IMPACT OF TERRITORY MANAGEMENT ON URBAN FLOOD: A TEST CASE

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EXTENDED ABSTRACT

La manutenzione del territorio, mediante la bonifica dei corsi d'acqua anche a scala di piccoli canali, da ogni tipo di ostruzione, in particolare sterpaglia, tronchi d'albero e detriti che impediscono il naturale e corretto drenaggio dell'acqua piovana, costituisce una importante necessità per la prevenzione da inondazioni anche per piccole scale urbane collocate in piccoli bacini idrologici. In questi casi, potrebbero risultare significativi anche piccoli interventi antropici, quali la costruzione di passi per l'attraversamento di fossati. Per una corretta valutazione delle azioni da mettere in atto, l'applicazione di sofisticati mezzi computazionali, modulata dalla competenza attenta di un esperto (*expert judgment*), costituisce uno strumento di indagine non solo utile, ma anche necessario. A tale scopo sono state proposte differenti tipologie numeriche. Tra queste, l'approccio matematico dello 'S*hallow water'*, con soluzione numerica ai volumi finiti (*Finite Volume Method*), basata sulla tecnica di Godunov-Riemann, implementata nel codice di calcolo commerciale utilizzato in questo lavoro, ha trovato interessanti calibrazioni e validazioni nella bibliografia internazionale. Un altro importante aspetto, anche per la progettazione di eventuali sistemi di *early-warning* a fronte di eventi piovosi, è la velocità di calcolo. A tale proposito, negli ultimi anni, è stata utilizzata la specificità di alcune schede grafiche implementate per un rendering veloce ed efficace dei 'video-games' che consentono di elaborare semplici calcoli numerici in parallelo utilizzando migliaia di microprocessori di cui sono costituiti. Questa tecnica hardware-software, implementata anche nel codice computazionale selezionato per svolgere questo lavoro, è basata sul *Graphical Processing Unit* (GPU), che consente di abbattere i tempi di calcolo anche di 80 volte. Il caso-studio utilizzato in questo articolo riguarda un evento piovoso avvenuto tra il 26 aprile e il 2 maggio 2014 che ha provocato fenomeni d'inondazione tra il 2 e il 3 maggio nella frazione di Pianello di Ostra in provincia di Ancona (Marche, Italia). Dopo una opportuna ricognizione del luogo e la relativa utile intervista degli abitanti del luogo, è stato effettuato un rilievo topografico mediante drone ad alta risoluzione (30 cm x 30 cm). Quindi è stato utilizzato un GIS e la cartografia disponibile, mentre i dati pluviometrici sono stati tratti dal sito disponibile in rete, relativi alla Stazione di Corinaldo a circa 9.1 km da Pianello d'Ostra. I dati pluviometrici sono stati elaborati mediante il metodo empirico del *Curve-Number* (CN), sviluppato dall' USDA *Natural Resources Conservation Service* (SCS). La valutazione del CN avviene mediante apposite tabelle realizzate dal SCS che prendono in considerazione la granulometria del terreno, le condizioni di umidità precedenti all'evento piovoso e l'uso del suolo. Il metodo consente di determinare la quantità approssimativa di deflusso in piccoli bacini, conseguente ad una data precipitazione, considerando anche le specifiche caratteristiche dell'area interessata. Sono state effettuate diverse simulazioni parametriche considerando, in particolare, lo stato di manutenzione del Fosso della Trocca che caratterizza il bacino in studio, con e senza presenza di detriti. Inoltre è stato considerato anche l'effetto della presenza di un piccolo ponte di attraversamento. La calibrazione del modello è stata effettuata considerando lo stato preesistente all'inondazione, con la sezione del fosso e del piccolo ponte interessata da detriti e verificando numericamente l'inondazione del centro abitato, con altezze della superficie dell'acqua esondata comparabile con quella realmente verificatesi (15-50 cm). Infine, considerando le condizioni attuali del fosso e la rimozione del piccolo ponte, la simulazione numerica prevede che, con le stesse condizioni pluviometriche, l'esondazione non sarebbe avvenuta.

ABSTRACT

The maintenance of the territory, through the recovery of the water courses even at the scale of small canals, from any type of obstruction, in particular weeds, tree trunks, all kinds of debris that prevent the natural and correct drainage of rainwater, constitutes an important need for flood prevention, even for small urban scale located in small hydrological basins. For a correct evaluation of the actions to be implemented, the application of advanced computational tools, beside expert judgment, appear to be not only useful, but also necessary. For this purpose, different numerical tools have been proposed. Among these, the mathematical approach of the 'Shallow water', based on the Finite Element Method and the Godunov-Riemann technique, used in the commercial computational code, selected in this paper, is very popular within the international context. Moreover, the selected commercial software is based on the Graphical Processing Unit (GPU), which can reduce the calculation times even by 80 times. The case study used in this article concerns a rainy event that occurred between April 26th and May 2nd, 2014 that caused flooding between May 2nd and 3rd in the Pianello di Ostra district in the province of Ancona (Marche, Italy). After an opportune site inspection and the relative useful interview of the inhabitants of the place, a topographic high resolution survey (30 cm x 30 cm) was carried out by means of a drone. Then GIS and the available cartography were used, while the pluviometric data were taken from the available website, relating to the Corinaldo Station about 9.1 km from Pianello d'Ostra. The rainfall data were processed using the Curve-Number (CN) empirical method, developed by the USDA Natural Resources Conservation Service (SCS). The method allows to determine the approximate amount of runoff in small basins, consequent to a given precipitation, also considering the specific characteristics of the area concerned. Several parametric simulations have been carried out considering, in particular, the state of maintenance of the Fosso della Trocca that characterizes the basin under study, with and without the presence of debris. Furthermore, the effect of the presence of a small crossing bridge was also considered. The calibration of the model was obtained considering the pre-event state of the canal and of the small bridge, that was affected by debris, and confirming by a numerical point of view, the urban flood occurrence, with heights of the surface of the water comparable to that actually occurred. (15-50 cm). Finally, considering the current conditions of the channel and the removal of the small bridge, the numerical simulation predicts that, with the same rainfall conditions, the flooding would not have occurred.

KEYWORDS: *Urban Flood, Shallow water numerical modelling, GPU, Territory management*

INTRODUCTION

In order to study flood phenomena, advanced utilized approaches are based on the balance equations of physics, pursued by the *Computational Fluid Dynamic* (CFD). Nearly, all CFD rely on solving Navier-Stokes flow equations (PASCULLI, 2008), supplemented by experimental laws that define the parameters related to the mass transport of material, the rate of erosion (for instance: PASCULLI & SCIARRA, 2006), etc. Besides the most common 'grid-based methods', another category of approaches was proposed: the mesh-less solution of the differential equation. Among others, *Smoothed Particle Hydrodynamics* (SPH) appears to be promising (PASCULLI & MINATTI, 2010; MINATTI & PASCULLI, 2011; PASCULLI *et alii*, 2013, 2014; PASTOR *et alii* 2014, among many others). The *Reduced Complexity Models* (RCM), to which, for example, *Cellular Automata* (CA) approach belongs (PASCULLI & AUDISIO, 2015), represents an important alternative to the CFD, in particular in order to predict morphological changes, within large area and over relevant time scale (climate evolution as well), both at reach (AUDISIO *et alii*, 2015; PASCULLI *et alii*, 2010) and at catchment scale (PASCULLI *et alii*, 2017a). Therefore, for the study of the phenomena considered in this paper, involving short time scale, a suitable compromise could be found in approaches capable to simplify CFD technique, like the *Shallow Water* approach implemented in RiverFlow2D (HYDRONIA, 2017) that was selected to perform the simulations discussed in the following sections. These approaches would be very useful within the framework of the study of morphology variations of a landscape (CALISTA *et alii*, 2016), but also in the study of Urban floods. Another important feature implemented in RiverFlow2D, is the possibility to include frequent wetting and drying phenomena, induced by rainfall variability, which may lower soil mechanical strength (for example, for pyroclastic soil: ESPOSITO *et alii*, 2013; PASCULLI *et alii*, 2017b), triggering possible erosion occurrences and accordingly, morphological variation of the territory. On the other hand, important phenomena like turbulence (DI NUCCI & RUSSO SPENA, 2018), are missed into the present version of the code.

MATHEMATICAL AND NUMERICAL MODELLING

As pre and post processor, the RiverFlow2D is based on SMS general purpose *Graphical User Interface* (GUI) for free surface flow models. The most physically realistic approach should be based on 3D modelling. However, the relative computational time's cost, for the spatial and temporal scale regarding this study, would had been very high. Accordingly, the *Depth-Averaged 2D, shallow-water,* approach (MURILLO & GARCIA-NAVARRO, 2010), adopted by the selected software, based on the assumption that the vertical depth of the flow is

negligible compared to the other flow's dimensions, was the right compromise. In order to consider also bed level jumps (considered as source terms in the related differential equations), due to the geomorphology of real complex landform, the software includes the *Augmented approximate Riemann solvers* approach. In addition, the selected software allows numerical processing of the simulations using techniques based on even parallel *Graphic Processing Unit* (GPU) cards which is capable to run many times faster (also 80 times faster!) than in single processor computers. In the following sub-chapters a summarized description of the utilized mathematical and numerical approaches, freely adapted from (HYDRONIA, 2017) in which more details are reported, is briefly discussed.

Hydrodynamic unsteady flow models

The following is the resulting system of the coupled partial differential equations, based on the water volume conservation, water momentum conservation and shallow water assumption (VREUGDENHIL, 1994):

$$\frac{\partial F(U)}{\partial t} + \frac{\partial F(U)}{\partial x} + \frac{\partial G(U)}{\partial t} = S(U, x, y) \quad (1)$$

$$U = \left(h, q_x, q_y\right)^T ; F = \left(q_x, \frac{q_x^2}{h} + \frac{1}{2}gh^2, \frac{q_x q_y}{h}\right)^T$$
$$G = \left(q_y, \frac{q_x q_y}{h}, \frac{q_y^2}{h} + \frac{1}{2}gh^2\right)^T \quad (2)$$

$$S = \left(0, \frac{p_{bx}}{\rho} - \frac{\tau_{bx}}{\rho}, \frac{p_{by}}{\rho} - \frac{\tau_{by}}{\rho}\right)^T \quad (3)$$

where: h is the water depth; $q_x = h\mathrm{u}$ and $q_y = h\mathrm{v}$ the unit discharges, resulting from the *shallow water* approach; (u,v) the depth averaged components of the velocity vector **u** along, respectively, x and y coordinates; g is the gravity acceleration; $gh^2/2$ the flux obtained after assuming a hydrostatic pressure distribution in every water column, as common practice in *shallow water* models. The source term $S(U,x,y)$ incorporates the effect of pressure forces, p_{bx} and p_{by}, over the bed, and the tangential forces, τ_{bx} and τ_{by}, generated by the bed stress, where $p_{bx}/\rho = ghS_{0x}$ and $p_{by}/\rho = ghS_{0y}$ while $S_{0x} = -\partial z/\partial x$ and $S_{0y} = -\partial z/\partial y$ are the bed slopes of the bottom level z. The tangential forces are characterized by selected rheological laws discussed briefly in the following sub-sections. The *Clear-water* option was exploited, based on the Manning friction law:

$$\tau_{bx} = S_{fx} \equiv \frac{n^2 \mathrm{u}\sqrt{\mathrm{u}^2 + \mathrm{v}^2}}{h^{4/3}}; \qquad \tau_{by} = S_{fy} \equiv \frac{n^2 \mathrm{v}\sqrt{\mathrm{u}^2 + \mathrm{v}^2}}{h^{4/3}} \quad (4)$$

where '*n*' is the Manning coefficient related, in some way, to the roughness coefficient. In the following a brief presentation of the meaning of this parameter is given.

Manning's coefficient

The Manning's '*n*' coefficient usually accounts for the effects of bed roughness, internal friction and variations in shape and size of the channel or canal cross section, obstructions, river meandering. This kind of coefficient was partially used as a tune parameter in the calibration process in order to adjust the numerical results to measured data. The initial guessed values, employed in this paper, were based on the tables reported in Chow (1959). The software allows to consider variable Manning factor within the basin through right polygonization and proportional to the flow depth.

Numerical solver

The general underlaying numerical approach is based on the Finite-volume scheme, by the integration in a volume or grid-cell Ω using Gauss theorem:

$$\frac{\partial}{\partial t}\int_{\Omega} U d\Omega + \oint_{\partial\Omega} E(F, G) \cdot n ds = \int_{\Omega} S d\Omega \quad (5)$$

where U, F, G and S are the vectors already described in (2), $\partial\Omega$ is the volume domain boundary, $n(n_x, n_y)$ is the outward unit normal vector to the volume Ω. Then, a piecewise representation of the conserved variables and an upwind and unified formulation of fluxes and source terms is applied (Murillo & Garcia Navarro, 2010):

$$\frac{\partial}{\partial t}\int_{\Omega_i} U d\Omega + \sum_{k=1}^{(\text{Number of Edges})_i} (E \cdot n - \overline{S})_k A_k = 0 \quad (6)$$

where Ω_i is the volume of the i-th computational cell, whose area of the k-th edge face is A_k. Then the approximate solution is always constructed as a sum of jumps or shocks, also involving rarefactions. The selected software uses variable time steps. The maximum allowed time-step is controlled by the user setting *Courant-Friederich-Lewy* (CFL) number, whose maximum theoretical value is equal to 1, proportional to the local grid-cell width, but also inversely proportional to velocity and depth.

TEST CASE

The territory under study is located in a flat area, on the edge of the hill slopes that border the valley of the Misa, at an average altitude of 50 meters a.s.l., along the Trocca Canal, a left tributary of the Misa river. The soils outcropping in the area under study are related to the continental quaternary cover, attributed by the most recent literature to deposits of alluvial fan, with the typical fan shape, weakly convex, formed by the transport and deposition of sediments with a high fine matrix (debris flow of the canal trench). The lithological composition of fan and alluvial deposits is given by clays and silts, locally with intercalated sandy lenses, to cover gravels of a predominantly calcareous nature that precede the clay-marly Plio-Pleistocene bedrock. The hydrography is only marked by Trocca Canal that characterizes the hydrographic basin. The basin has an extension of about 2 km², with a maximum height

of 173 m and a minimum of 50 m a.s.l., with a mainly hilly morphology, wide with gentle slopes, smooth steep and completely cultivated. The channel runs at the center of the valley, generally, with an almost rectangular section and escarpments affected by arboreal and shrubby associations, collecting the surface runoff waters of its basin. Just upstream of the town of Pianello, the canal is crossed by the street junction between the variant to the S.P. 360/01 and the S.P. 360 and then continues at the open air course through the town of Pianello up to the S.P. Arceviese.

Then, the channel crosses as a culvert the S.P. Arceviese and the part of the town of Pianello which develops downstream of it, for a length of about 135 meters. In the last section before the confluence in the Misa River, the channel runs again in the open air, contained by side walls and bottom in cement. The general hydrogeological scheme is represented by clays and silts with thin sandy intercalations and by gravels with sands. The clayey-muddy lithotypes has a medium-low permeability, but local increases in the sandy fraction can allow the establishment of discontinuous water levels while the gravel lithotype has a good permeability.

SIMULATIONS

In order to perform parametric simulation the following assumptions were selected:

1) the rainfall has been constant over time (hypothesis used for the application of the CN in order to determine the amount of the runoff water);

2) all the runoff water of the upstream basin has discharged into the canal in consideration;

3) no evaporation and no infiltration (except what has already been considered in the CN method);

4) the Pezzoli's law has been used for the correcting time, necessary for the CN method;

5) the hydrograph was taken from the regional weather-hydro-rainfall information system:
(http://app.protezionecivile.marche.it/sol/indexjs.php?lang=it);

6) for rainfall parameters:

a) once the CN method was applied, the value of the Antecedent Moisture Conditions (A.M.C.) was acquired;

b) the rainfall during the previous 5 days was considered in order to estimate the total amount of water available for runoff through the estimate of saturation and the trapping of water in the soil depressions in general; the higher the CN, the higher the amount of the runoff water; it is a percentage of the total rainfall.

In Fig. 1 the rainfall and the cumulate of the selected event, measured at Corinaldo (Ancona, Marche, Italy) gauges are given.
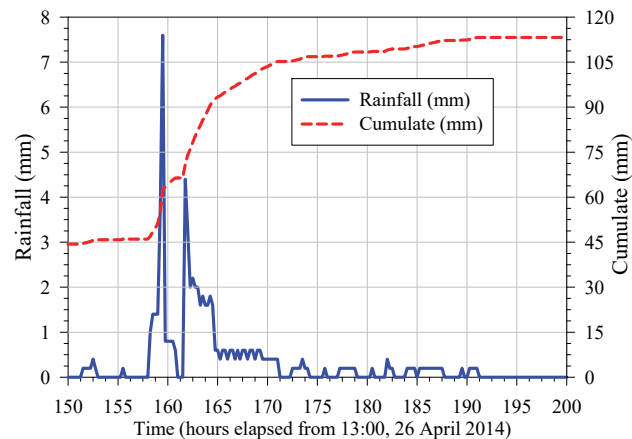

Fig. 1 - Rainfall and Cumulate of the selected event, measured at Corinaldo (Ancona, Marche, Italy) gauge

The Curve Number (CN) method, developed by the USDA Natural Resources Conservation Service (SCS) (USDA, 1986), is an empirical method based on rainfall and runoff measurements performed on small river basins. The method is very efficient for determining the approximate amount of runoff due to a given rainfall in a specific area.

A given pluviometric inflow $P[mm]$ does not generate outflow until its value reaches the threshold value, called *Absorption Capacity* $I_a[mm]$, this because a percentage of the inflow infiltrates through the soil or is retained by morphological depressions.

The specific surface runoff $Q_p[mm]$ is proportional to the rainfall inflow as the specific infiltrated volume $F[mm]$ is proportional to the maximum potential retention of the soil $S[mm]$, therefore it follows that:

$$\frac{Q_p}{P - I_a} = \frac{F}{S} \tag{7}$$

Setting the mass balance condition: $F = P - I_a - Q_p$, the following relation is given:

$$Q_p = \frac{(P - I_a)^2}{P - I_a + S} \tag{8}$$

which expresses the estimate of the specific runoff volume as a function of rainfall volume and of two characteristic basin parameters. The I_a parameter depends on the soil conditions such as: initial humidity, retention in morphological depressions, infiltration, land use; therefore, it is difficult to quantify this parameter directly. Regarding the land use, from the plot reported in Fig. 2 a percentage of about 92% was deduced.

An empirical relation links I_a to S through the expression $I_a = 0.2\ S$ from which we get:

$$Q_p = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{9}$$

S can be expressed as a function of the Runoff Curve Number CN, which can vary from 0 to 100, from the relation:

$$S = 25.4 \left(\frac{1000}{CN} - 10 \right)$$ (10)

Considering the equations (7) and (8), a bundle of curves to each of which corresponds to a different CN value is given.

It worth to notice that the relation (9) has physical meaning only if $P > 0.2S$ in agreement with the concept of absorption capacity previously exposed. The evaluation of the CN is carried out by means of special tables created by the SCS which take into consideration: the grain size of the soil, the humidity conditions prior to the rain event and the use of the land. Then using the Geological Map of the Marche Region at scale 1: 10000 and site inspection we evaluated the average granulometry of surface deposits. Afterwards the soil humidity conditions were evaluated based on the rainfall of the 5 days preceding the event and the season in which the event occurred (Antecedent Moisture Condition, A.M.C.). Based on the land use map (Fosso della Trocca, Fig. 2) we estimated that almost all (92%) is for agricultural use, so, based on Table 2-2b reported in (USDA, 1986), we evaluated a basic CN value equal to 85, valid for category II of humidity A.M.C. However, the number obtained must be corrected by equations (11).

$$CN_I = \frac{CN_{II}}{2.38 - 0.0138 \cdot CN_{II}}$$ (11)

Ultimately, the CN value relative to Category I is obtained. CN is placed in equation (10) and therefore (9) and Q_P is obtained which constitutes the net runoff. Through the equation (12), we obtain the maximum flow:

$$Q = \frac{Q_P \cdot A}{t_c} \cdot \frac{1000}{3600}$$ (12)

where $A[km^2]$ is Basin area and t_c [h] time of concentration relative to the basin.

The hydrological time of concentration is calculated by Pezzoli's law. Finally, the flow curve is constructed, introduced as a table in the River Flow 2D code, obtained by the rational method (the whole area subtended is equal to the total amount of the fallen water, estimated by the Hyetograph). The flow curve is a trapezoid with ascendant limb whose duration is equal to time of concentration, while the descendent limb has a duration equal to 5/3 time of concentration; the section at constant flow is determined considering the rainfall that was cumulated during 5 days before the event.

Finally, the resulting maximum value of the flow, was equal to 4.7 m³/s.

Land Use Chart - Trocca Canal's Basin

Reference: Land Use Chart 2007 1:10000 - Regione Marche
http://www.regione.marche.it/Regione-Utile/Paesaggio-Territorio-Urbanistica/Cartografia/Repertorio/Cartausosuolo10000_2007
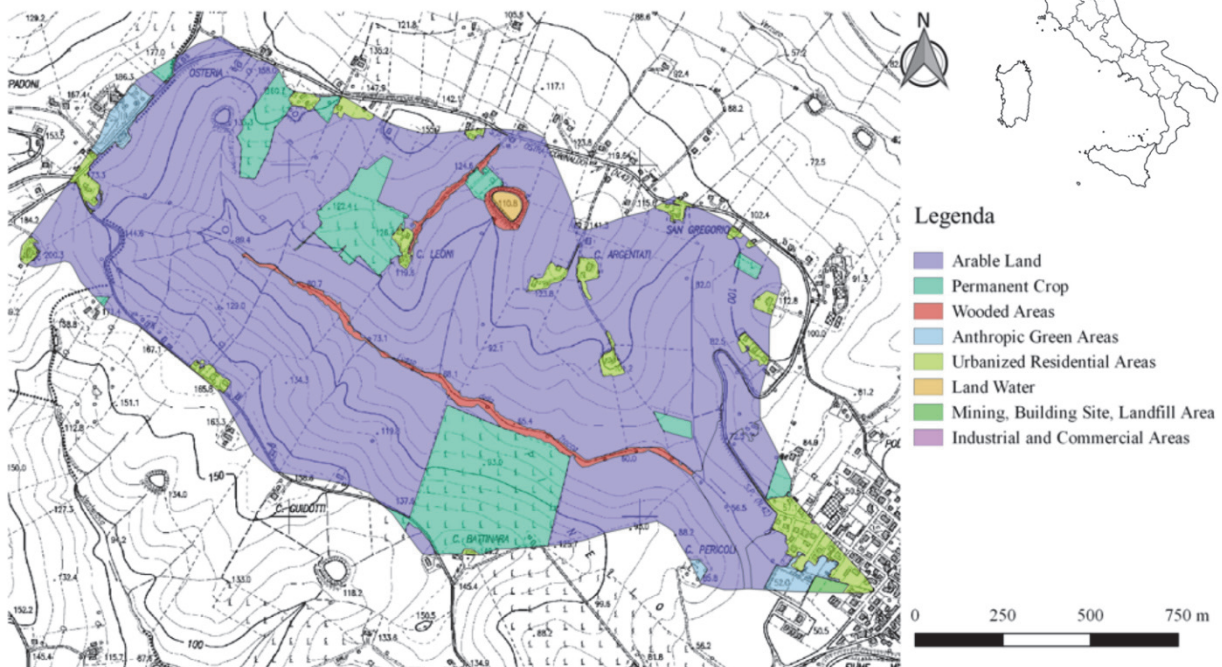

Fig. 2 - Land Use Chart to determine the necessary coefficient to determine CN coefficients

CONCEPTUAL MODEL

In Fig. 3 the plots of the spatial domain selected for the simulation are given. In particular the section A-A' with the view direction from upstream to downstream along which the depth of the flood water, acquired by numerical simulation, are indicated. Moreover the locations of the small bridge (labelled by 1) and the culvert (labelled by 2), related to the canal, are
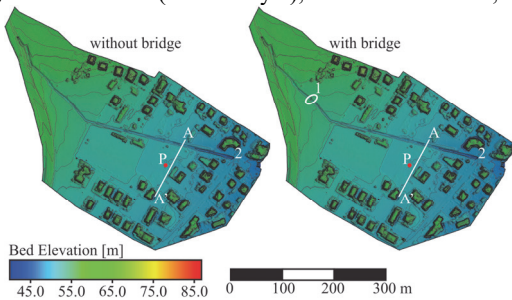
reported. In Fig. 4 the distribution of the Manning coefficient, by means of tables reported in Chow (1959) is given.

Then, in order to evaluate the velocity through the coulvert (label 2 in Fig. 3) the Chezy' law was applied.

Fig. 3 - Topographical plots of the spatial domain selected for the simulations
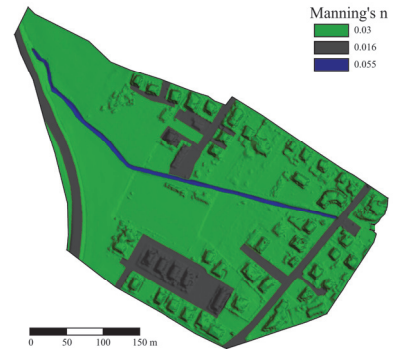

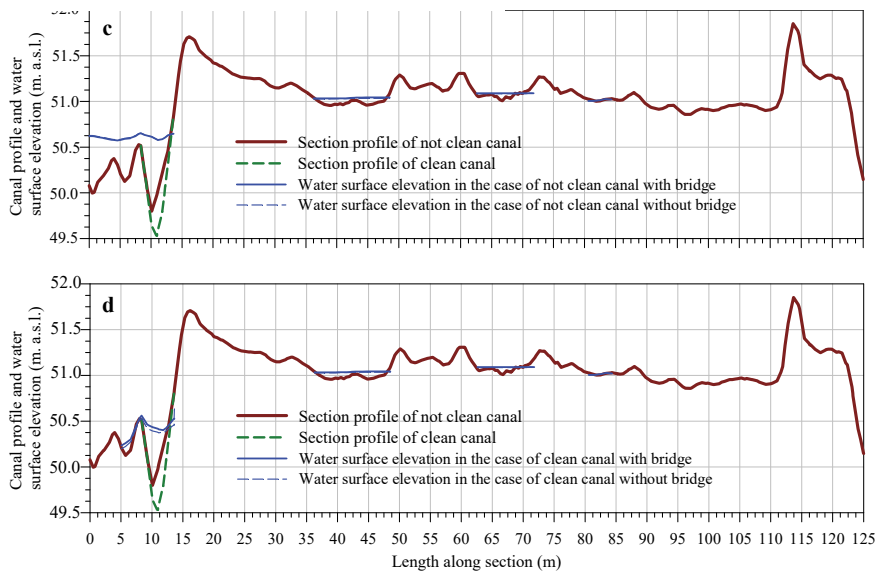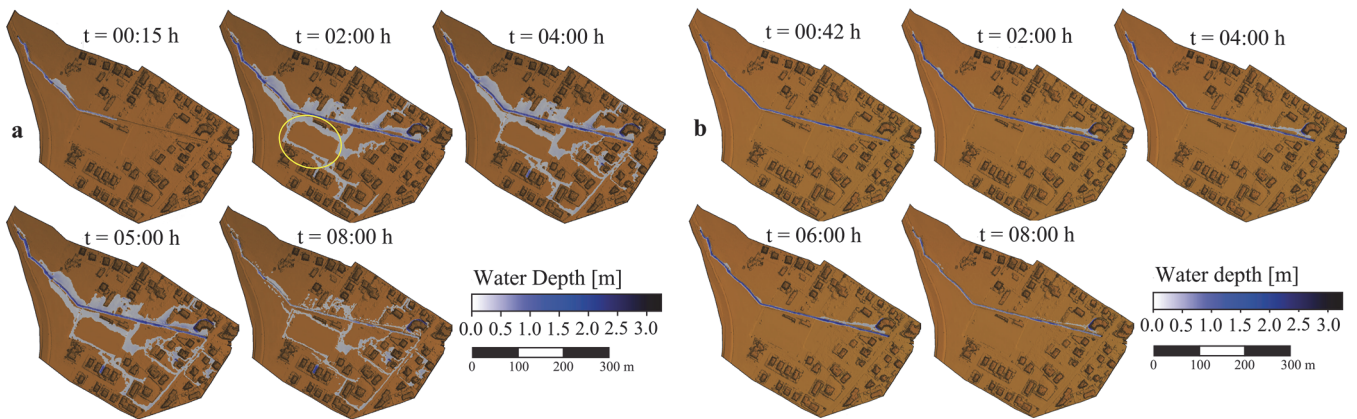Fig. 4 - Distribution of the Manning coefficient

Fig. 5 - 4.7 m³/s discharge; a) not clean canal with small bridge; b) clean canal without small bridge; c) not clean canal, profile of water surface elevation, with small bridge; d) clean canal, profile of water surface elevation with and without small bridge
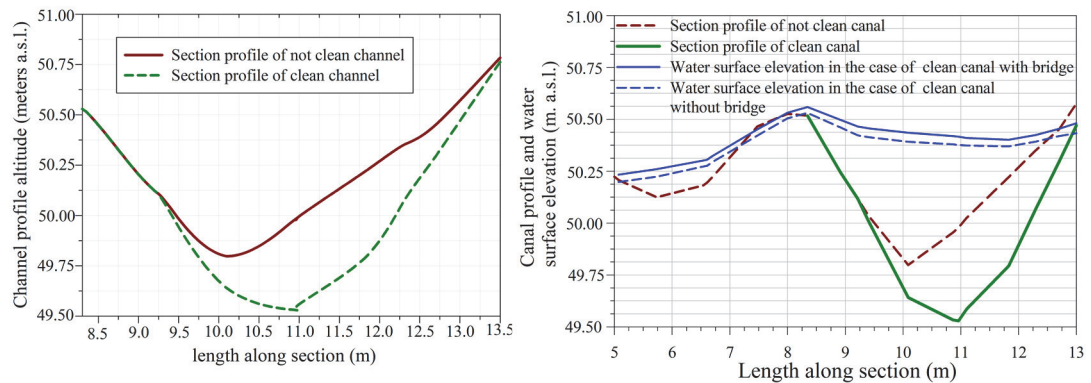
Fig. 6 - At the left, the sections (A-A' in Fig. 3) of clean and not clean channel; at the right, 4.7 m³/s discharge, clean canal with and without bridge after 6:30 h since the selected start of the event

RESULTS

In Fig. 5, the outputs of simulations obtained assuming 4.7 m³/s discharge, accordingly the previous discussion, are given. In Fig. 5a is reported the numerical simulation of the transient of what may be happened during the flooding event of May 2014. It was assumed the solid section line reported in Fig. 6 left, due to debris deposition, branches, trees, leaves and the small bridge.

As it appears clearly, also from Fig. 5c, the simulation, based on the above discussion, is congruent to the actual flooding occurrence. Also the water depth, about 50 cm at least along the section A-A', appears to be close to the experimental values. It worth noting that the soccer field, indicated by the yellow ellipse (Fig. 5a), was raised about 30 cm after the flooding that at the time had invaded it. However, the topographic data used for the simulations reported in this paper was only recently detected. Fig. 5b and Fig. 5d display the numerical simulation, assuming clean canal, without the small bridge. Also, in this case, it worth noting that, from Fig. 6 right, the presence of the small bridge could affect the flooding impact.

CONCLUSIONS

The application of numerical modeling technique, such as Shallow Water used in this paper, with a high resolution topographic model, is a powerful tool for predict the response of the surface water drainage system, to a reference rainy event for the studied area.

Accordingly, in this work the importance of a correct maintenance of rainwater drainage canals, even on a small scale and for small towns, was highlighted. In addition, also a correct planning of the anthropic impact which, although small, can have a significant impact on the hydrological risk should be pursued.

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