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Final document on the third year, third activity: "Coupling meteorological and hydraulic modelling to develop a hydro-meteorological chain. Simulation of a test case"

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Abstract

The purpose of the collaboration between LAMPIT (Department of Soil Defence, University of Calabria) and CMCC is to develop an hydro-meteorological chain in order to obtain a reliable tool in the context of flood evolution prediction able to provide quantitative information of practical importance within the civil protection activities.

The LAMPIT contribution to the project concerns the mathematical description of both the generation and propagation of flood events at basin scale. The work here presented has been carried out in close cooperation with CIRA researchers (dr. Pasquale Schiano and dr. Paola Mercogliano) and DISTART (Dipartimento di Ingegneria delle Strutture, dei Trasporti, delle Acque, del Rilevamento, del Territorio - University of Bologna) researchers (Prof. Armando Brath, Ing. Elena Toth and Ing. Alessio Domeneghetti).

The mathematical representation of the flow processes is based on the fully dynamic shallow water equations. The solution of these equations, excluding some simplified cases, can be obtained by numerical integration only. Many schemes based on fully dynamic and simplified shallow water equations have been proposed in literature. Some of these schemes have been implemented in the LAMPIT laboratory and applied to simulate simple cases of overland flow as already presented. Afterwards the implemented codes have been applied to simulate overland flow over real topography. In this contest some numerical anomalies appeared due to the presence of small water depth over high slope and irregular topography. According to that a careful analysis of these problems has been made and some numerical techniques have been implemented in order to prevent them. Finally the developed model has been applied to simulate a rainfall event in a Reno sub basin. A Digital Elevation Model (DEM) with 20 m cell size has been generated from topographical maps of the area in 1:10000 scale, using a GIS software and the Corine map has been used to obtain the land use/land cover for the watershed. Varying in time and in space effective rainfalls, computed by DISTART researchers, have been fed in the model as input data. The model has been calibrated and validated using the rainfall event occurred in Reno basin on 7-9 th november 2003. The numerical results have been compared with the observed data and found to be satisfactory. A sensitivity study of the roughness parameter has been also carried out. Finally the hydro-meteorological chain has been implemented to simulate the same rainfall event on Reno basin at Pracchia Station starting from rainfall data simulated by the CIRA researchers using a meteorological model. The developed model seems to be an useful tool for the simulation of overland flow events.

Keywords: Hydrometeorological chain, Flood propagation

JEL Classification:

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INTRODUCTION

The dynamics of rainfall, infiltration, surface runoff and erosion processes would be more easily understood with a correct, adequate and scale-variant mathematical representation of these interactive processes.
Mathematical models are useful analysis tools to understand problems in watersheds associated with runoff, and to find solutions through land use changes and best management practices. However, before a model is applied in the field, it must be tested and checked to ensure that the model represents the real world adequately.
The LAMPIT contribution to the project concerns the mathematical description of both the generation and propagation of the surface –runoff at basin scale.
In particular the mathematical representation of the flow processes is based on the fully dynamic shallow water equations. The solution of these equations, excluding some simplified cases, can be obtained by numerical integration only. Many schemes based on fully dynamic and simplified shallow water equations have been proposed in literature. During the project some of these schemes are implemented in the LAMPIT. Generally in simulation of overland flow some numerical anomalies appear due to the presence of small water depth over high slope and irregular topography. According to that a careful analysis of these problems has been made and some numerical techniques have been implemented in order to prevent them (Final document on the second year third activity: "*Analysis of the hydrometeorological chain performances on a real basin*", First document on the third year: "*Numerical techniques for preventing computational instability problems to simulate floods due to low-intensity rainfall*"). A major component of model development is its verification and validation. In literature itis a general rule that the verification and validation procedure consists of some steps: 1. verification by analytic solutions to ensure that a numerical model shall solve the mathematical equations correctly and predict the physical processes adequately and realistically; 2. validation by laboratory experiments such as simulated rainfall experiments conducted in controlled environments and simplified testing conditions; 3. and validation by field measurements to prove that the model has the capability of predicting the behaviour of natural phenomenon, at least approximately. Indeed the analyses related to the first two steps (model verification by analytic solution under simplified conditions and its validation by published data) have been already reported in previous reports (Final document on the second year second activity: "*Preliminary results obtained by using the hydraulic propagation model and sensibility analysis with respect to the parameters*")
This work presents the results of the validation by field measurements or observed field data. In particular the implemented code has been applied to a watershed to predict runoff under variable rainfall intensity. In this way the predictive ability and adequacy of the model for real application has been tested.
The model has been applied to simulate the rainfall event occurred in a Reno sub basin on 7-9th november 2003. The identified watershed is the most upstream part of Reno river basin (Italy), at the closure section of Pracchia, located in the Tuscan part of the Reno basin, and near the Regione Emilia Romagna. The drainage area is around 40 km^2 and there are no reservoir upstream nor other important hydraulic structures that may modify the natural hydrological and hydraulic process of the event.
The flood event that took place on 7-9 th November was a severe meteorological event with high rainfall intensities for some hours.

A Digital Elevation Model (DEM) with 20 m cell size has been generated from topographical maps of the area in 1:10000 scale, using a GIS software. The Corine map has been used to obtain the land use/land cover for the watershed.
It is well known that during a rainfall event a part of the rain volume is intercepted by vegetal cover and it is subsequently evaporated; another part of the rainfall volume which reaches the surface after interception loss infiltrates into soil. The remaining rainfall volume is transformed into surface runoff. The estimation of the losses and consequently of the effective rainfalls has been computed by the research group of the DISTART (University of Bologna). These net rains represent the input data of the implemented two dimensional numerical model.
The numerical results obtained by the numerical model are compared with the observed data.
Moreover in this contest is necessary to choose the values of the parameters which will be representative of the entire watershed and of the hydraulic process. In particular it was noticed by some authors (Bhardwaj and Kausulhal, 2009; Venkata et al., 2008; Shih et al., 2008; Jinkang et al., 2007; England et al., 2007; Jain and Sing, 2005) that the runoff volume, the hydrograph shape and the time to peak were affected by the change in the values of the roughness parameter. According to that a sensitivity study of the roughness parameter has been carried out.
Finally the hydro-meteorological chain has been implemented to simulate the same rainfall event on Reno sub basin watershed starting from rainfall data simulated by the CIRA researchers using a meteorological model.

1 MATHEMATICAL FORMULATION

In the previous report, according to a comparative analysis on numerical schemes, the MacCormack's scheme and HLL scheme have been improved and some numerical techniques have been implemented in order to simulate real overland flow situations. In order to highlight the work carried out in this period itis necessary to underline some aspects of the previous report.
The implemented codes are based on the fully two dimensional conservative shallow water equations:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} = \mathbf{S} \tag{1}$$

where:

$$\mathbf{U} = \begin{pmatrix} h \\ hu \\ hv \end{pmatrix} \tag{2}$$

$$\mathbf{F} = \begin{pmatrix} hu \\ hu^2 + gh^2/2 \\ huv \end{pmatrix}; \quad \mathbf{G} = \begin{pmatrix} hv \\ huv \\ hv^2 + gh^2/2 \end{pmatrix} \tag{3, 4}$$

$$\mathbf{S} = \begin{pmatrix} r \\ gh\left(S_{0x} - S_{fx}\right) \\ gh\left(S_{0y} - S_{fy}\right) \end{pmatrix} \tag{5}$$

with:
t is time; x, y are the horizontal coordinates; h is the water depth; u, v are the depth-averaged flow velocity in x- and y- directions; g is the gravitational acceleration; S_{0x}, S_{0y} are the bed slopes in x-

and *y*- directions; S_{fx}, S_{fy} are the friction slopes in *x*- and *y*- directions, which can be calculated from Strickler's formula as:

$$S_{fx} = \frac{u\sqrt{u^2 + v^2}}{K_S^2 \; h^{4/3}} \qquad\qquad S_{fy} = \frac{v\sqrt{u^2 + v^2}}{K_S^2 \; h^{4/3}} \tag{6,7}$$

r is the net rain intensity.

The finite volume method, widely adopted in the literature, has been used to discretize the previous equations. It considers the integral form of the shallow water equations that allows a quite easy implementation of shock capturing schemes on different mesh type.
The system of equation is integrated over an arbitrary control volume $\Omega_{i,j}$ and, in order to obtain surface integrals, the application of Green's theorem to each component of the vectors **F** and **G** leads to (Hirsch, 1990):

$$\frac{\partial}{\partial t}\int_{\Omega_{i,j}} \mathbf{U} d\Omega + \oint_{\partial\Omega_{i,j}} [\mathbf{F},\mathbf{G}]\cdot\mathbf{n}\, dL = \int_{\Omega_{i,j}} \mathbf{S} d\Omega \tag{8}$$

where $\partial\Omega_{i,j}$ being the boundary enclosing $\Omega_{i,j}$, **n** is the unit vector normal and *dL* is the length of each boundary. Denoting by $\mathbf{U}_{i,j}$ the average value of the flow variables over the control volume $\Omega_{i,j}$ at a given time, the equation (8) may be discretized as:

$$\mathbf{U}_{i,j}^{n+1} = \mathbf{U}_{i,j}^{n} - \frac{\Delta t}{\Omega_{i,j}} \sum_{r=1}^{4} \left[\mathbf{F},\mathbf{G}\right]_r \cdot \mathbf{n}_r \, \Delta L_r + \Delta t \mathbf{S}_{i,j}^{n} \tag{9}$$

The finite volume method, as represented by the equation (8), allows the decomposition of a two dimensional problem into a series of locally one dimensional problems to compute the normal flux through every side of a cell. Many algorithms have been proposed for the flux vectors computation: the most diffused in literature have been examined and implemented (Costanzo and Macchione 2004; Costanzo and Macchione 2005; Costanzo and Macchione, 2006a; Costanzo and Macchione 2006b).
In the analysis presented herein the first order upwind HLL scheme has been applied. This choice is due to its low computational time and the simple implementation that makes HLL scheme competitive for the application on vast watersheds.
HLL scheme is an approximate Riemann solver based on the work of Harten et al. (1983) and known as the HLL Riemann solver. This scheme, applied to the two dimensional equations, gives the following expression for the numerical flux across the edge of the computational cell Ω_L on the left and Ω_R on the right:

$$[\mathbf{f},\mathbf{g}]_r \cdot \mathbf{n}_r = \begin{cases} [\mathbf{f},\mathbf{g}]_L \cdot \mathbf{n}_r & if \;\; s_L \geq 0 \\ \dfrac{s_R\left([\mathbf{f},\mathbf{g}]\right)_L \cdot \mathbf{n}_r - s_L\left([\mathbf{f},\mathbf{g}]\right)_R \cdot \mathbf{n}_r + s_L s_R\left(\mathbf{U}_R - \mathbf{U}_L\right)}{s_R - s_L} & if \;\; s_L \leq 0 \leq s_R \\ [\mathbf{f},\mathbf{g}]_R \cdot \mathbf{n}_r & if \;\; s_R \leq 0 \end{cases} \tag{10}$$

Equation (10) depends on the value of the wave speeds s_L and s_R, therefore it is necessary to introduce approximate expressions of these variables. The wave speed estimators used in this work are obtained by the application of the two-rarefaction Riemann solver theory (Toro,2001):

$$s_L = \min\left([u,v]_L \cdot \mathbf{n}_r - \sqrt{gh_L}, u^* - \sqrt{gh^*}\right); s_R = \max\left([u,v]_R \cdot \mathbf{n}_r + \sqrt{gh_R}, u^* + \sqrt{gh^*}\right) \tag{11}$$

where:

$$u^* = \frac{1}{2}\left([u,v]_L + [u,v]_R\right)\cdot \mathbf{n}_r + \sqrt{gh_L} - \sqrt{gh_R}; \quad \sqrt{gh^*} = \frac{1}{2}\left(\sqrt{gh_L} + \sqrt{gh_R}\right) + \frac{1}{4}\left([u,v]_L - [u,v]_R\right)\cdot \mathbf{n}_r \tag{12}$$

Particular conditions are applied to s_L and s_R if there is a dry cell.

As for all explicit methods, both schemes have been subjected to the stability restriction given by the well-known Courant–Friedrich–Lewy (CFL) condition as follows:

$$\Delta t = C \frac{\Delta x}{\max(\sqrt{u^2 + v^2} + \sqrt{gh})} \tag{13}$$

where C is the Courant number.

In this context for the presence of low values of water depth, as those that generally characterize the rainfall runoff process in the early stage of the phenomenon, the Courant number used in the simulations is small ranging from 0.1 to 0.3.
The source term vector was rewritten as $\mathbf{S} = \mathbf{S}_b + \mathbf{S}_{fr}$ in which:

$$\mathbf{S}_b = \begin{pmatrix} r \\ ghS_{0x} \\ ghS_{0y} \end{pmatrix} \tag{17}$$

$$\mathbf{S}_{fr} = \begin{pmatrix} 0 \\ -ghS_{fx} \\ -ghS_{fy} \end{pmatrix} \tag{18}$$

The terms S_{0x} and S_{oy} are simply discretized in central manner.
A great problem concerns the wet/dry fronts, for this reason the simulations were carried on imposing a thin layer of water equal to 10^{-10} m on dry cells. When the simulated water depth is lower than the thin layer, the value of water level has been set equal to it and the velocities are null. Moreover following some authors (Brufau et al. 2004, Liang and Borthwick 2009), water added to maintain the thin layer is subtracted from the adjacent cell containing most water in order to maintain mass conservation.
To maintain the front velocity components, the conserved variables *uh* and *vh* in the adjacent cell, where water has been subtracted, are also modified accordingly so that *u* and *v* remain the same as before. In the same contest, a particular subroutine has been implemented by which the dry cells surrounded by other dry cells, in the absence of rain, are excluded from the computation. This allowed to avoid the calculation on cells with very small height of water and at the same time to reduce the threshold of the thin layer of water to 10^{-10} m.

However, this simple treatment is not sufficient for overland flow simulations where water level gradients over relatively steep dry grounds occur inducing unreasonably large velocities. Then, in this work, specific treatments for calculating wet/dry fronts are also applied (Liang and Borthwick 2009, Delis et al. 2008, Aureli et al. 2008, Begnudelli and Sanders 2007, Brufau et al. 2004). In particular for the typical case presented in figure 1 in which

$$\left\{\left[z(i,j)+h(i,j)\right]<z(i,j+1)\right\},h(i,j+1)\leq h_{dry} \tag{19}$$

there is no exchange of mass or momentum between the cell (*i, j*) and the adjacent cell. In this situation, the flux terms are set equal to zero. The contribution of spatial variation of the free surface is also equal to zero.

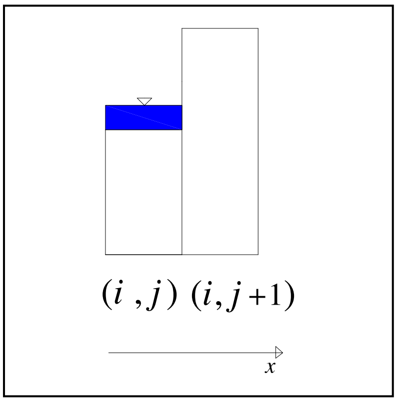

Figure 1. Wet/Dry fronts

In fact, singularities can still arise with regard to the bed friction term when the water depth becomes very small as it is often present in overland flow simulations. For small water depths, the bed friction term dominates over other terms in the momentum equation, as the term $K^2h^{4/3}$ appears in the denominator.
In literature few works concern in detail the consequences of the discretization of the friction term. In this work this is a very evident problem due to the low values of water depths. According to Burguete et al. (2007), the technique based on the limitation of the friction term's values has been implemented in order to avoid incorrect values of the friction term in unsteady cases of advancing front over dry and rough surfaces. Since the maximum effect of the friction force is to stop the water flow, a necessary condition in the solution is that the updated value of the unit discharge along the two spatial directions (*hu*) and (*hv*) at *n+1* time step after the addition of the discrete friction term retains the same sign of the value at the previous time level *n*. i So a maximum value of the friction force has to be considered. For example, along the *x* directions the momentum equation can be written as:

$$(hu)^{n+1}_{i,j}=(hu)^{n}_{i,j}-\frac{\Delta t}{\Omega_{i,j}}\left[\left(f_x\Delta x-g_x\Delta y\right)\right]^n+\Delta t S^n_{bxi,j}-\Delta t S_{frxi,j} \tag{20}$$

with f_x and g_x the components of the vectors **F** and **G** along the *x* direction, S_{bx} and S_{frx} the components along the same direction of the vectors $\mathbf{S_b}$ and $\mathbf{S_{fr}}$ (Equations .17-18)
Considering $(hu)_{i,j}^{*}$ as follow:

$$(hu)^{*}_{i,j} = (hu)^{n}_{i,j} - \frac{\Delta t}{\Omega_{i,j}}\left[\left(f_x \Delta x - g_x \Delta y\right)\right]^{n} + \Delta t S_{bxi,j} \tag{21}$$

The condition suggested by Burguete et al. (2008) is shown in the equation (22):

$$(hu)^{n+1}_{i,j}(hu)^{*}_{i,j} \geq 0 \tag{22}$$

or:

$$(hu)^{*}_{i,j}\left[(hu)^{*}_{i,j} - \Delta t S_{frx}\right] \geq 0 \text{ that implies } S_{frx} \leq \frac{(hu)^{*}}{\Delta t} \tag{23}$$

when the above condition is not fulfilled the velocity is set equal to zero.
Moreover for small water depths also a semi-implicit approach to discretize friction terms is used.
In literature there are some different semi-implicit approaches to discretize the friction term. In this work the semi-implicit approach proposed by Fiedler and Ramirez (2000), Brufau et al. (2004), Delis et al. (2008) and Burguete et al. (2008) has been implemented. It implies the introduction of a coefficient θ that is the implicitness degree of the friction term discretization, for example along the x direction the term $S_{frx} = g\frac{\sqrt{u^2+v^2}}{K^2 h^{4/3}}(uh)$ of the equation (18) is discretized as follow:

$$\begin{aligned}\Delta t\left\{g\frac{\sqrt{u^2+v^2}}{K^2h^{4/3}}\left[\theta(uh)^n + (1-\theta)(uh)^{n+1}\right]\right\} &= \Delta t\theta S^n_{frx} + \Delta t\left(-g\frac{\sqrt{u^2+v^2}}{K^2h^{4/3}}(1-\theta)(uh)^{n+1}\right) = \\ &= \Delta t\theta S^n_{frx} + \Delta t\left((1-\theta)(uh)^{n+1}\frac{Sf^n_{rx}}{(uh)^n}\right)\end{aligned} \tag{24}$$

Combing Equation (24) with the discretization of the shallow water equations:

$$(uh)^{n+1}_{i,j} = \frac{(uh)^n_{i,j} - \frac{\Delta t}{\Omega_{i,j}}\sum_{r=1}^{4}\left(f\delta x - g\delta y\right)^n_r + \Delta t S^n_{bx_{i,j}} + \Delta t\theta Sf^n_{rx_{i,j}}}{1-(1-\theta)\Delta t\frac{S^n_{frx_{i,j}}}{(uh)^n_{i,j}}} \tag{25}$$

The above mentioned implemented numerical techniques allowed to avoid the numerical instabilities due to the presence of low values of water and to simulate real flood event.

2 HYDRAULIC SIMULATION OF THE FLOOD EVENT OCCURRED IN A RENO SUB BASIN ON 7-9 TH NOVEMBER 2003

The predictive ability and adequacy of the implemented model has been tested by applying it on the Reno sub basin at Pracchia station to simulate runoff.

Description of the watershed

The identified watershed is the most upstream part of Reno river basin (Italy), at the closure section of Pracchia, located in the Tuscan part of the Reno basin, and near the Regione Emilia Romagna. The drainage area is around 40 km^2. A Digital Elevation Model (DEM) with 20 m cell size has been generated from topographical maps of the area in 1:10000 scale, using a GIS software. In particular the shape files have been digitalized by means of a ArcGis function, called Topo to Raster, that is a suitable interpolation method to the generation of hydrologically correct DEM. The previous technique allows to obtain a well-connected drainage catchment and a correct representation of the thalwegs of rivers. Then a 20 m x 20 m DEM has been carried out discretizing the domain through a structure mesh of 255 x 255 cells.

In summary, by using particular tools within ArcGis, the following procedure has been used:

- Location of the end section of the Reno sub basin (Pracchia Station);
- Watershed delimitation;
- Characterization of river network
- Generation of 20 m x 20 m DEM

Figure 2 shows the watershed while figure 3 shows the generated DEM and its consequently division in structured mesh of 20 m cell size.

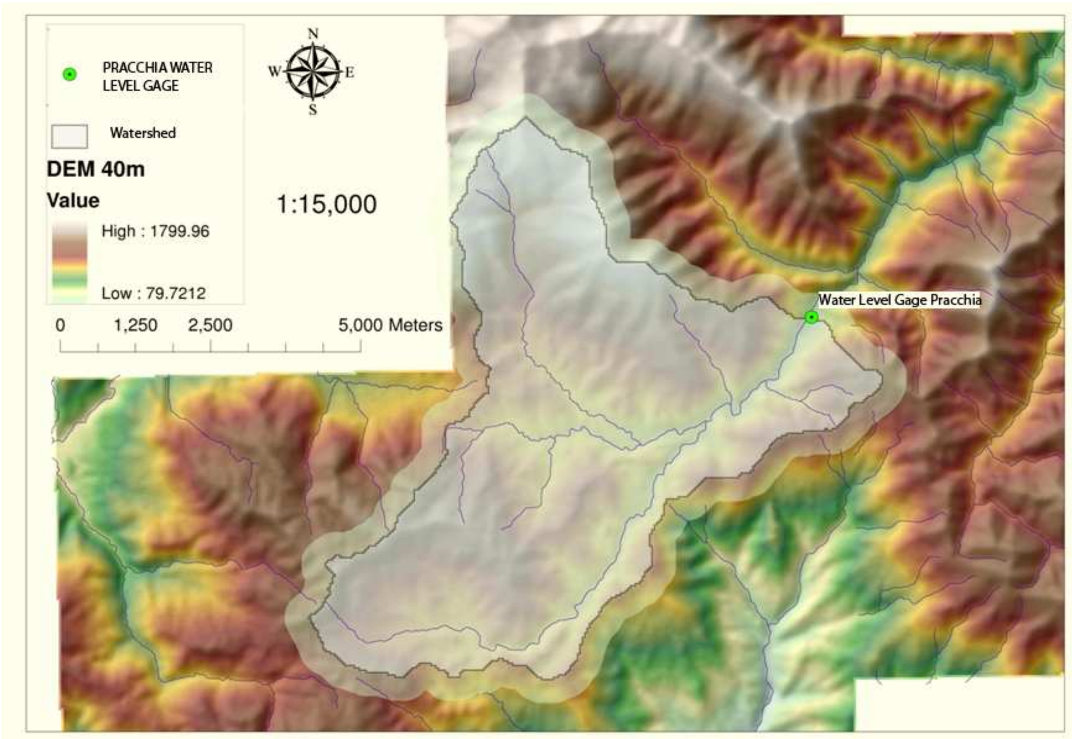

Figure 2. Watershed location

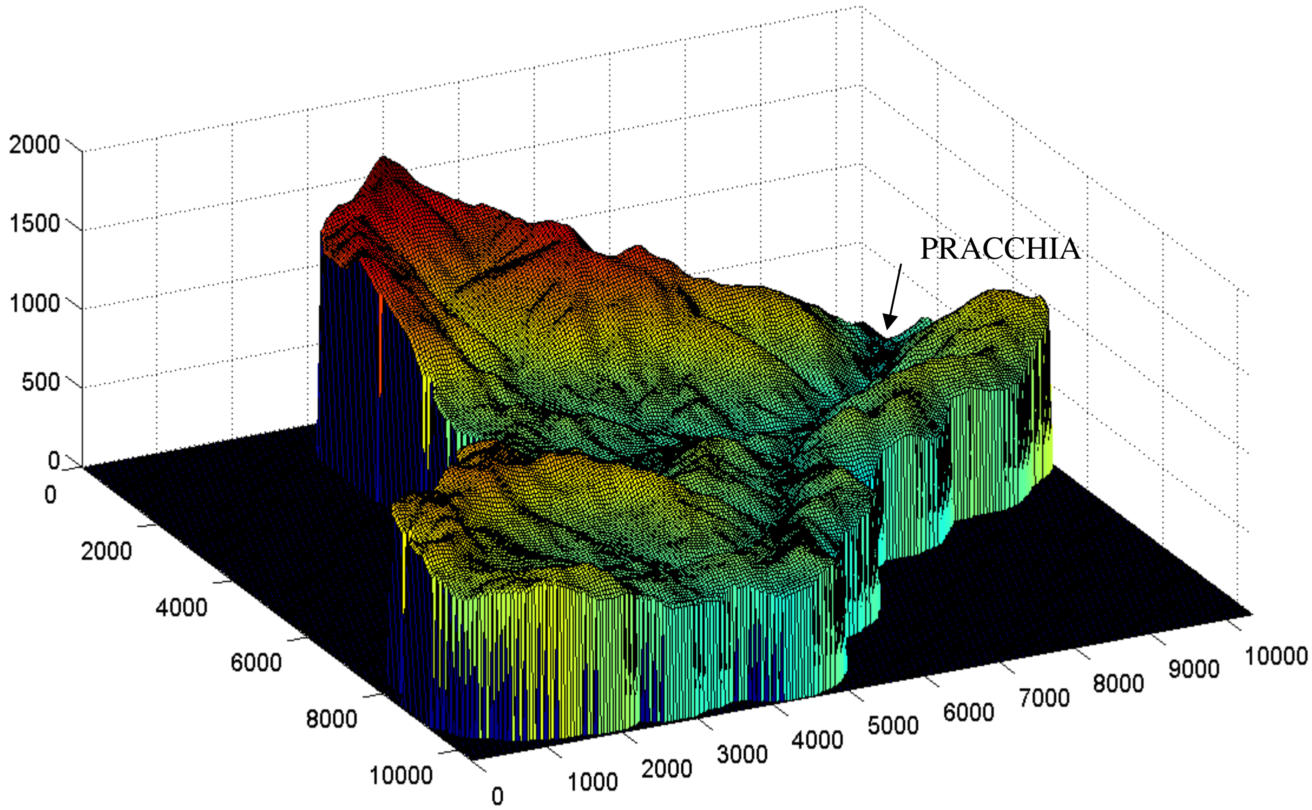

Figure 3. Generated DEM 20 m x 20 m

Model Calibration

The calibration of the hydraulic model consists in the evaluation of the model parameters in such a way to match the observations with acceptable accuracy and precision. Calibration of the implemented hydraulic model is based on minimization of the difference between actual and simulated outflow hydrograph at the watershed outlet.

The flood event occurred from 7 to 9 November 2003, used in simulation, was characterized by high rainfall intensities.

Hydrological data collected by the University of Bologna were used in this study. In particular ground precipitation data are available in the form of the observed hourly rainfall depths that were measured in each one of the nine raingauges located within or close to the catchment (Case Bezzi, Orsigna, Pracchia, Maresca, Piastre, Monte Oppio, S. Marcello, Prunetta and Cireglio) as shown in figure 4.

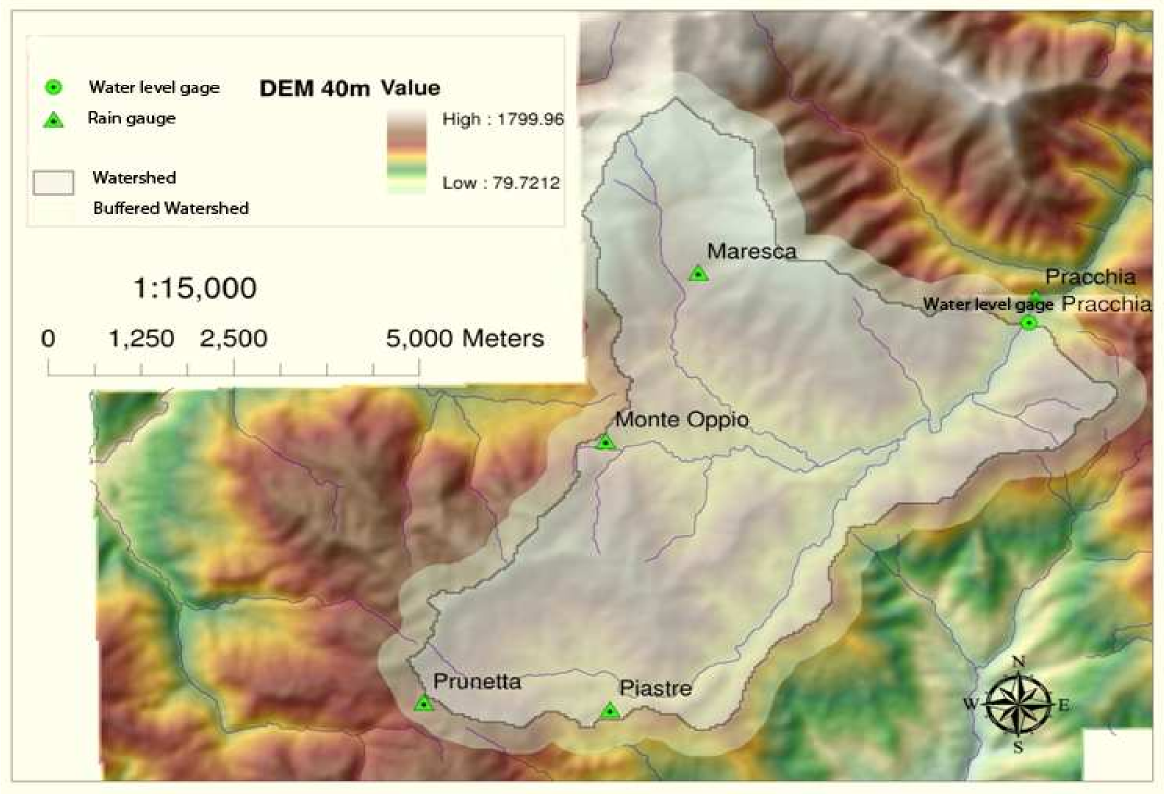

Figure 4. Operative raingauges inside the watershed

The hyetograph of the hourly rainfall in the 9 gauges during the event is shown in figure 5.

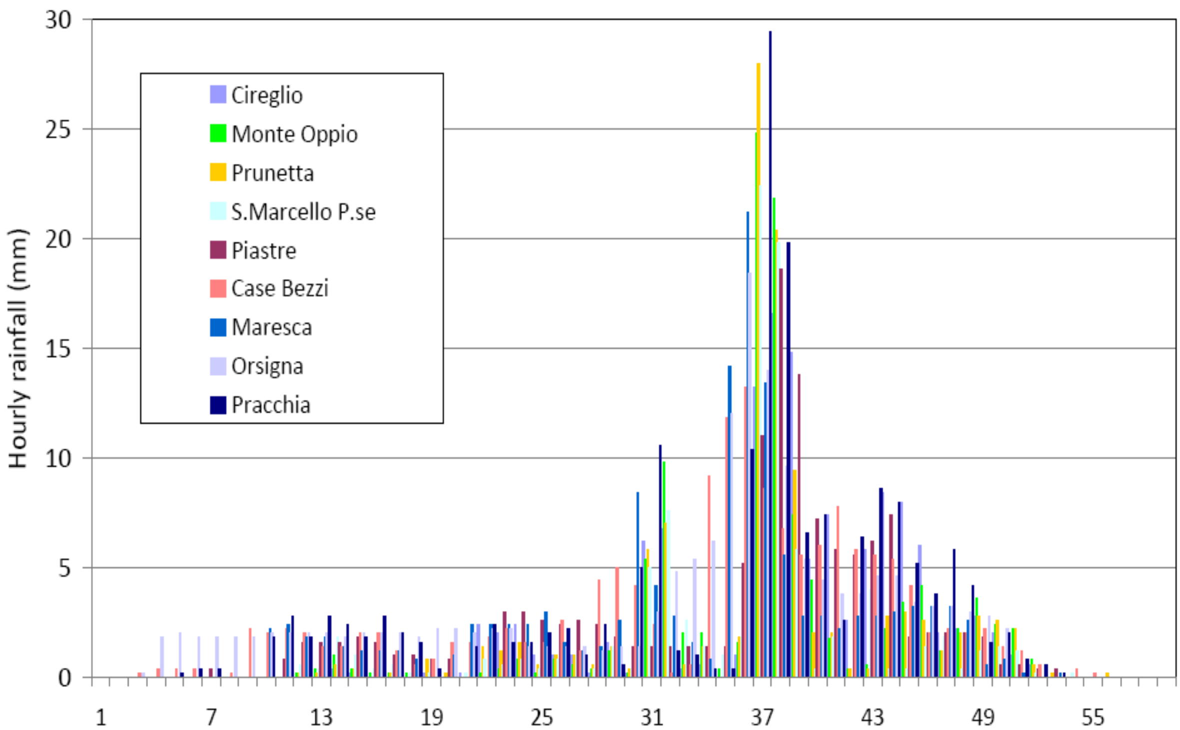

Figure 5. Observed rainfall (from 0:00 7th November 2003)- elaborated by University of Bologna's researchers

The observed water levels recorded at 30 minutes time intervals at Pracchia cross-section, the closure section of the watershed were also used. In particular these data were transformed in the discharge hydrograph (figure 6) by the University of Bologna's researchers using a properly rating curve.

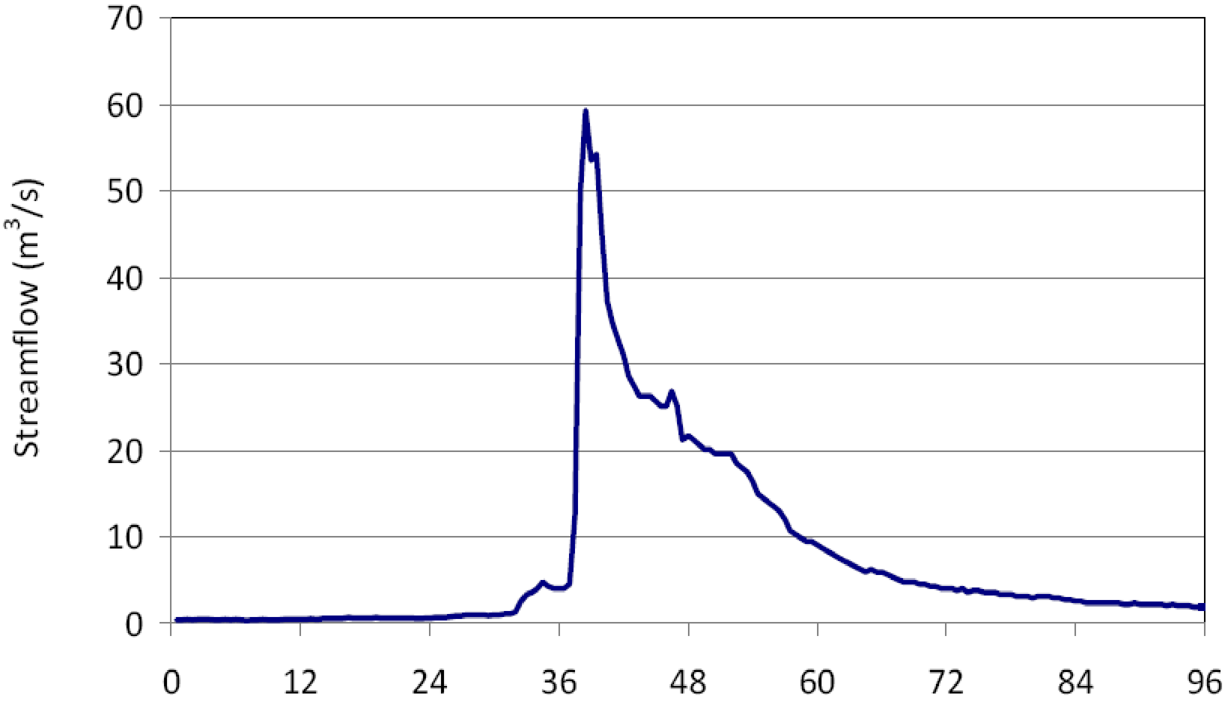

Figure 6. Discharge hydrograph at Pracchia station (from 0:00 7th November 2003)- elaborated by the University of Bologna's researchers

The hydrologic study has been carried out by the research group of the University of Bologna.
In particular they carried out a reliable assessment of the spatial distribution of both the total rainfall fields and of the part that actually becomes surface runoff (net rainfall), thus, on the basis of the observed rainfall data, for each hour, a rainfall field, spatially-distributed over the entire watershed area was estimated. The Mean Areal Precipitation (MAP) over the watershed, computed by the research group of the University of Bologna, accumulated over each hour of the event is depicted in the gross MAP hyetograph of figure 7.
The cumulated gross precipitation during the entire event is 139.85 mm, for a corresponding total volume over the watershed of 5556000 m^3.
The estimation of the losses and consequently of the effective rainfalls has been computed by the research group of the DISTART (University of Bologna). According to that, in every cell of the domain, the runoff coefficient has been estimated in order to evaluate the net precipitations. These net precipitations, spatially distributed, represent the input data of the implemented hydraulic model.

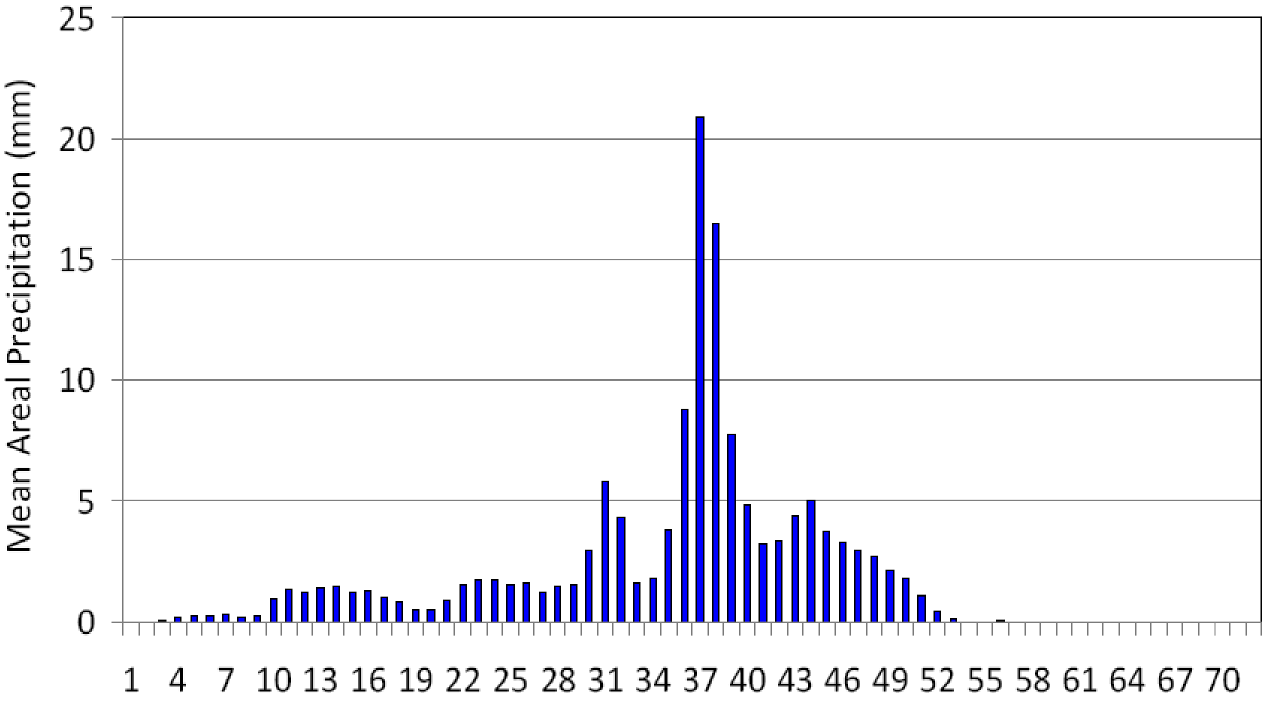

Figure 7. Mean Areal Precipitation (from 0:00 7th November 2003) – elaborated by the research group of the University of Bologna

Before a rain event, the flow is composed of the base flow part only. When the rainfall starts, in case of unsaturated soil conditions, a period of time elapses before the flow begins to rise (period when the rainfall is intercepted by the vegetation, fills the soil surface cavities and makes up the soil-moisture deficits). Once the surfaces and soils are saturated, the effective rainfall starts to contribute to flow as surface runoff: this part of the hydrograph is called the rising limb, up to the peak. After the peak, the slope of the curve flattens over time from its initial steepness as the quickflow component passes and base flow becomes dominant.

The flood hydrograph may be separated into two main components: the area under the hump, representing surface runoff, and the lower part near the time axis, representing the baseflow, i.e. the part of the flow contributed from interflow and groundwater.

The result of this separation on the discharge hydrograph of figure 6 made by the research group of the University of Bologna, is shown in figure 8.

The area under the hydrograph of figure 8 is equal to the total surface runoff volume, that is 1720300 m^3.

The above described implemented numerical model has been applied in order to simulate the propagation of the surface run-off.

Moreover in this contest is necessary to choose the values of the roughness parameters. The Strickler's roughness coefficient of each overland flow cell is determined on the values published in the literature for appropriate land cover (Mahmood and Yevjevich, 1975; Chow et al., 1988; Julien, 2002)

In particular assuming the Strickler's roughness coefficient for forest equal to 15 $m^{1/3}/s$, for discontinuous urban fabric and industrial or commercial units equal to 20 $m^{1/3}/s$ and for channel cells equal to 35 $m^{1/3}/s$ (simulation 1), the numerical results are in good agreement with the observed discharge hydrograph at the outlet station shown in figure 8.

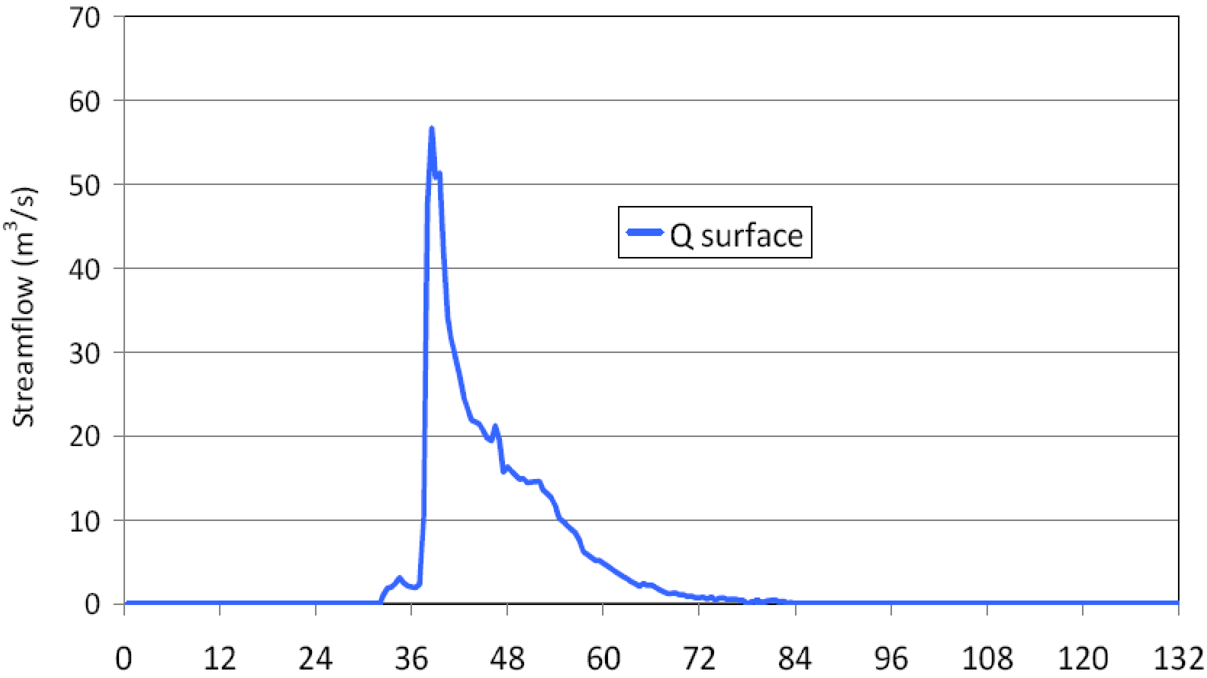

Figure 8. Surface runoff hydrograph at Pracchia station (from 0:00 7th November 2003) elaborated by the research group of the University of Bologna

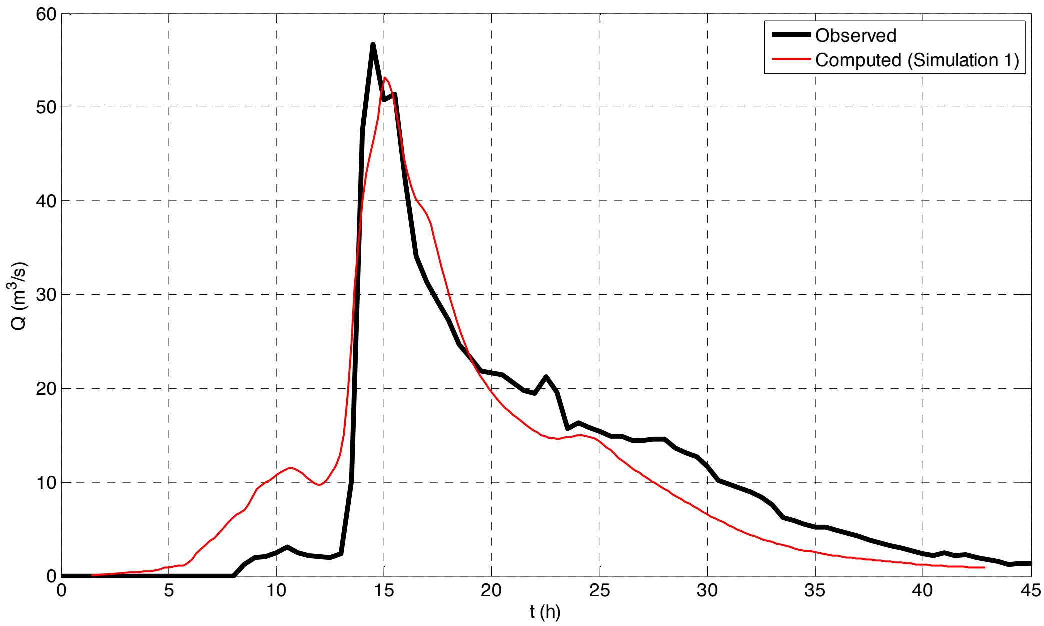

Figure 9.Comparison between observed and computed (case 1) runoff hydrograph at Pracchia station from 00:00 8th November 2003

These values of parameters for various land use were found appropriate for obtaining a good match in the analyzed flood event. As can be seen from figure 9 the computed peak discharge, time to peak discharge and run off volume agree reasonably well with their corresponding observed values. Although the shape of the computed hydrograph is overall similar to that observed, in the first hours the numerical model presents an overestimation of the discharge.

In this phase of the calibration of the model, a sensitivity analysis concerning the influence of the roughness parameter on the numerical results has been carried out. Simulations have been carried out considering a constant value of roughness in all the domain (k = 8 $m^{1/3}$/s, k = 15 $m^{1/3/}$s, k = 25 $m^{1/3}$/s, k = 30 $m^{1/3}$/s) as shown in figure (10) and then assuming a variety of spatial distributions of the coefficients (figure 11).
In particular, the following spatial distributions of the roughness parameters have been considered:

- simulation 1: forest and land occupied by agriculture k = 15 $m^{1/3}$/s; discontinuous urban fabric and industrial or commercial units k = 20 $m^{1/3}$/s ; channel cells k = 35 $m^{1/3}$/s ;
- simulation 2: forest k = 10 $m^{1/3}$/s; land occupied by agriculture k = 15 $m^{1/3}$/s, discontinuous urban fabric and industrial or commercial units k = 20 $m^{1/3}$/s ; channel cells k = 30 $m^{1/3}$/s;
- simulation 3: forest k = 8 $m^{1/3}$/s; land occupied by agriculture k = 15 $m^{1/3}$/s, discontinuous urban fabric and industrial or commercial units k = 20 $m^{1/3}$/s ; channel cells k = 35 $m^{1/3}$/s.

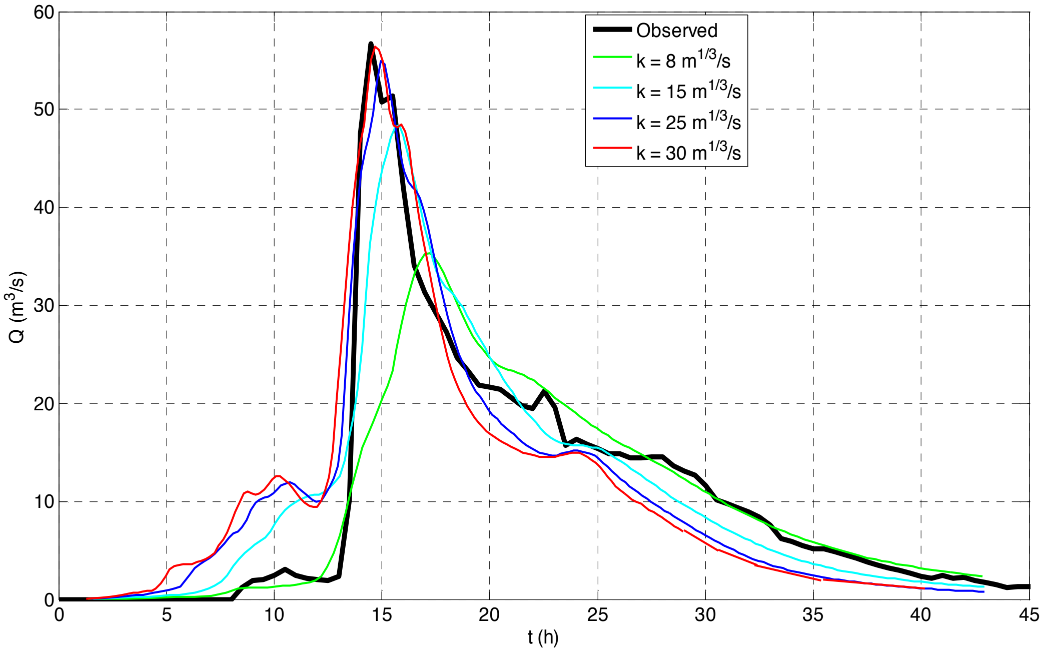

Figura 10. Comparison between observed and computed surface runoff at the outlet of the watershed assuming the Strickler's roughness coefficient constant in all the domain (k = 8 $m^{1/3}$/s, k = 15 $m^{1/3}$/s, k=25 $m^{1/3}$/s e k = 30 $m^{1/3}$/s) from 0:00 8 november 2003

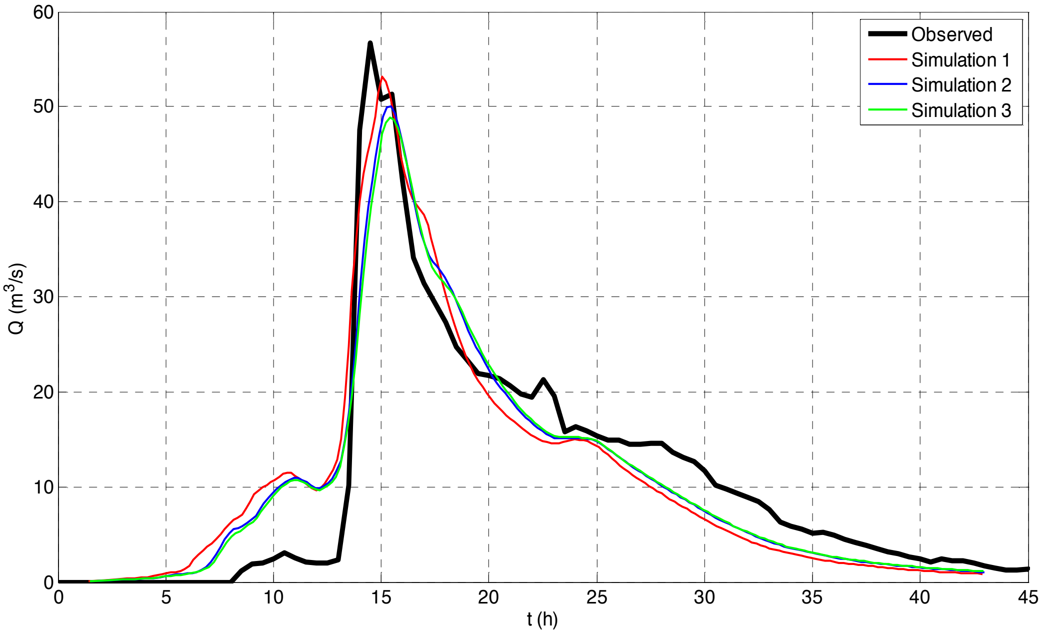

Figura 11. Comparison between observed and computed surface runoff at the outlet of the watershed assuming some spatial distribution of the Strickler's roughness coefficients (simulation1, simulation 2 simulation 3) from 0:00 8 november 2003

The numerical results are affected by the value of the roughness coefficient, especially in the estimation of the peak flow and this is much more evident when assuming a constant value of roughness in all the domain, while the differences are less evident when the roughness coefficient spatially varying with the type of land cover has been used.

Although the arrival times agree with those observed, in all simulations the numerical model presents in the first part of the rising limb of the flow an overestimation of the discharges.

Probably this overestimation is due to the infiltration model that may have underestimated the infiltration ratio. However, considering that in the calibration of the model the formation of the surface runoff and its propagation have been carried out separately in a decoupled way, it is believed that the achievements are more than satisfactory.

Hydro-meteorological chain

After the calibration of the model, the hydro-meteorological chain has been implemented to simulate the same rainfall event on Reno watershed at Pracchia station, starting from rainfall data simulated by the CIRA's researchers using a meteorological model. In particular the input rainfall data are the outputs of the two version of the meteorological model using that runs on different mesh size (7 km and 2.8 km respectively).
In both cases the mesh size of the meteorological model is coarser than that used in the propagation model so it has been necessary a spatial interpolation of the rainfall data in the finer mesh used in the propagation. This has been made simply by considering that all the computational cells of the hydraulic model within the cell of the meteorological model, have a constant rain value. In this way, the rainfall data have been distributed in the computational

domain for the propagation. In figures 12-13 the results of the two different meteorological simulations in terms of mean areal precipitations over the considered watershed are reported.

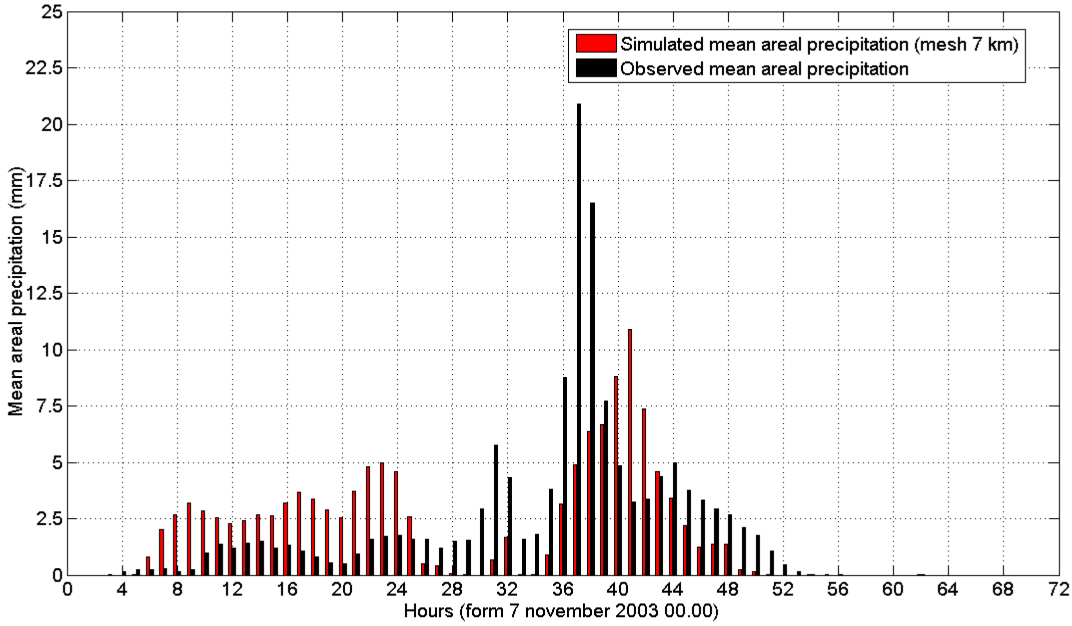

Figure 12. Observed Mean Areal Precipitation (from 0:00 7th November 2003) and simulated rains by CIRA's researchers using a 7 km cell size

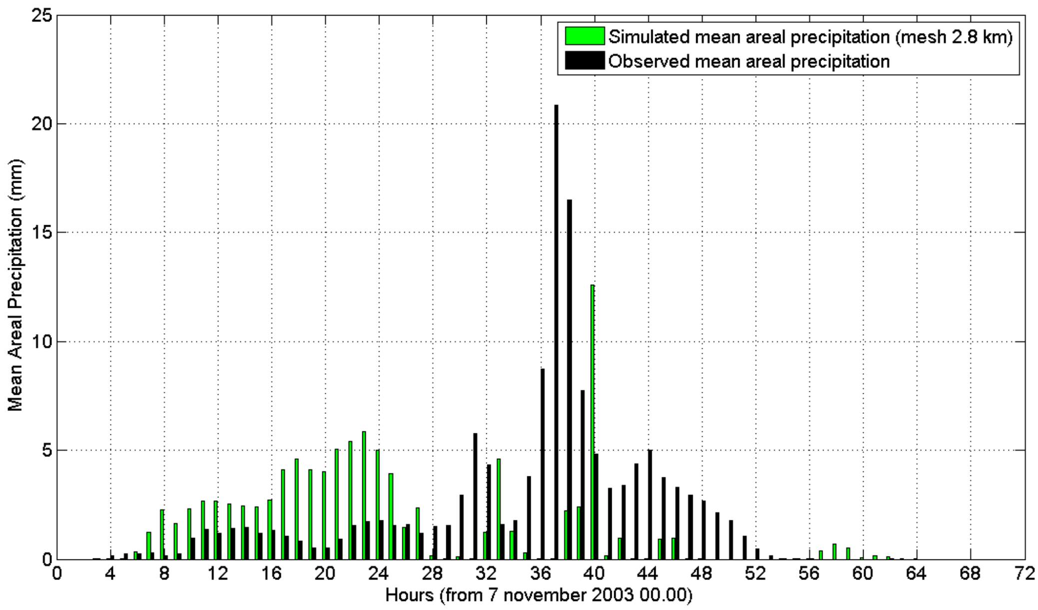

Figure 13. Observed Mean Areal Precipitation (from 0:00 7th November 2003) and simulated rains by CIRA's researchers using a 2.8 km cell size

According to the calibration phase, the net rainfalls have been computed from the simulated gross rainfall by the meteorological model, using the same run-off coefficients elaborated by the research group of the University of Bologna. These net rainfalls are the input data of the propagation model in order to simulate the surface run–off. The figures 14-15 show the numerical results obtained using the meteorological data on 7 km cell size and on 2.8 km cell size.

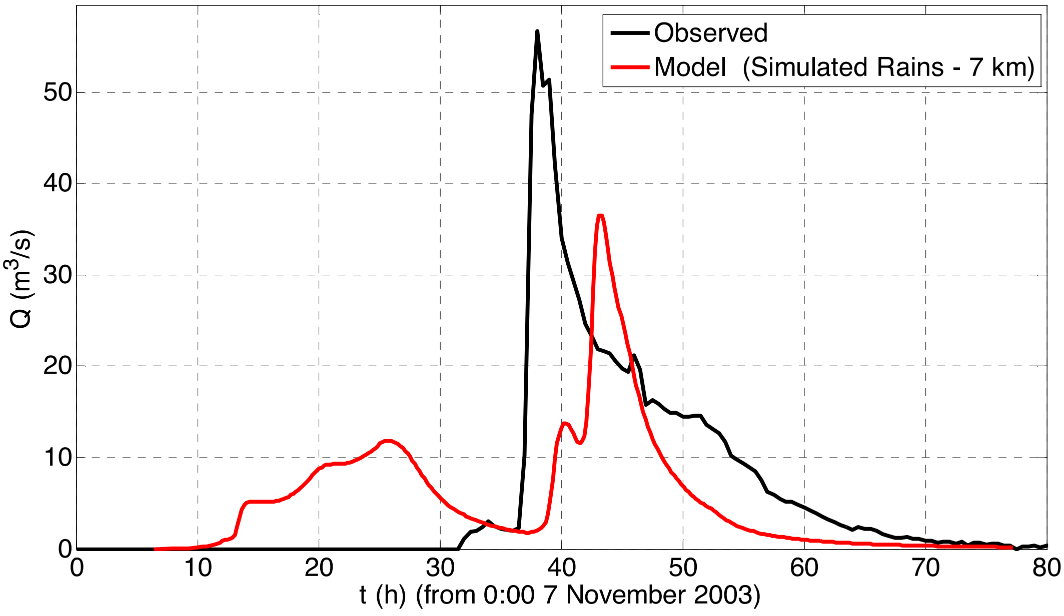

Figura 14. Comparison between observed and computed surface runoff at the outlet of the watershed using the simulated rainfalls on a mesh with 7 km size

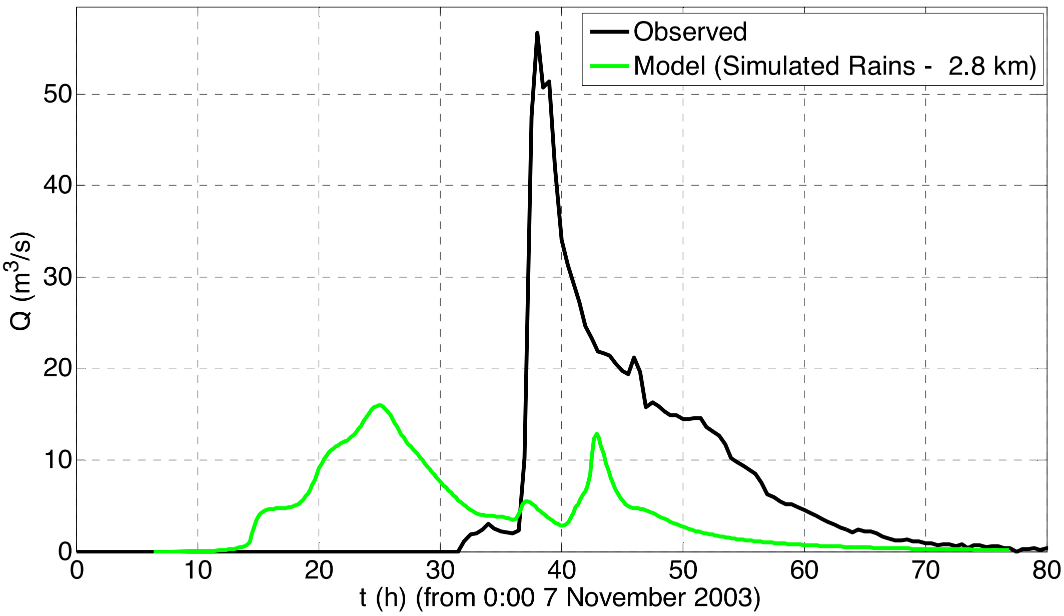

Figura 15. Comparison between observed and computed surface runoff at the outlet of the watershed using the simulated rainfalls on a mesh with 2.8 km size

The numerical results obtained using the meteorological data on the mesh of 7 km are more similar to the observed ones due to a better prediction of the rainfall distribution (figure 15). The obtained results are very encouraging because it should be recalled in mind that no calibration has been performed for the hydro-meteorological chain as a whole.

SUMMARY AND CONCLUSIONS

This work represents the conclusion of the research project on "Hydraulic modeling of floods caused by intense rainfall events". The close collaboration between the CIRA and LAMPIT research groups has allowed the analysis of a series of theoretical aspects and applications in order to develop a hydro-meteorological chain.

The contribution of LAMPIT to the project concerned many different activities aimed to analyze the theoretical issues relating to structuring the hydro-meteorological chain. In particular the goal of LAMPIT was the mathematical description of both the generation and propagation of the surface –runoff at basin scale.
The experience of LAMPIT research group about the advanced flood modeling has been applied to implement numerical codes organised in such a way to receive the gross rainfall computed by CIRA as input data in order to simulate the surface runoff of the rainfall events.

According to an in-depth bibliographical review, a number of two dimensional schemes have been implemented and validated to the analysis of overland flow events.
The mathematical description of the flow processes is based on the fully dynamic shallow water equations. The integration of these equations, excluding some simplified cases, can be obtained by numerical methods only. The finite volume method, widely adopted in the literature, has been used to discretize them. It allows the decomposition of a two dimensional problem into a series of locally one dimensional problems to value the normal flux through every side of a cell. Many algorithms have been proposed for the flux vectors evaluation: the most diffused ones in literature have been examined and implemented.
Particularly the MacCormack second order space centered scheme and the first order upwind HLL scheme have been applied. This choice is consequent to a large comparative survey on the performances of several first and second order upwind and central finite volume numerical schemes that have been carried out in LAMPIT laboratory, focusing the attention on both computational aspects, such as the implementation burdensomeness and computational times, and practical aspects as the accuracy of the solution in terms of maximum water levels, arrival times and velocities.
It is important to notice that in the simulation of overland flow events the convective inertial terms in the momentum equations are significantly lower than the values of the topographic surface slope in those situation in which a strong topographic gradient occurs. Whenever that eventuality happens, it is justified to neglect these terms in order to avoid an useless increase of the computational times. According to that in literature the use of different approximations of the unsteady flow equations is very common in order to simulate the overland flow processes.
Therefore, in this project, a comparative analysis on the accuracy of the results obtained by the simplified models (diffusive model and kinematic model) and those obtained by complete model has been carried out. In particular, models based on fully dynamic, diffusive and kinematic wave approach have been developed, tested and validated with the numerical tests commonly used in the literature.

The analysis of the above mentioned tests seems to suggest that, for overland flow simulations, the diffusive model is able to provide a very good approximation of the fully dynamic model. However the results coming from the numerical simulation of an experimental test characterized by a more complex domain lead to mitigate that conclusion. In particular, the results of a test relative to an impulsive rainfall event with the generation of a shock wave suggest that the use of simplified models in situations characterized by impulsive phenomena over complex topographies may lead to important errors.

In this context, the 2D fully dynamic shallow water equations seem to be the required approach to deal with real situations because it allows to analyse in depth the flow behaviour also in presence of a locally complex topography.

From a numeric point of view, the overall results obtained by using the MacCormack and the HLL scheme are quite good and no problems of numerical instability have been observed despite the small values of the simulated water depths.

In simulation of a flood caused by a rainfall event some numerical anomalies appear due to the presence of small water depth over high slope and irregular topography. According to that, a careful analysis of these problems has been made and some numerical techniques have been implemented in order to prevent them.

After a thorough bibliographic review on the specific treatment of the wet-dry fronts, a numerical technique to simulate also these situations has been applied. Moreover, with regard to the friction term, two semi-implicit approaches have been analyzed and then applied in order to avoid numerical instabilities due to the presence of very low water depth.

The study of overland flow processes in a real situation often refers to large areas; as a consequence, in order to avoid a significant increase in terms of both computational times and memory storage, the computational domain is obtained by using very coarse cells. Therefore an analysis on the accuracy of the numerical solutions in relationship to the size of computational cell has been performed. This analysis has shown that an increase of cell size causes more important negative effects on the HLL scheme than in the MacCormack scheme; this result has been expected since the MacCormack scheme has a second order of accuracy in both time and space. Moreover, as the generated flood wave becomes more impulsive the increase of the cell size seems to cause poorer simulations.

A major aspect of model development is its verification and validation. For the verification, the implemented code has been applied to simulate many test cases proposed in literature and to simulate the surface run-off over simple basins. The numerical results have been compared with analytic solutions to ensure that the numerical model shall solve the mathematical equations correctly and predict the physical processes adequately and realistically. Then the model has been applied to simulate rainfall experiments conducted in controlled environments and with simplified testing conditions. In all the cases the numerical results obtained by the implemented schemes are consistent with the analytical solution or with the observed data.

Finally the predictive ability and adequacy of the implemented model, based on HLL upwind scheme, has been tested by applying it to simulate the rainfall event occurred in a Reno sub basin on 7-9 th november 2003 and it has been validated by field measurements and observed field data.

The identified watershed is the most upstream part of Reno river basin (Italy), at the closure section of Pracchia, located in the Tuscan part of the Reno basin, and near the Regione Emilia Romagna. The drainage area is around 40 km^2 and there are no reservoir upstream nor other important hydraulic structures that may modify the natural hydrological and hydraulic process of the event.

The flood event that took place on 7-9 th November was a severe meteorological event with high rainfall intensities for some hours.

A Digital Elevation Model (DEM) with 20 m cell size has been generated from topographical maps of the area in 1:10000 scale, using a GIS software. The Corine map has been used to obtain the land use/land cover for the watershed.
The estimation of the losses and consequently of the net rainfalls have been computed by the research group of the DISTART (University of Bologna). These net rains have been used as input data of the implemented two dimensional numerical model.
The numerical results obtained have been compared with the observed data elaborated by the DISTART. The discharge hydrograph at the outlet Pracchia station has been compared with the numerical results obtained by the hydraulic model. Moreover a sensitivity study of the roughness parameter has carried out. In particular assuming the Strickler's roughness coefficient for forest equal to 15 $m^{1/3}/s$, for discontinuous urban fabric and industrial or commercial units equal to 20 $m^{1/3}/s$ and for channel cells equal to 35 $m^{1/3}/s$, the numerical results are consistent with the observed discharge hydrograph at the outlet station. The computed peak discharge, time to peak discharge and run off volume are consistent with their corresponding observed values. In this phase of the calibration of the model, a sensitivity analysis has been carried out on the influence of roughness parameter on the numerical results. Simulations have been carried out considering a constant value of roughness in all the domain and then assuming a variety of spatial distributions of the coefficients according to the land use. The results indicate that they are affected by the value of the roughness coefficient, especially in the estimation of the peak flow and this is much more evident when assuming a constant value of roughness in all the domain, while the differences are less evident spatially varying roughness coefficient with the type of land cover. In all simulations, although the arrival times are always consistent with those observed, the numerical model presents in the first part of the rising limb of the flow an little overestimation of the discharges.

Finally the hydro-meteorological chain has been implemented to simulate the same rainfall event on Reno sub-basin starting from rainfall data simulated by the CIRA researchers using a meteorological model. In particular the input rainfall data are the outputs of the two version of the meteorological model using that runs on different mesh size (7 km and 2.8 km respectively).
In both cases the mesh size of the meteorological model is coarser than that used in the propagation model so it has been necessary a spatial interpolation of the rainfall data in the finer mesh used in the propagation. The numerical results obtained using the meteorological data on the mesh of 7 km are more similar to the observed ones due to a better prediction of the rainfall distribution
The obtained results are very encouraging considering the need for a more accurate calibration of the entire Hydro-meteorological chain. This suggests further studies such as: the treatment of the irregularities of the surface topography aimed at a more accurate simulation of the overland flow on slopes; the thickening of the computational domain at the hydrographic network and areas of interest for the hydraulic risk and applications to simulate other test cases.

References

Aureli F.; Maranzoni A.; Mignosa P. and Ziveri C. (2008). "Dam-Break Flows: Acquisition of Experimental Data through an Imaging Technique and 2D Numerical Modeling". *Journal of Hydraulic Engineering*, Vol. 134, No. 8: 1089–1101.

Begnudelli L. and Sanders B. F. (2007). "Conservative Wetting and Drying Methodology for Quadrilateral Grid Finite-Volume Models". *Journal of Hydraulic Engineering*, Vol. 133, No. 3: 312–322.

Bhardwaj A. and Kaushal M. P. (2009). "Two-dimensional physically based finite element runoff model for small agricultural watersheds: II. Model testing and field application". *Hydrological. Processes*, 23, 408–418 .

.

Brufau P., García Navarro P. and Vazquez-Cendon M. E. (2004). "Zero mass error using unsteady wetting–drying conditions in shallow flows over dry irregular topography". *International Journal of Numerical Method in Fluids*, 45:1047–1082, John Wiley & Sons Ltd.¶

Burguete J., Garcìa-Navarro P., Murillo J. (2008). "Friction term discretization and limitation to preserve stability and conservation in the 1D shallow-water model: Application to unsteady irrigation and river flow." *International Journal for Numerical Methods in Fluids* 58: 403–425

Burguete, J, García-Navarro P., Murillo J. and García-Palacín I. (2007). "Analysis of the friction term in the one-dimensional shallow water model". *Journal of Hydraulic Engineering* 133(9), 1048-1063.

Fiedler, F. R., Ramirez, J. A. (2000). "A numerical method for simulating discontinuos shallow flow over an infiltrating surface". *International Journal of Numerical Method in Fluids*, 32: 219-240, John Wiley & Sons Ltd.

Costanzo, C., Macchione F. (2004). "Prestazioni di alcuni schemi bidimensionali ai volumi finiti per problemi di dam break". Proceedings of the *XXIX Convegno di Idraulica e Costruzioni Idrauliche*, Trento, 2004, Ed. Bios:Cosenza, 2004, 1: 829-836.

Costanzo, C., Macchione, F. (2005). "Comparison of two-dimensional finite volume schemes for dam break problem on an irregular geometry". Proceedings of the *XXXI IAHR Congress*, Seoul, Korea 2005, Theme D, 3372-3381. CD-ROM.

Costanzo C., Macchione F. (2006). "Tecniche numeriche per la simulazione della propagazione di piene su fondo irregolare". Proceedings of *Tecniche per la Difesa dall'Inquinamento*, G. Frega (a cura di), Editoriale Bios, Cosenza, 2006, Vol. 26 : 423-440.

Costanzo, C., Macchione F. (2006). "Modelli di simulazione dei fenomeni di allagamento in zona urbana: applicazione ad un caso reale". Proceedings of the *XXX Convegno di Idraulica e Costruzioni Idrauliche - IDRA2006*, Roma, 10 - 15 settembre, 2006, Casa Editrice Università degli Studi di Roma La Sapienza, CD-ROM.

Chow,V.T., Maidment, D.R., Mays, L.W, (eds.). (1988). "*Applied Hydrology*", McGraw-Hill International Editions, New York.

Delis A.I., Kazolea M. and Kampanis N. A. (2008). "A robust high-resolution finite volume scheme for the simulation of long waves over complex domains". *International Journal for Numerical Methods in Fluids* 56:419–452.

England J. F. Jr., Velleux M. L., Julien P. Y. (2007). "Two-dimensional simulations of extreme floods on a large watershed". *Journal of Hydrology* 347, 229– 241

Fiedler F. R., Ramirez J. A. (2000). "A numerical method for simulating discontinuous shallow flow over an infiltrating surface". *International Journal for Numerical Methods in Fluids* (32) : 219–240

Harten A., Lax P., van Leer B., 1983. On upstream differencing and Godunov-type schemes for hyperbolic conservation laws. *SIAM Review*, 25: 35-61.

Hirsch C., 1990. *Numerical computation of internal and external flows*. John Wiley e Sons.

Jain M. K., Singh V. P. (2005). "DEM-based modelling of surface runoff using diffusion wave equation". *Journal of Hydrology* 302, 107–126

Jinkang D., Shunping X., Youpeng X., Xu C., Singh V. P. (2007). "Development and testing of a simple physically-based distributed rainfall-runoff model for storm runoff simulation in humid forested basins". *Journal of Hydrology* 336, 334– 346

Julien P. Y. (2002). "*River Mechanics*". Cambridge University Press (UK).

Liang Q. and Borthwick A. G.L. (2009). "Adaptive quadtree simulation of shallow flows with wet–dry fronts over complex topography". *Computers & Fluids* 38: 221–234.

Macchione F. , Costabile P. , Costanzo C. . (2009). RP0059-Final document on the second year third activity : "*Analysis of the hydrometeorological chain performances on a real basin*"., 2009, Project: Impacts on the Monitoring Activity of Territory and the Prevention of Hydrogeological Disasters. –Division. Impacts on Soil and Coast (ISC) - Centro Euro Mediterraneo Cambiamenti Climatici.

Macchione F. , Costabile P. , Costanzo C. (2009) . Final document on the third year, second activity: *Numerical techniques for preventing computational instability problems to simulate floods due to low-intensity rainfall* "., 2009, Project: Impacts on the Monitoring Activity of Territory and the Prevention of Hydrogeological Disasters. –Division. Impacts on Soil and Coast (ISC) - Centro Euro Mediterraneo Cambiamenti Climatici.

Mahmood K., Yevjevich (eds.). (1975). "Unsteady Flow in Open Channels". Water Resources Publications, Fort Collins, Colorado.

Shih D. S., Li M. H, Wu R. S. (2008). "Distributed Flood Simulations with Coupling Gauge Observations and Radar-rainfall Estimates". *Water Resour Manage* 22:843–859

Toro E.F., 2001. *Shock –Capturing Methods for Free Surface Shallow Flows*. Wiley, Chichester.

Venkata R. K., Eldho T. I., Rao E. P, Chithra N. R. (2008). "A Distributed Kinematic Wave–Philip Infiltration Watershed Model Using FEM, GIS and Remotely Sensed Data". *Water Resour Manage* 22:737–755.

Yoon T. H., Kang S. K. (2004). "Finite volume model for two-dimensional shallow water flows on unstructured grids". *Journal of Hydraulic Engineering*, ASCE, vol. 130 (7), pp. 678-688.