave model, the SCS-1D and the SCS models are presented. It has been chosen as representative of a dry soil condition.

"Figure 5" shows the comparison of the obtained results and the measured data for the Arnás basin in the August 15th, 2006 event.

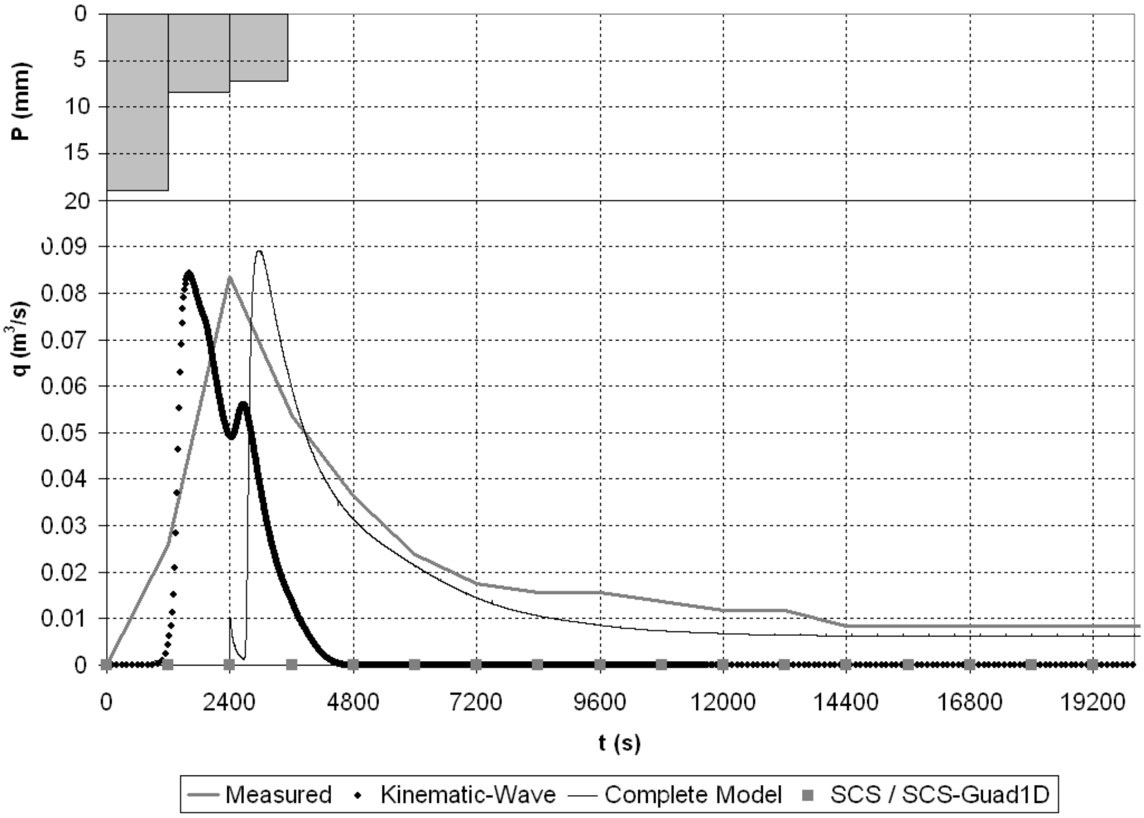

Figure 5: Comparison of the results and measured data for Arnás basin in dry conditions.

Table 2 Computation time of each model in a 2.4 GHz / 2 Gb RAM computer.

	Complete Model	Kinematic-Wave	SCS-1D	SCS
Dry event	67 minutes	27 minutes	3 minutes	1 minute

According with the results obtained both distributed models demonstrated their capability simulating hydrological and hydraulic processes in the Arnás basin in dry soil conditions showing good accuracy.

On the other hand, the SCS unit hydrograph has shown not so good behaviour simulating events in the Arnás catchment in dry conditions. It is important to remark that in this concrete case, the SCS unit hydrograph method predicts a null response both for the Arnás catchment and the seven-divided Arnás catchment connected by means of the 1D numerical model.

It is important to remark that although the semi-distributed model has no advantages over the aggregated in the case of simulating Arnás basin is in the case of unconnected and bigger basins than Arnás where the SCS-1D model would present it's best characteristics in terms of accuracy and computation time.

As future work, a complete hydrological-hydraulic model in terms of the complete model and the kinematic wave model is going to be developed adding infiltration and subterranean flow processes

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