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FLORA-2D: A New Model to Simulate the Inundation in Areas Covered by Flexible and Rigid Vegetation

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***Abstract*— A two-dimensional (2D) hydraulic model for river flood inundation prediction is presented. This model named FLORA-2D (FLOod and Roughness Analysis) solves the shallow-water equations at each node of a regular mesh covering the channel and floodplain. Its special feature is the ability to consider the flow resistance due to vegetation as a function of both space and time. So, during a flood, in each grid node the resistance of vegetation is calculated considering the hydraulic characteristics of the flow which may vary over time as well as the characteristics of the plant. The model was tested in a study of a flood event which occurred on the River Bradano, Southern Italy, in March 2011. A first evaluation of the behavior of the model shows a good correspondence with the theories used in the code. Furthermore a satellite image acquired during the flood provided an observed flood extent against which to compare the predicted extent.**

***Index Terms*— Two-dimensional models, hydraulic roughness, vegetation, floods.**

I. INTRODUCTION

Hydraulic analysis can be carried out using more or less complex mathematical models to determine the values of the variables involved and the increasing sophistication of both hardware and software permits the achievement of complex elaborations within satisfactory time periods. Flood inundation modelling can be accomplished with one of several approaches: one-dimensional (1D) models based on the Saint-Venant's equations, two-dimensional (2D) models that solve the shallow-water equations and three-dimensional (3D) models that solve Navier-Stokes equations and hybrids that combine, for example, 1D and 2D approaches. Nowadays, the advent of computing resources allows us to apply easily two-dimensional model approaches to study flood propagation in the areas in which the flow motion is not one-dimensional. Many numerical 2D models to solve shallow water equations have been developed and they applied: the method of characteristics [3], the method of finite difference [8]−[10], the method of finite elements [2] and, finally, the method of finite volume [24].

In the numerical approaches, flow resistance is commonly represented by parameters such as Manning's roughness coefficient (n), Chezy's resistance factor (C) or Darcy-Weisbach's friction factor (f). Generally, hydraulic simulation models use Manning's n coefficient and conventional approaches to evaluate flow resistance use reference publication [6]. This choice is used in order to determine a roughness coefficient which groups all sources of flow resistance, including vegetation, into Manning's n coefficient [23]. In 2D models, we can consider a spatial variation of the roughness using a mesh in which each node has a roughness coefficient depending on the type of vegetation. But during a flood, the vegetation resistance varies according to flow depth and velocity.

For relatively shallow inundation (<1m), the resistance due to vegetation can be a dominant factor in the inundation process. LiDAR data can be used to generate the maps of vegetation height [7] from which the maps of the flow resistance can be obtained.

In this paper, a 2D hydraulic model is presented that simulates the inundations simultaneously considering the spatial and temporal variation of the resistance due to the vegetation. Besides, a comparison between modeled and observed flood extents was conducted.

II. BACKGROUND

Many authors have carried out studies in developing the flow resistance caused by vegetation. Generally they distinguish between shrubs and woody vegetation and between completely and partially submerged vegetation [1]. In the literature, these studies are based on flume experiments and experimental observations in laboratory conducted with artificial models of vegetation, such as rigid cylinders or plastic strips, or with small scale flexible plants, such as macrophytes.

Li and Shen [15] studied the effects of flow resistance of tall non-submerged vegetation by investigating the wake caused by various cylinder set-ups and verified that different patterns of groupings of cylinders significantly affected flow rates. Petryk and Bosmajian [19] proposed the vegetation-density method to calculate Manning's n values in the case of un-submerged rigid vegetation. In their model, n value is a function of hydraulic radius and vegetation density. Other authors [18] revisited the proposal of Li & Shen on the basis of the results obtained in the laboratory by treating trees as cylinders. Righetti and Armanini [20] verified with experimental data their formula for evaluation of vegetation resistance based on an analytical two layer model for sparsely distributed bushes under uniform flow conditions.

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About shrubs, Kouwen and Unny [14] developed a method to evaluate the flow roughness due to submerged grass using plastic strips and concluded that the friction factor of vegetation f_d was a function of the relative roughness for the erect and waving regimes, and appeared to be a function of the Reynolds number for prone roughness. Kouwen and Fathi-Moghadam [13] integrated their study conducted in 1997 on coniferous trees in flume experiments obtaining a good correlation of the friction factor of vegetation with the flow velocity normalized with a vegetation index. This is a parameter correlated with shape, flexibility and biomass of the particular tree species.

Wu and Shen [22] studied the variation of the vegetative roughness coefficient with the depth of flow, both in submerged and non-submerged conditions. Using horsehair mattress as floodplain bushes and shrubs, the author concluded that the roughness coefficient decreased with increasing depth under the non-submerged condition. For fully submerged vegetation, the roughness coefficient increased for low inundation but then decreased to an asymptotic constant rising level. Freeman and Rahmeyer [9] defined a methodology to determine flow resistance coefficients for submerged and partially submerged shrubs and woody vegetation. Also Jarvela [11]−[12] studied submerged and non-submerged vegetation and showed that changes in depth, velocity, Reynolds number and vegetation density are key factors and that the maximum friction factor was obtained for low Reynolds number and velocity.

III. MODELLING OF FLOW WAVE PROPAGATION WITH FLORA-2D

The model proposed is FLORA-2D (FLOod and Roughness Analysis) produced by collaboration between the School of Engineering of the University of Basilicata (Italy) and the research society RSE (Research on Energy System). It is a review of the proposal submitted by Molinaro et al. [17].

The general equations which govern the flood propagation in FLORA-2D are the “shallow water equations” simplified by eliminating the convective terms. This simplification can be used when flooding of vast flat areas is studied. In this case: (i) the dynamic forces are relatively small compared to other forces (inertia, friction, gravity), (ii) the resolution of the numerical scheme is generally low and generate spatial derivatives not very significant during the discretization and, finally, (iii) the flow velocity is often low. The basic equations therefore become:

$$\begin{cases} \dfrac{\partial h}{\partial t} + \dfrac{\partial q_x}{\partial x} + \dfrac{\partial q_y}{\partial y} = 0 \\ \dfrac{\partial q_x}{\partial t} + gh\dfrac{\partial h}{\partial x} + gh\left(C_f q_x - S_x\right) = 0 \\ \dfrac{\partial q_y}{\partial t} + gh\dfrac{\partial h}{\partial y} + gh\left(C_f q_y - S_y\right) = 0 \end{cases} \quad (1)$$

These simplified equations are discretized in time using a fully implicit finite differences model as shown below:

$$\begin{cases} \dfrac{h^{n+1} - h^n}{\Delta t} + \left(\dfrac{\partial q_x}{\partial x}\right)^{n+1} + \left(\dfrac{\partial q_y}{\partial y}\right)^{n+1} = 0 \\ \dfrac{q_x^{\,n+1} - q_x^{\,n}}{\Delta t} + gh^n\left(\dfrac{\partial h}{\partial x}\right)^{n+1} + gh^n\left(C_f^{\,n} q_x^{\,n+1} - S_x\right) = 0 \\ \dfrac{q_y^{\,n+1} - q_y^{\,n}}{\Delta t} + gh^n\left(\dfrac{\partial h}{\partial y}\right)^{n+1} + gh^n\left(C_f^{\,n} q_y^{\,n+1} - S_y\right) = 0 \end{cases} \quad (2)$$

The index “n” and “n+1” indicate the value of the hydraulic variables at “t” and “t+Δt” time respectively during the Δt computational interval. For the space discretization an orthogonal staggered grid is used (Fig. 1). This choice avoids the "chess-bordering" phenomena.

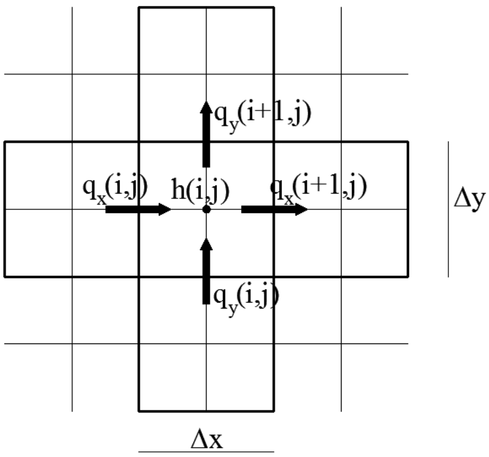

Fig. 1. Orthogonal grid for the space discretization in FLORA 2D.

By an iterative method the flow rate q_x and q_y are obtained resolving the following equations:

$$\begin{cases} q_x^{\,p} = -\dfrac{gh^n \Delta t}{1 + gh^n C_f^{\,n} \Delta t}\left(\dfrac{\partial h}{\partial x}\right)^p + \dfrac{gh^n S_x \Delta t + q_x^{\,n}}{1 + gh^n C_f \Delta t} \\ q_y^{\,p} = -\dfrac{gh^n \Delta t}{1 + gh^n C_f^{\,n} \Delta t}\left(\dfrac{\partial h}{\partial y}\right)^p + \dfrac{gh^n S_y \Delta t + q_y^{\,n}}{1 + gh^n C_f \Delta t} \end{cases} \quad (3)$$

where h^p, $q_x^{\,p}$ e $q_y^{\,p}$, are the p^{th} attempt values of the $(n+1)^{th}$ time step Δt.

The resistance coefficient C_f, using the Manning formula, takes the following expression:

$$C_f = \left(n^2 |q| / h^{\frac{10}{3}}\right) \quad (4)$$

The Manning coefficient n is calculated according to the Petryk and Bosmajian formula when the vegetation is rigid and the Freeman et al. proposal in the case of flexible vegetation.

Petryk and Bosmajian [19] developed the

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vegetation-density method to determine the roughness coefficient for a densely vegetated floodplain. Starting by the Manning's formula and assuming the forces in the longitudinal direction of a reach, they proposed the following equation in which vegetation density is expressed by the ratio $\Sigma A_i/(AL)$:

$$n = n_0 \sqrt{1 + \left(\frac{C_d \Sigma A_i}{2gAL}\right)\left(\frac{1}{n_0}\right)^2 R^{\frac{4}{3}}} \tag{5}$$

For flexible plants, Freeman and Rahmeyer [9] identified four significant parameters that relate drag or resistance to flow and plant variables: (i) the ratio of the flow drag force to the forces resisting plant distortion, (ii) the ratio of flow depth and the plant height, (iii) the blockage of the plants to the flow on the channel bottom, and (iv) the Reynold's number. They are presented in the following relationship:

$$C_d \, or \, \frac{V^*}{V} = f\left(\frac{\rho V^2 A}{E_s A_s}, \frac{Y_0}{H}, MA, R_e\right) \tag{6}$$

When flow depths reached 80 percent of the plant height (case of fully submerged vegetation), the n coefficient can be evaluated as:

$$n = K_n 0.183\left(\frac{E_s A_s}{\rho A_i V_*^2}\right)^{0.183}\left(\frac{H}{Y_0}\right)^{0.243}(MA_i)^{0.243}\left(\frac{\nu}{V_* R}\right)^{0.115}\left(\frac{1}{V_*}\right)R^{\frac{2}{3}}S^{\frac{1}{2}} \tag{7}$$

in which E is expressed as:

$$E_s = 7.648E06\left(\frac{H}{D_s}\right) + 2.174E04\left(\frac{H}{D_s}\right) + 1.809E03\left(\frac{H}{D_s}\right) \tag{8}$$

IV. APPLICATION

The study was carried out in a flat area of about 80 km^2 in Southern Italy stretching for 8 km upstream of the river mouth of the river Bradano (Fig. 2). Here the river flows to the Ionian sea and the land cover is a combination of agriculture, meadows, nature areas partly consisted of forests.

Plano-altimetric survey of the study area was created in 2006 by the Interregional Authority Basin of Basilicata. It was made with laser-scanning technology and digital aerial photogrammetry. Acquisition data was formulated by a Topeye system named "Topeye MKII" that works in full waveform way in order to give a better description of all ground elements. In fact, the "Topeye MKII" is able to record multiple echoes besides the first and the last pulse [5] −[4].

Often laser scan data are used to generate spatially-distributed friction coefficient for use in a two-dimensional model of flood inundation [16]. In this paper, it was used to define only the map of vegetation because the friction coefficient is calculated during the hydraulic computation as a function of both the plant and the water level.

The laser-scan set of data has a measurement density of 4 points per square meter, an altimetrical accuracy in open areas of 0.15 m and planimetric accuracy of 0.30 m. The raw data delivered by the sensor (x,y,z – triples) was processed into gridded elevation models. A Digital Surface Model (DSM) was extracted and its elevation points were classified into: ground, vegetation and building points. The gridded computational domain was created from the ground points with space resolution of 10 m. Similarly, a vegetation 10 m resolution grid was extracted from the vegetation points of the DSM. Using the digital aerial photogrammetry, two main classes of vegetation were defined: flexible and rigid. For the rigid vegetation nine types of plants were considered: citrus, cedar, cypress, eucalyptus, fruit trees, high bush, olive groves, pine trees and vines. For each type, variables of (5) were defined to allow the computational model to calculate the Manning coefficient n. n_0 was taken as 0.04 m$^{-1/3}$s, C_d was imposed equal to 1 according to Petryk and Bosmajian [19], the frontal area of vegetation blocking the flow A_i was calculated as the product of plant diameter and water height, A and L were derived from the digital aerial photogrammetry, R was considered to be equal to the water height (Fig. 3).

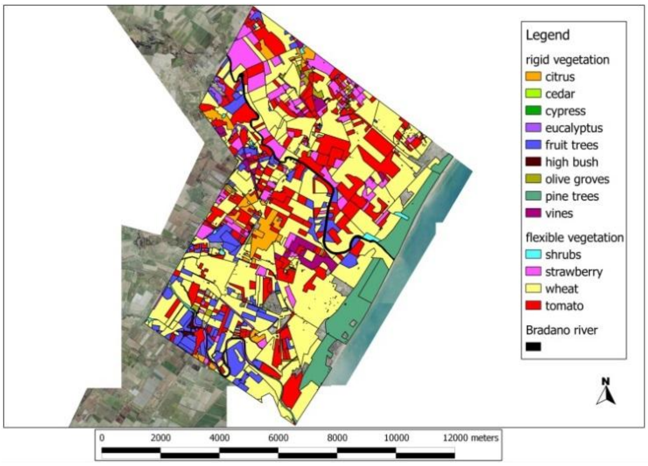

Fig. 2. Vegetation classification in the study area. Blank areas are buildings

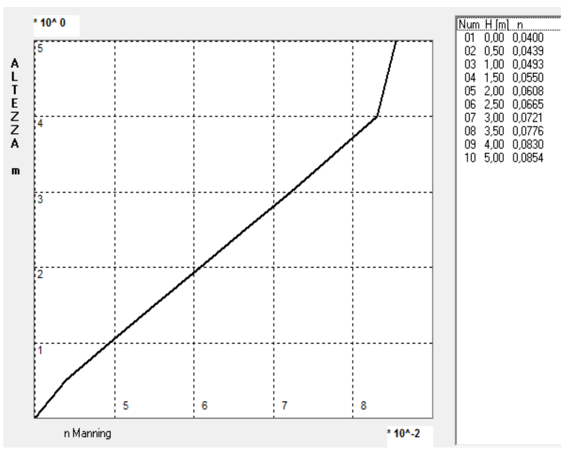

Fig. 3. Example of relationship between the Manning's *n* coefficient and water level for rigid vegetation in the FLORA-2D

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Four classes of plants were considered in the case of flexible vegetation: strawberry, shrubs, tomato and wheat. They were identified among the most widespread in the study area. In the (7) the variables were defined for each type. The limitations in the application of Freeman's proposal presented in Table I were considered.

TABLE I. VALIDITY RANGE OF THE VARIABLES IN EQ.2 IN FREEMAN'S MODEL

Variables	Minimum value	Maximum value
water depth (m)	0.4	1.4
velocity (m/s)	0.15	1.1
n ($m^{-1/3}s$)	0.04	0.14
plant height (m)	0.20	1.52
plant width (m)	0.076	0.91
plant density (plants/m^2)	0.53	13
E (N/m^2)	5.3×10^7	4.8×10^9
Re	1.4×10^5	1.6×10^6

The values of the variables were defined considering rigid and flexible vegetation in March.

Following substantial heavy rain on 1 March 2011, the river Bradano, Southern Italy, was subject to significant flooding in about a 30 year return period. The flood event determined a wide inundation with damage to the main and secondary road networks and to agriculture and the loss of animals. The hydrograph of this event in Fig. 4 was considered as the upstream boundary condition in FLORA-2D. It was obtained from the rainfall data and using the AD2 hydrological model [21]. Synthetically, this method evaluates the water balance considering the following hydrological elements as relevant: (i) the precipitation input, (ii) superficial infiltration into the soil; (iii) direct overland flows, (iv) subsurface flow and (v) deep infiltration into groundwater.

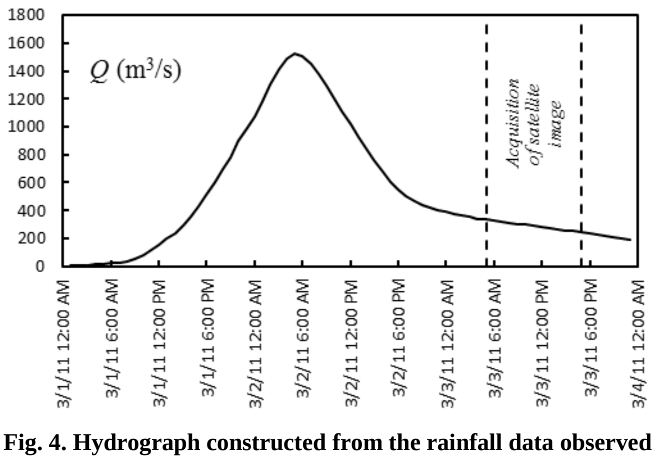

Fig. 4. Hydrograph constructed from the rainfall data observed on March 1, 2011 and using the AD2 hydrological model with acquisition time interval of the satellite image.

V. RESULTS

The simulation time was about 15 hours.

Some tests were performed to verify the behavior of the hydraulic model for both the shrubs and woody vegetation.

Fig. 5 shows the variation of *n* roughness coefficient during the flood in a cell of the computational domain covered by rigid vegetation as high bush. According to the proposal by Petryk e Bosmajian, the *n* coefficient increases as the water depth *h*.

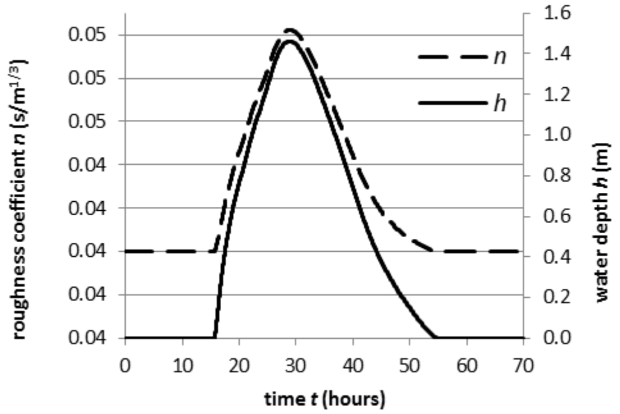

Fig. 5. Temporal variation of n coefficient and water depth h in a cell of the computational domain covered by rigid vegetation.

The estimation of the roughness of the flexible vegetation is much more complex because the variables involved are more numerous than in the case of woody vegetation. In Fig. 6, the case of a cell covered by shrubs with 1 meter height is represented and the interval close to the time when the flood wave arrives on that cell is highlighted. The temporal variation of the water depth and velocity is also shown.

Two zones of submersion are identified: partial when the water depth h is less than the height of the plant h_{veg} and total when h is greater than h_{veg}.

The model performs the Freeman's theory quite well. In fact, the roughness coefficient increases with water depth in the case of partial submergence and it decreases when the plant is completely submerged. The values of *n* at the extremes of the range considered were affected by the controls introduced in the hydraulic model that reflect the range of validity of Freeman's formula. The velocity has an initial peak when the wave impacts on the cell because the convective terms have been neglected. Then, for $h<h_{veg}$, the velocity decreases because of the increase of resistance offered by the vegetation. When $h>h_{veg}$, the velocity increases with decreasing resistance due to the bending of the plant.

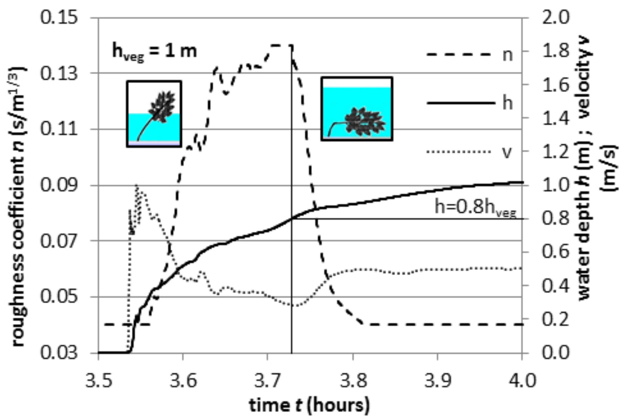

Fig. 6. Temporal variation of *n* coefficient, water depth *h* and velocity *v* in a cell of the computational domain covered by flexible vegetation.

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A COSMO-SkyMed image of the study area was provided by the Civil Protection of Basilicata and used to compare the predicted extent. The image was acquired in March 2011, at 24-36 hours after the flood peak.

The shape and the extension of the flood were qualitatively compared.

The reproduction of the hydrograph of the flood event of March 2011 has some uncertainties. In fact, it has been evaluated through a hydrologic and hydraulic modelling because, in the control sections, there are no measures of discharge but only of water level (Fig. 4). Other limitations are due to the image acquisition as the difficulty in detecting the water below dense vegetation (Fig. 7) and the elapsed time between the start of the flood and the satellite survey.

Fig. 8 displays the comparison between observed and simulated flood extent and it shows a satisfactory correspondence of inundated areas. The simulated inundation is normally continuous whereas the satellite image has patches of inundation. This patches of inundation, that are surveyed between 24 and 36 hours after the start of the flood, may be the effect of the drainage network in the right of the river, going from upstream to downstream. Instead, in the hydraulic simulations, this drainage network was not considered.

VI. Conclusion

The definition of the roughness coefficient in the hydraulic models of floods is difficult and subjective. Generally, it is expressed as Manning’s *n* coefficient and it depends on a number of factors including: surface roughness, vegetation, channel irregularities, channel alignment, scour and deposition, obstructions, size and shape of the channel, stage and discharge, season changes, temperature and suspended material and bedload. Manning’s *n* value should be calibrated whenever observed water surface profile information is available. But when this is not possible, values obtained from experimental data should be used as guides in selecting *n* coefficients. Compilations of n for stream and floodplain can be found in books and works by several authors.

To reduce the subjectivity in the choice of the *n* coefficient the flooding model FLORA-2D was implemented in which the resistance coefficient varies in space and time. Therefore, during a flood the *n* coefficient of each type of plant changes with the hydraulic variables as water depth and velocity.

This model was founded on the “shallow water equations” simplified by eliminating the convective terms and calculates the resistance coefficient according to the Petryk and Bosmajian formula when the vegetation is rigid and the Freeman et al. proposal in the case of flexible vegetation.

A first evaluation of the behavior of the model was carried out both in the case of woody vegetation and in the case of flexible vegetation. It shows a good correspondence with the theories of Petryk and Bosmajian [19] and Freeman et al. [9] respectively.

In addition, a qualitative comparison between the flooded area simulated with FLORA-2D and that observed by satellite has been conducted.

We are still working on the FLORA-2D. First, we are applying the model to other floods. We also want to integrate the code to allow the user to create a one-dimensional simulation at the river networks and channels. As shown in the application, the drainage network influences the flood propagation and the time of persistence of water on the floodplain.

Fig. 7. Eucalyptus wood at the mouth of Bradano river during the inundation of March 2011. The water below the trees shows in the picture has not been detected on the satellite image.

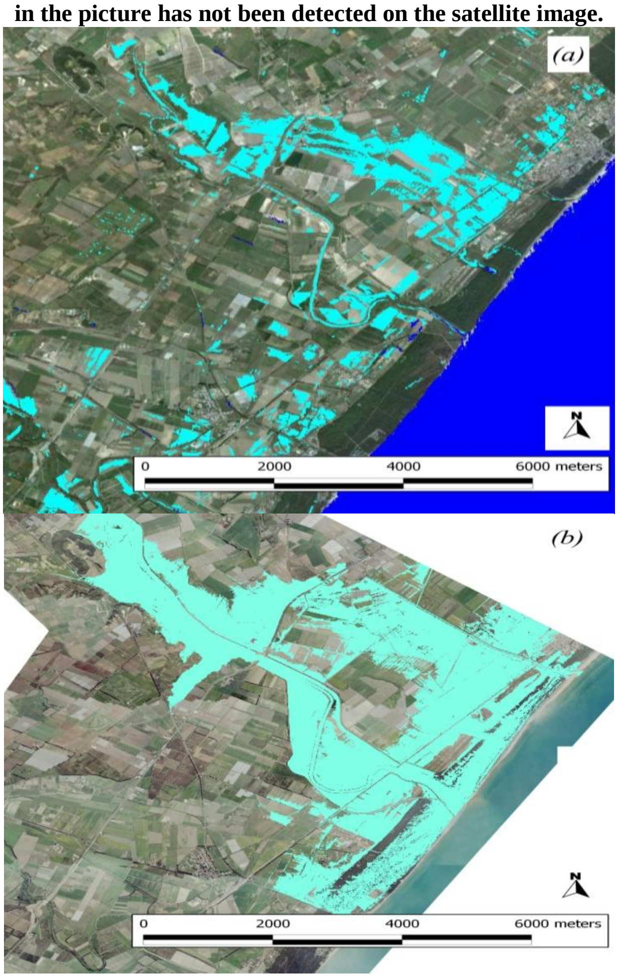

Fig. 8. Comparison between observed (a) and simulated (b) flood extent. A COSMO-SkyMed image was used to define the observed inundation and the results of FLORA-2D were employed to map the simulated inundation.

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APPENDIX

A = cross sectional flow area (m^2),
Ai = frontal area of an individual plant blocking flow (m²)
A_s = total cross-sectional area of all of the stems of an individual plant (m^2),
ΣA_i = total frontal area of vegetation blocking the flow (m^2),
C_d = effective drag coefficient for the vegetation in the direction of flow,
C_f = resistance coefficient;
Ds = steam diameter (m)
E_s = modulus of plant stiffness (N/m^2),
g = the gravitational constant (m/s^2),
h = water depth;
H = average undeflected plant height (m),
L = length of channel reach (m),
M =relative plant density, number of plants per m^2,
n = Manning's roughness coefficient,
n_0 = Manning's boundary-roughness coefficient,
q_x, q_y = specific flow rates in the x and y direction;
R = hydraulic radius (m),
S_x, S_y = ground slope components in the x and y direction;
t = time;
u, v = components of the flow velocity vector in the x and y direction;
V^*=shear velocity (m/s),
V= mean channel velocity (m/s),
x,y =orthogonal coordinates in the horizontal plane;
Y_0 = flow depth (m),
ρ = fluid density (kg/m^3)
R_e = Reynolds number,
υ_τ = eddy viscosity introduced by Boussinesq,
υ = fluid dynamic viscosity (m²/s),
S = Bed or energy slope, dimensionless.

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Luciana Giosa received the "Laurea" (M.S.) degree in Environmental Engineering in 2000 and the master's degree in "New tools for land management" in 2005 from the University of Basilicata (Italy) and the Ph.D in "Environmental and Hydraulic Engineering" in 2007 from University of Calabria (Italy). In 2006 she became subject matter expert in "Hydrological and Hydraulic Risk" and "Hydraulic Laboratory" at the School of Engineering of the University of Basilicata. She has a broad interest in hydrology and hydraulics, flood prediction, LiDAR technology, mathematical modeling to simulate natural disasters, flood and landslide hazard, risk management and G.I.S. applications. Her research activity has produced publications in national journals (i.e. *Italian Journal of Engineering Geology and Environment* and *L'acqua*) and national (i.e. *National Conference of hydraulics*) and international (i.e *River Basin Management IV* and *Flood Recovery Innovation and Response Conferences*) proceedings. She has been involved in the international MEDDMAN project Integrated water resources management, development and confrontation of common and transnational methodologies for combating drought within the MEDOCC region (2006-07) and was training coordinator in the project POI.DRO "Experts in environmental monitoring and hydrogeological safety" (2010-2012) organized by Italian Universities and research Institutes.

Leonardo Mancusi Civil Engineer graduated of the Polytechnic of Turin (Italy) with 23 years of professional work experience in studies and practical applications concerning the hydraulic safety of dams and water resources.
From 1989 to 2003, working at ISMES (Istituto Sperimentale Modelli e Strutture) in Bergamo (Italy), he performed, for about 250 dams in Italy, the Dam Break Analysis to determine, for the purpose of civil protection, the flooded areas for hypothetical dam failure.
From 2004 to now, after the transfer from ISMES to the current company, RSE S.pA. (Research on Energy Systems), due to sale of a business segment, he is working in the research and development field. To research, he is currently collaborating with the School of Engineering of University of Basilicata at Potenza (Italy).
His research interests are in flood hazard mapping and also in developing hydrological models for flood forecast and hydroelectric production forecast. He developed models and software tools, based on GIS system, for flood waves propagation computation, to support operations of hydropower reservoirs for flood attenuation and to make forecasts of hydropower production.
He has recently presented contribution at international conferences or workshops as UFRIM Urban Flood Risk Management, Graz (Austria) 2011 or 9th ICOLD European Club Symposium, Venice(Italy) 2013 or ICOLD International Benchmark Workshop on Numerical Analysis of Dams, Graz (Austria) 2013. He has recently published articles in national journals (i.e Rivista L'ACQUA 4/2013 pp. 41-48) and international (i.e Hydrological Processes DOI: 10.1002/hyp.9788, 2013).

Aurelia Sole Full Professor in the field of Computational Hydraulic, Environmental Models and GIS, Management of Hydraulic and Hydrologic risk. Teaching staff coordinator of PhD in Methods and Technologies for Environmental Monitoring, from 2007 to 2012 Director of Department of Engineering and Environmental Physics - University of Basilicata; Researcher in the field of Water Management, flood risk evaluation by hydrodynamic models and Geographic Information Systems; coordinator of national and international research projects; Member of scientific committee of Flood Recovery Innovation and Response (FRIAR) Conferences, Wessex Institute of Technology. Author of more than of 100 scientific and technical papers in the fields of: hydraulic engineering, with particular attention to: hydrologic problems; applications and proposal of new models to analyse flood risk in urban and natural environment; dam break; river dynamics and morphology, distributed models supported by GIS; control and evaluation of pollution in water bodies, generated from point and non point sources pollution, vulnerability evaluation of flood and landslide prone areas.