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FULLY-HYDRODYNAMIC MODELLING SUPPORTINGFLOOD HAZARD ASSESSMENT AND COMMUNICATION: A REFERENCE FRAMEWORK

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EXTENDED ABSTRACT

La perimetrazione delle aree potenzialmente inondabili e la conseguente redazione delle mappe di pericolosità, previste dalla Direttiva 2007/60/CE del 23 ottobre 2007 del Parlamento Europeo, riguardante la valutazione e la gestione del rischio di alluvione, costituiscono materia complessa sulla quale possono essere trasferiti molti dei significativi progressi conseguiti dalla ricerca idraulica del settore.

Un primo aspetto riguarda certamente gli strumenti fisico-matematici per il calcolo delle correnti a superficie libera che si propagano in alvei naturali o in aree inondabili. Esse sono descritte matematicamente mediante le equazioni di moto vario, note come equazioni di De Saint Vénant o delle acque basse (*Shallow Water Equations*, SWE). Lo studio della corrente in moto vario conseguente al repentino crollo delle dighe murarie (*dam break*) ha rappresentato il più impegnativo campo di applicazione nel quale sono rifluite le modalità più innovative di integrazione numerica delle suddette equazioni e di trattazione del termine sorgente. La formulazione conservativa delle SWE e la loro integrazione mediante schemi shock capturing hanno consentito di inglobare la corretta simulazione delle discontinuità della corrente (onde a fronte ripido, propagazione del fronte in alvei asciutti) nonché i fenomeni idraulici localizzati e i cambi di regime di moto. Questi sono aspetti molto importanti anche per una valutazione accurata della pericolosità idraulica in correnti generate da esondazioni fluviali, anche in relazione all'interazione tra corrente e manufatti. Fino a qualche decennio fa, le SWE sono state utilizzate secondo una schematizzazione mono-dimensionale, per descrivere la propagazione della piena anche nelle aree golenali. Infatti l'uso delle equazioni bidimensionali era poco praticabile per due motivi: la mancanza di dati topografici di dettaglio, che ne potessero giustificare l'utilizzo, e l'eccessivo onere computazionale associato. Tuttavia, la schematizzazione 1-D presenta delle limitazioni intrinseche che non sempre la rendono adeguata per la simulazione di fenomeni che avvengono fuori alveo. Questo è il motivo per cui oggi, sempre più frequentemente, i calcoli di propagazione sono eseguiti con modelli bidimensionali. Questi, però, ancora oggi non sono sempre basati sulle equazioni bidimensionali complete, ma implementano semplificazioni ottenute trascurando qualcuno dei termini delle equazioni complete. Pur se tali semplificazioni possono portare delle riduzioni degli oneri computazionali, esse non consentono di pervenire ad una corretta valutazione di dettaglio dei parametri che presiedono alla quantificazione della pericolosità idraulica. Come è noto, infatti, il grado di pericolosità di inondazione è associato principalmente alla velocità e alla profondità della corrente e l'affidabilità del loro calcolo dipende dal grado di dettaglio fisico-matematico insito nel modello utilizzato. Le differenze in gioco sono rese facilmente evidenti dal confronto dei risultati delle simulazioni ottenute dai modelli semplificati con quelli forniti dal modello completo.

Il grado di dettaglio richiesto per l'analisi puntuale della pericolosità è oggi molto favorito dalle nuove tecniche di acquisizione dei dati topografici, quale la tecnica di tipo LiDAR, e dalla crescente potenza di calcolo. La crescente disponibilità di dati territoriali di tipo LiDAR e di tecniche di *High Performance Computing* stanno favorendo un crescente interesse verso l'applicazione dei modelli numerici basati sulle equazioni complete su larga scala. Quest'ultima considerazione apre il campo alla prospettiva di simulare su base idraulica i fenomeni di generazione e propagazione delle piene a scala di bacino mediante le SWE complete. Infatti è possibile trasferire a questo tipo di applicazione le strategie messe a punto in altri ambiti (*dam break*) per far fronte alle problematiche numeriche connesse alla trattazione delle celle asciutte-bagnate e ai termini sorgente. I risultati numerici, mostrati in questo articolo, appaiono del tutto incoraggianti. Le prime applicazioni pratiche di questo tipo di approccio potrebbero riguardare la simulazione delle piene impulsive (*flash floods*) che si verificano nei piccoli bacini. L'applicazione delle equazioni complete su un dominio di calcolo che coincide con l'intero bacino idrografico consente di inglobare in un fenomeno unitario sia gli scorrimenti superficiali (*overland flow*) sia i moti delle acque incanalate nel reticolo idrografico. Infine, tra le attività richieste dalla normativa Europea in materia di alluvioni, vi sono la comunicazione del rischio alle popolazioni esposte e il coinvolgimento attivo delle parti interessate ai processi di pianificazione e gestione del rischio di alluvione. Infatti occorre che la popolazione potenzialmente esposta al rischio acquisisca un adeguato livello di consapevolezza degli impatti di un'inondazione. Per tale ragione, una modalità innovativa di comunicazione può essere la visualizzazione delle classiche mappe mediante tecniche di realtà virtuale. Alcune applicazioni di tali tecniche sono mostrate per una potenziale alluvione del centro storico della città di Cosenza (Calabria, Italia). Obiettivo di questo articolo è fornire una review aggiornata sugli aspetti richiamati sopra, insieme a pratiche indicazioni e spunti di riflessione per la redazione delle mappe di pericolosità e per la comunicazione del rischio.

ABSTRACT

From a hydraulic point of view, flood propagation in natural channels or in floodplains should be simulated using the fully-dynamic shallow water equations (SWEs), although their kinematic or diffusive approximations are still commonly used in practical applications. Indeed, only the use of the fully dynamics equations, formulated in a conservative form, allows the correct treatment of localized hydraulic phenomena and regime changes, factors that are very important for risk assessment. Currents originated by dam break phenomena are a field of study where these localized phenomena arise in a preponderant way.

Until a few decades ago, the SWE were essentially developed following a one-dimensional approach, using various schematization and numerical tricks for describing the propagation in floodplain areas. The reasons why the 1-D approach was the preferred one were twofold: the lack of high-resolution topographic data for the detailed description of the hydraulic processes across the section and the limited computational efforts. Nowadays, the importance of these aspects are dramatically reduced and the use of the two-dimensional SWEs starts to be considered as the reference approach for flood propagation studies.

Although the use of the fully dynamic wave equations may generate accurate results, the complexity of the associated numerical solvers and their computational times favored the development of simplified approach whose reliability is questionable especially for urban flood simulation.

LiDAR data availability and the development of high performance computing technology allow the researchers to develop also flood simulations at the basin scale based on the 2D fully dynamic shallow water equations. In simulations like these, it is not very simple to achieve stable computations in presence of very shallow depths over abrupt changes of the bottom slopes and dry/wet interfaces. However, the significant improvements made in the river flows modeling, flood propagation and dam breaking flows allowed one to obtain stable results also in these complex situations.

So a lot of work has been carried out in the context of the hydraulic numerical simulations for flood mapping in order to fulfill the European Floods Directive. However, it should be born in mind that the Directive itself requires to take care of risk communication with the people involved, encouraging the active involvement of the interested parties in the development of flood management plans. The integration of the classic 2-D flood maps, obtained using the models mentioned before, with 3-D representations of flood inundations using virtual reality techniques might allow non-expert public an adequate perception of the flooding impact.

Following all these considerations, the paper reviews the current state-of-the-art for hydraulic modelling of floods, focusing on the above-mentioned topics and providing practical suggestions for flood hazard assessment and communications.

***Keywords**: Shallow Water Equations, dam-break, 1-D and 2-D flood mapping, overland flow, 3-D virtual environment, flood risk communication*

INTRODUCTION

The flood-prone areas delimitation and the consequent mapping of flood hazard required by the European Floods Directive (2007/60/CE), concerning the assessment and management of flood risk, are complex issues on which the scientific community has achieved significant results in recent years.

From a hydraulic point of view, flood propagation in natural channels or in floodplains should be simulated using the fully dynamic shallow water equations (SWEs), although their kinematic or diffusive approximations are still commonly used in practical applications. Indeed, only the use of the fully-dynamic equations, formulated in a conservative form, allows the treatment of localized hydraulic phenomena and regime changes, that are very important aspects to be correctly computed if we want to achieve an accurate assessment of the flood hazard. A field of study where these problems arise in a preponderant way are the currents originated by dam break phenomena. Dam break wave propagation studies represent the historical field of application of SWEs and several more and more reliable numerical models were proposed, in the last two or three decades, to simulate this phenomenon.

Until a few decades ago, the SWE were essentially developed following a one-dimensional approach, using various schematization and numerical tricks for describing the propagation in floodplain areas. The reasons why the 1-D approach was the preferred one were twofold: the lack of high-resolution topographic data for the detailed description of the hydraulic processes across the section and the limited computational efforts. However, 1D numerical schematizations may suffer from inherent limitations, which do not always allow one to properly simulate the phenomena that take place in the riverside areas.

For these reasons, although the 1D approach still remains the most frequently used method, even in flat flood areas, the use of the two-dimensional SWEs starts to be considered as the reference approach for flood propagation studies.

Although the use of the fully dynamic wave equations may generate accurate results, the complexity of the associated numerical solvers and their computational times favored the development of simplified approach to reduce computation costs. However, performances and limitations of the simplified models, applied in urban flood simulation, have not been deeply investigated yet, even though some studies focused on comparative analyses of flood propagation models. Furthermore, the suitability of the approximate shallow water equations to be used for pedestrians and vehicles hazard assessment in urban flooded areas has not yet been fully verified in the literature. The flood hazard degree, related to the flood conditions at which loss of stability might occur, is mainly related to relationships between velocity and water depth, whose accuracy depends on the physical-mathematical aspects that characterize the model used.

Moreover, nowadays the methods for mapping flood-prone areas cannot ignore the new topographic surveying techniques, greatly enhanced by LiDAR-type techniques and the enormous increase in computing power. LiDAR data availability and the development of high performance computing technology allow to facilitate the application of fully dynamic shallow water equations on larger and larger areas, so that in the near future they could be commonly applied even at the basin scale.

Therefore, according the discussion presented so far, a lot of work has been carried out in the context of the hydraulic numerical simulations for flood mapping. However, it should be born in mind that the European Floods Directive requires to take care of risk communication with the people involved, encouraging the active involvement of the interested parties in the development of flood management plans. This is essentially due to the fact the general public is directly confronted with flood events and flood damages, and, for this reason, they should be increasingly involved in flood protection. For these reasons, it is increasingly recognized that the integration of the classic 2-D flood maps, obtained using the models mentioned before, with 3-D representations of flood inundations using virtual reality techniques might allow non-expert public an adequate perception of the flooding impact. As highlighted by the emerging field of research related to visual risk mapping, the importance of virtual reality techniques for flood risk communication might represent a novel tool for emergency planning and risk management.

Following all these considerations, the paper reviews the current state-of-the-art for hydraulic modelling of floods, focusing on the above-mentioned topics and providing practical suggestions for flood hazard assessment and communications.

MATHEMATICAL AND NUMERICAL MODELLING

The shallow water equations (SWEs) represent mass and momentum conservation and can be obtained by depth averaging the Navier–Stokes equations in the vertical direction, under the hypothesis that the wave length of the phenomenon is much higher than the depth of the water where the phenomenon takes place. From a mathematical point of view, the shallow water equations are a time-dependent system of nonlinear partial differential equations of hyperbolic type. The SWEs can be written in one and two dimensions. For the sake of brevity, only the two-dimensional model is described here. The two-dimensional shallow water equations in conservative form are:

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

where:

$$\mathbf{U}=\begin{pmatrix} h \\ hu \\ hv \end{pmatrix}; \quad \mathbf{f}=\begin{pmatrix} hu \\ hu^2+gh^2/2 \\ huv \end{pmatrix}$$
$$\mathbf{g}=\begin{pmatrix} hv \\ huv \\ hv^2+gh^2/2 \end{pmatrix}; \mathbf{S}=\begin{pmatrix} q \\ gh\left(S_{0x}-S_{fx}\right) \\ gh\left(S_{0y}-S_{fy}\right) \end{pmatrix} \tag{2, 5}$$

in which 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, that can be calculated from Strickler's formula; q is the later inflow or the net rainfall to simulate an overland flow event.

Only in very special cases is it possible to derive analytical solutions to these equations and, therefore, numerical methods must be used to obtain solutions to solve practical problems which include discontinuities in the solution. Many authors proposed numerical schemes for the integration of the 1-D and 2-D SWEs. A complete review of numerical schemes is reported in Leveque (2002), in Hirsch (2007) and in Toro (2009). In particular, many shock capturing Finite Volume schemes have been widely implemented owing to their capacity to simulate various types of flow even in the presence of discontinuities. Considering the finite volume discretization, the equation (1) is integrated over an arbitrary control volume Ω_i and applying the divergence theorem to each component of the vectors **f** and **g** in order to obtain surface integrals, it becomes as (see e.g. Hirsch, 2007):

$$\frac{\partial}{\partial t}\int_{\Omega_i}\mathbf{U}d\Omega+\oint_{\partial\Omega_i}[\mathbf{f},\mathbf{g}]\cdot\mathbf{n}\,dL=\int_{\Omega_i}\mathbf{S}\,d\Omega \tag{6}$$

where $\partial\Omega_i$ being the boundary enclosing Ω_i, **n** is the unit vector normal and L is the length of each boundary.

Denoting by $\mathbf{U_i}$ the average value of the flow variables over the control volume Ω_i at a given time, the Equation (6) can be discretized as:

$$\mathbf{U}_i^{n+1}=\mathbf{U}_i^n-\frac{\Delta t}{\Omega_i}\sum_{r=1}^{3}\left[\mathbf{f},\mathbf{g}\right]_r^n\cdot\mathbf{n}_r\,\Delta L_r+\Delta t\mathbf{S}_i^n \tag{7}$$

Specifically, for the evaluation of the numerical flux in Equation (7), two-dimensional Finite Volume schemes are being used more frequently, which allow analysis of the flood propagation phenomena over complex and irregular topography (see for example: Bradford & Sanders, 2002; Brufau *et alii*, 2002; Toro, 2009; Toro & García -Navarro, 2009; Costabile & Macchione, 2015).

Apart from the computation of numerical fluxes, the numerical integration of the SWEs in complex topographies requires further specific algorithms to the numerical treatment of the bottom slope, the friction slope and the wet-dry fronts. In particular, the treatment of source terms of the shallow water equations is a crucial topic for the numerical models (Murillo *et alii*, 2007; Valiani & Begnudelli, 2006; Murillo & García-Navarro, 2010; Chertock *et alii*, 2015; Vacondio *et alii*, 2016; Costabile *et alii*, 2009; Costabile *et alii*, 2012a); Costabile *et alii*, 2013; Liang *et alii*, 2015; Xia *et alii*, 2017). Particular attention should be paid also to the treatment of the friction slope. The pointwise discretization of the terms leads to numerical instabilities. Therefore, an implicit or semi-implicit treatment of the friction source term (Brufau *et alii*, 2004; Costabile *et alii*, 2013; Liang *et alii*, 2007; Cea & Blade, 2015) is preferred. Finally, it is important to implement a robust wet-dry procedure (for further details one may refer to Costabile *et alii*, 2013).

FIELDS OF APPLICATION

Numerical modelling of dam-break wave propagation

Flood wave computation due to the collapse of a dam can be analytically solved only for some theoretical schematisations (Ritter, 1892; Dressler, 1952; Stoker, 1957). Since the inertial terms in the momentum equation play a fundamental role, this represents the typical situation for which the use of the fully dynamic wave equations are necessary. Therefore, several numerical models have been developed in this field and many experimental studies have been carried out in order to collect a number of test cases for models validation.

Starting from the early experimental studies (Chaudhry, 1993; Braschi *et alii,* 1994; Bechteler *et alii*, 1992; Chervet & Dalléves, 1970; Bellos *et alii*, 1992; Fraccarollo & Toro, 1995; Aureli *et alii*, 2000), some authors developed detailed experiments related to dam break wave propagation with obstacles or based on particular channel configuration, in order to reproduce two-dimensional effects, (Ozmen-Cagatay & Kocaman, 2011; LaRoque *et alii*, 2012; Elkholy *et alii*, 2016). Other experiments have been carried out in presence of erodible bottom or with granular material (Soares-Frazão *et alii*, 2007; Zech *et alii*, 2008; Sarno *et alii*, 2011; Martinez *et alii*, 2011; Soares-Frazão *et alii*, 2012; Moraci *et alii*, 2015; Di Cristo *et alii*, 2017; Qian *et alii*, 2017). Finally, some experiments have been carried out also in order to estimate the impact load exerted by a dam-break wave on an obstacle (Aureli *et alii*, 2015).

This large number of laboratory experiments allows the researcher to develop sophisticated numerical methods aimed at testing the performances of numerical methods for the solution of the SWEs. As mentioned in the previous section, unsteady flow equations should be expressed in a conservative form and shock-capturing numerical schemes should be employed. Therefore, a lot of numerical schemes for the simulation of dam-break test cases are available in literature (Garcia & Kawhawita, 1986; Chaudhry, 1986; Bellos & Sakkas, 1987; Bellos *et alii,* 1992; Soulis, 1992; Alcrudo & García-Navarro, 1994; Jin & Fread, 1997; Brufau & García-Navarro, 2000; Macchione & Morelli, 2003; Zoppou & Roberts, 2003; Zhou *et alii*, 2004; Liang *et alii*, 2006; Aureli *et alii*, 2008; Ying *et alii*, 2009; Liang & Borthwick, 2009; Biscarini *et alii*, 2010; Singh *et alii*, 2011; Gupta & Singh, 2015; Kalita, 2016; Peng *et alii*, 2015 Cozzolino *et alii*, 2017; Castro-Orgaz & Chanson, 2017). In this context, some comparative studies aimed at the evaluation of shock-capturing schemes in dam-break flood computations can be also found in the literature (see for example Macchione & Morelli, 2003).

In real world applications, computations must necessarily employ numerical approaches that take into account friction and irregular topography of the riverbed. Several studies related to dam-break simulations of real events can be found in the literature (Hervouet & Petitjean, 1999; Hervouet, 2000; Valiani *et alii*, 2002; Macchione & Viggiani, 2004; Yochum *et alii*, 2008; Petaccia *et alii*, 2008; Ying *et alii*, 2009; Gallegos *et alii,* 2009; Altinakar *et alii*, 2010; George, 2011; Singh *et alii*, 2011; Wang *et alii*, 2011; Pilotti *et alii*, 2011; Bosa & Petti, 2013; Gavardashvili, 2013; Petaccia & Natale, 2013b; Kim *et alii*, 2014; Kim & Sanders, 2016; Haltas *et alii*, 2016).

It seems important to underline that the numerical solvers developed for dam break computations can be used also as flood routing module for the propagation of discharge hydrographs originated by the progressive erosion of an earth-fill dam, whose computation required specific methods (see for example Macchione, 2008; Macchione & Rino 2008, Macchione *et alii,* 2016a). An example of this can be found in Macchione *et alii* (2016b), in which a two-dimensional shallow water model has been used for the numerical simulation of the Big Bay dam failure, whose hydrograph has been reconstructed using the Macchione (2008) model. In Fig. 1, the simulated maximum water depths (Fig. 1a) and the flood evolution have been reported (Figs. 1b, 1c, 1d).

Flood mapping: advances and numerical approaches

Numerical modelling of flood wave propagation based on shallow water equations has rapidly developed in the last years, shifting from 1-D to 2-D models to simulate hydrologic floods events. The choice of the correct modelling approach is debated in the literature, as documented by several comparative studies (Horritt & Bates, 2002; Tayefi *et alii*, 2007; Alho & Aaltonen, 2008; Bohorquez & Darby, 2008; Cook & Merwade, 2009; Neal *et alii*, 2012). In any case, the significant advances in the numerical flood modelling, in computer technology and in the topographic surveying techniques has fostered the use of 2-D representations of flood-prone area, rainfall-runoff and debris flow propagation (Lin *et alii*, 2011; Tessitore *et alii*, 2011; Guan *et alii*, 2017). Moreover, as already mentioned about dam break simulations, the use of shock capturing schemes allows the management of discontinuities and changing in flow regime throughout the computational domain. These aspects, often neglected by several commercial software, are very important for reliable assessment of hazard hydrodynamic parameters within the flood area.

Paradoxically, all these considerable efforts produced to achieve more and more stable and accurate schemes, have raised worries in the literature because of the tendency of attributing excessive reliability to them. In fact, flood hazard assessments are affected by different sources of uncertainty (hydrological data, the hydraulic parameters, calibration and validation data, the governing equations describing the physical processes, the way to take into account man-made structures interacting with the flow, etc..) which have significant consequences on the simulations reliability. For this reason, several studies are focused on assessments of uncertainty (among the most recent one see Merwade *et alii*, 2008; Di Baldassarre & Montanari, 2009; Bales & Wagner, 2009; Di Baldassarre *et alii*, 2010; Grimaldi *et alii*, 2013; Domeneghetti *et alii*; 2013; Jung & Merwade, 2011), in many of them there is a tendency to overcome the deterministic approach by the development of probabilistic ones. In a probabilistic approach, a fully dynamic 2-D model is not necessarily required (see i.e. Di Baldassarre *et alii*, 2010). This is valid when the analysis is limited to the floodplain mapping and attention is focused on the probability of a given cell to be wet or dry (Horritt & Bates, 2001; Horritt & Bates, 2002; Falter *et alii*, 2013). However, accurate approach should be required when the hydraulic variables are used for hazard assessment throughout the flooded area. Flood wave propagation, velocities, water depths and time to peak are key-elements for emergency planners and the potential loss of life estimate (Jonkman *et alii*, 2008; Xia *et alii*, 2011; Gómez *et alii*, 2011; Russo *et alii*, 2013).

Among the several issues that can be discussed within the topics related to flood mapping, this paper only highlights, for the sake of brevity, the predictive properties of the 2-D fully dynamic shallow water equations, underlining both the limitations of the 1-D modeling respect the 2-D approach, and some negative consequences related to the use of a simplified 2-D modeling.

Limitations of the 1-D modeling highlighted by the 2-D approach

One-dimensional models are still very popular due to their reduced computational time, their ease of implementation and the reduced need of topographic data if compared to 2-D models (Werner & Lambert, 2007; Castellarin *et alii*, 2009; Xu *et*

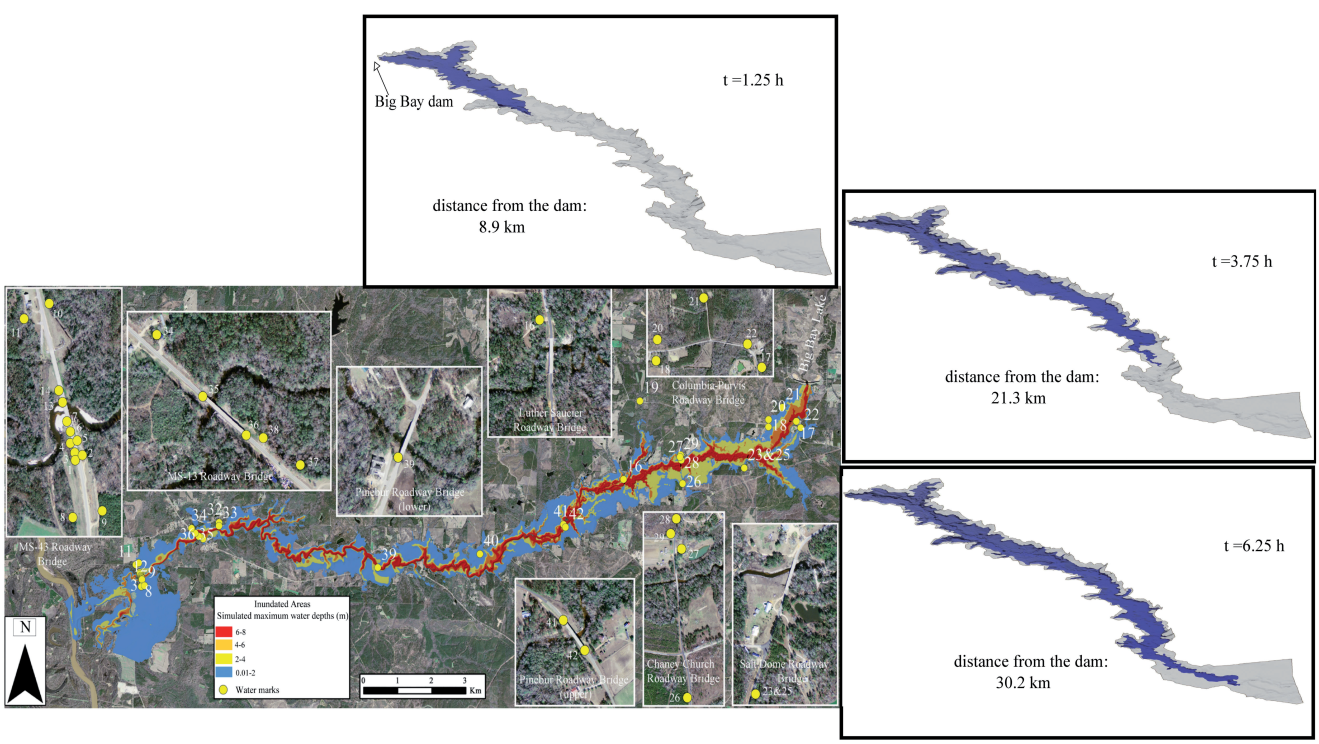

Fig. 1 - Maximum water depths (a) and flood propagation evolution simulated (b,c,d) for the Big Bay dam failure, using the Macchione (2008) model

alii, 2017). However, the 1-D approach neglects the transversal variation of hydrodynamic parameters that may be important, especially in river with wide floodplains. In situations like these, momentum transfer mechanisms between the main channel and the floodplains have been considered in the literature, for both steady or uniform flow (Huthoff *et alii*, 2008; Proust *et alii*, 2009) and unsteady flow (Cao *et alii*, 2006; Costabile & Macchione, 2012). In particular, since the lateral distribution of the velocity is very far from uniform in this kind of sections, the classical approach (divided channel method), based on the use of the Manning law for computing flow velocity in each subsection, cannot be used anymore. Examples of one-dimensional models applications to real-world situations in unsteady state can be found in classical books (Mahmood & Yevjevich, 1975; Cunge *et alii*, 1980) or in literature where water courses of limited slope or almost prismatic channel are considered (Helmiö, 2005; Wright *et alii*, 2008). The applications to complex rivers with frequent transients through the critical state and in presence of hydraulic singularities are very few (Liu & Wu, 2011; Petaccia *et alii*, 2013).

1-D approaches can be considered good choices for river channel flow. In the case of out-of bank flow, in order to achieve results similar to those simulated by the 2-D modelling, it is essential to implement a channels network approach (Fig. 2a). This requires greater skill as well as considerable experience in hydraulic modeling (Costabile *et alii*, 2015a). Nevertheless,

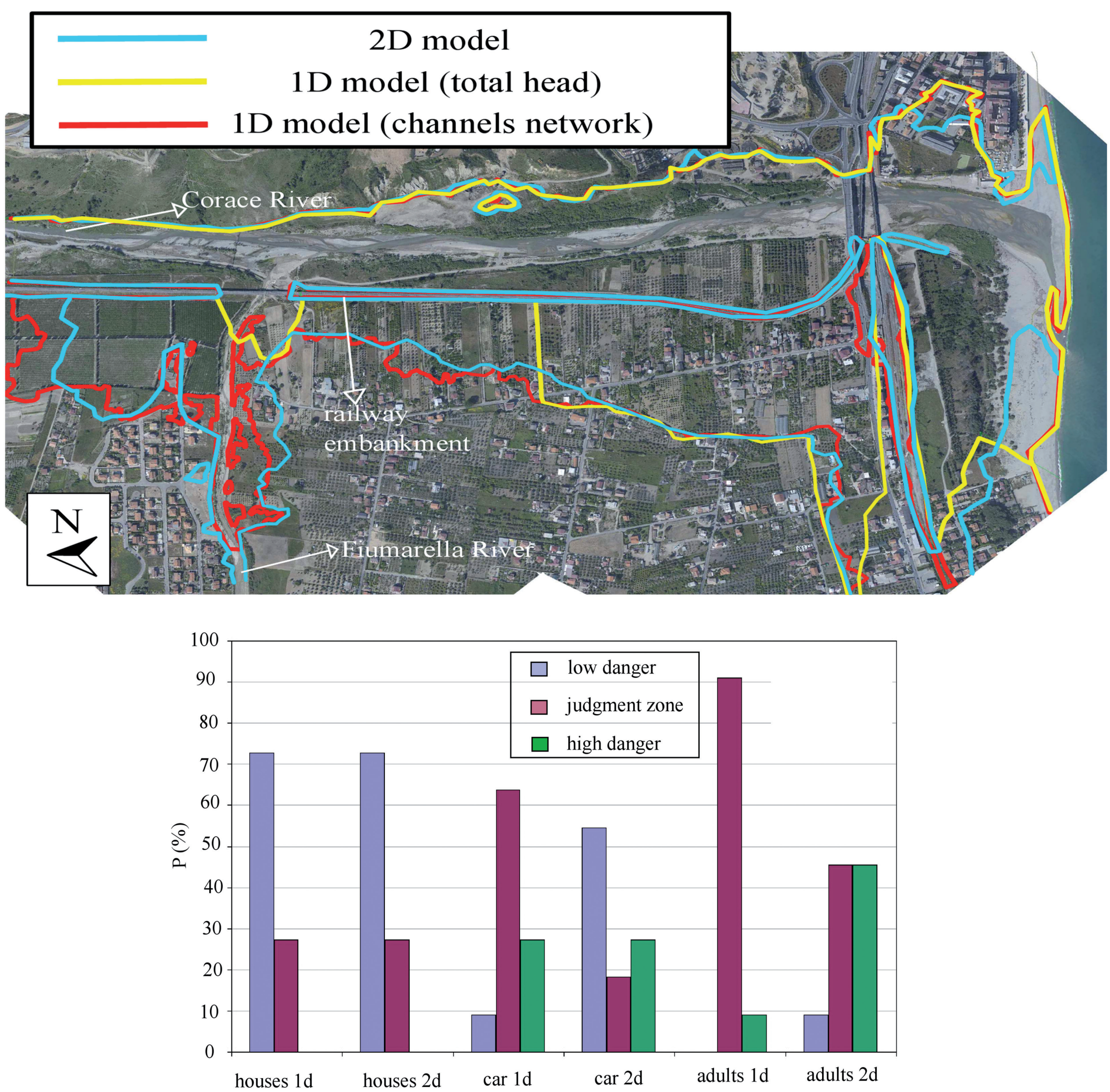

Fig. 2 - Flooded areas (a) and flood hazard histogram predicted by 1-D and 2-D models (b)

similar results obtained in flooded area delimitation do not necessarily mean comparable values in terms of hazard parameters within the computational domain (Costabile *et alii*, 2015b), as deduced from the Fig. 2b.

Further drawbacks associated to the use of the 1-D modelling are represented by its intrinsic limitations in the description of the changing in the transversal flow regime. For example, it has been shown that even for a channelized flow with regular banks, significant flow regime variations can occur, as it can be seen by means of a 2-D simulations (Fig. 3). Moreover, the transversal water depths variation across the section are of particular interest in practical cases, as highlighted in Fig. 4 in the case of interaction with a bridge.

Drawbacks of 2-D simplified models

Although the reduction of the computational times associated to the use of 2-D fully dynamic modelling can be achieved using parallel computations or GPU programming (Vacondio *et alii*, 2017; Dazzi *et alii*, 2017), several techniques that can approximate the solutions provided by the two-dimensional shallow water models with fewer computations were developed.

Recently, in literature these approximations consist in the integration of 1-D and 2-D approaches (Li & Wang, 2012; Morales-Hernández *et alii*, 2016), in porosity-based methods for representing sub-grid scale features in coarse resolution models (Costanzo & Macchione, 2006; Guinot & Soares-Frazão, 2006;

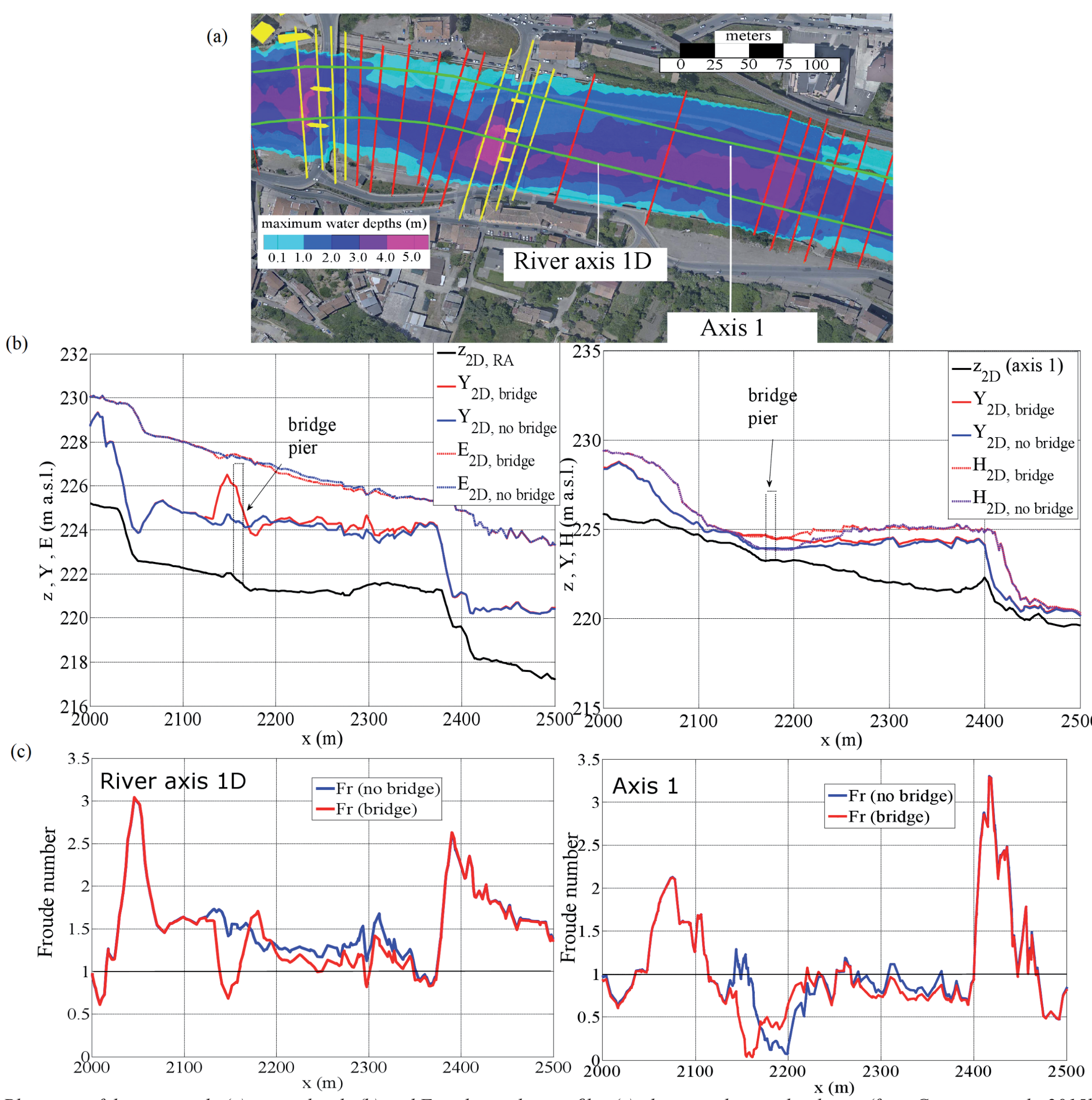

Fig. 3 - Plan view of the case study (a), water levels (b) and Froude number profiles (c) along two longitudinal axes (from Costabile *et alii 2015b, modified)*

Yu & Lane, 2006; Sanders *et alii*, 2008; Guinot, 2012; Kim *et alii*, 2015; Bruwier *et alii*, 2017; Ferrari *et alii*, 2017), in models that consider inertia and diffusion but ignore advection (Aronica *et alii*, 1998; Bates *et alii*, 2010; Almeida & Bates, 2013; Zhang *et alii*, 2014; Skinner *et alii*, 2015; Martins *et alii,* 2015), in diffusive models neglecting the inertial terms of the full SWE leading to a degradation of the original hyperbolic model to a parabolic one (Prestininzi & Fiori, 2006; Prestininzi, 2008; Apel *et alii*, 2009; Dottori & Todini, 2013; Szymkiewicz & Gasiorowski, 2012). The latter approximation is traditionally justified by the fact that, in several cases, flooding over plain areas is characterized by a slow evolution. Moreover, models using a simplified set of equations might lead to faster computational times. However, diffusive models could be computationally less effective than dynamic models when high resolution meshes are used due to more restrictive stability criteria. In the literature, there are several studies related to the benchmarking of simplified two-dimensional shallow water models (Horritt *et alii*, 2007), focusing also on urban settings (Fewtrell *et alii*, 2011).

The application of 2-D numerical models based on the diffusive wave equations, mainly referred to inundations due to slow-varying floods, can be found in several works (see for example Aronica *et alii*, 2002; Bradbrook *et alii*, 2004). Hunter *et alii*, 2008 compared fully dynamic shallow water codes and diffusive models for an urban test site that highlighted some differences in both water depths and extent dynamics, due to the different schematization of the physical process and the numerical solvers used. Néelz & Pender (2012) analyzed several commercial models used for flood risk modelling in the UK in a number of numerical cases. Neal *et alii* (2012)

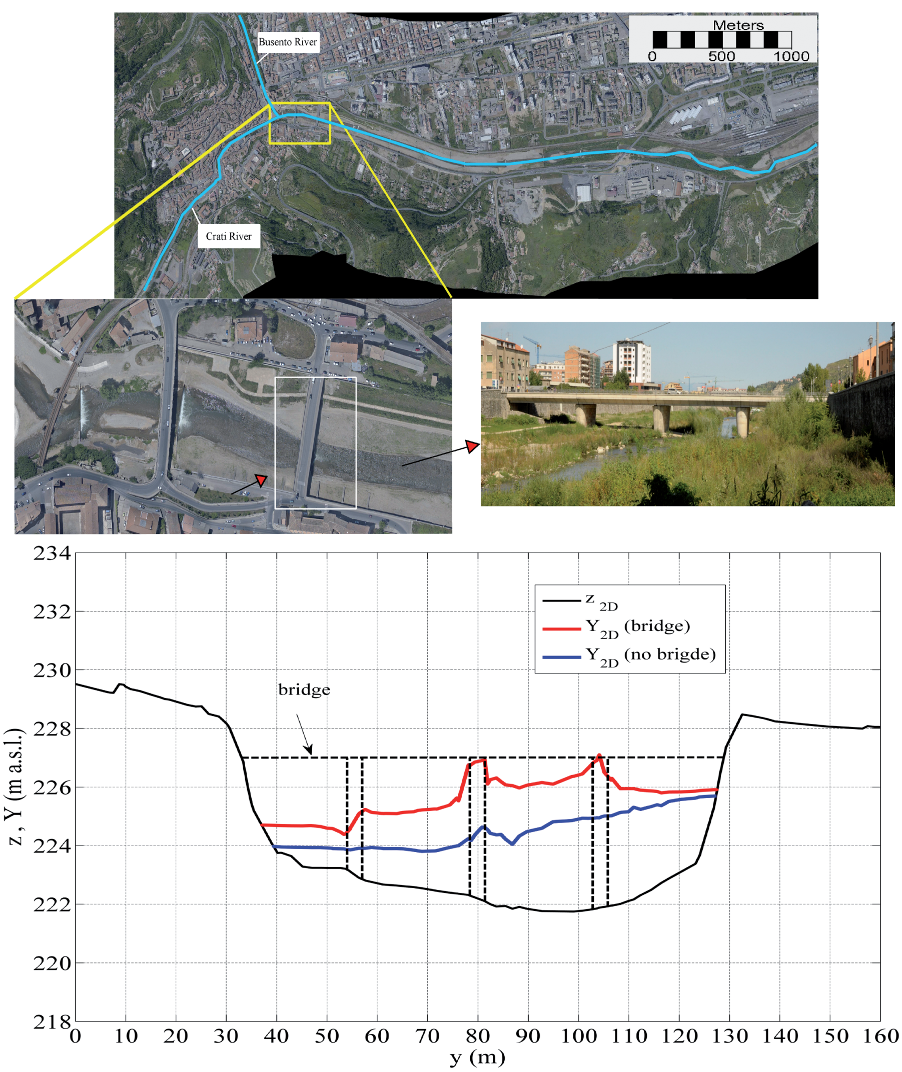

Fig. 4 - Total head and water elevations across a section simulated by the 2-D model (bridge scenario) (from Costabile et alii, 2015b)

applied three two-dimensional models based, respectively, on diffusive, inertial or shallow water waves. They concluded that fully dynamic shallow water models may be unnecessarily complex because simpler schemes can perform just as well, in terms of both velocity and depths, but only for gradually varied flow. In fact, in situations characterized by low friction and supercritical flow, simplified models can produce large error in terms of mass balance and might become unstable. Prestininzi (2008) presented a diffusive model to simulate an impulsive wave propagation on a physical model. The author compared the results of the diffusive model with the experimental data and with other published numerical results associated to the use of a fully dynamic model. The proposed diffusive model gave a good description of the inundation arrival times and local peak values but failed in reproducing some local phenomena.

Costabile *et alii* (2017) analyzed the consequences of simplifications of the shallow water equations. In particular, a numerical diffusive-type model (DFW) have been compared with a fully dynamic wave equation model (FDW) using as a reference the results of experimental test cases reproducing an urban district (Fig. 5).

The applications of the two models highlighted the intrinsic strong limitations of the DFW model applied to the urban flooding due to its poor prediction of the shock waves that might be induced by the interaction between the flood flow and the buildings. These effects are accurately described by the FDW approach but significantly underestimated by the DFW model whose performances become worse in more complex buildings arrangements and in situations characterized by impulsive flood hydrographs (see Figs. 6 and 7).

Therefore, the use of diffusive-type models can be questionable, especially for flood hazards assessment in urban districts, due to the poor simulations around the buildings that represent the elements for which the damages and the risk are particularly relevant. Moreover, as mentioned before, the computational times of the diffusive model are more or less 2.5-3 times greater than those of the fully dynamic model.

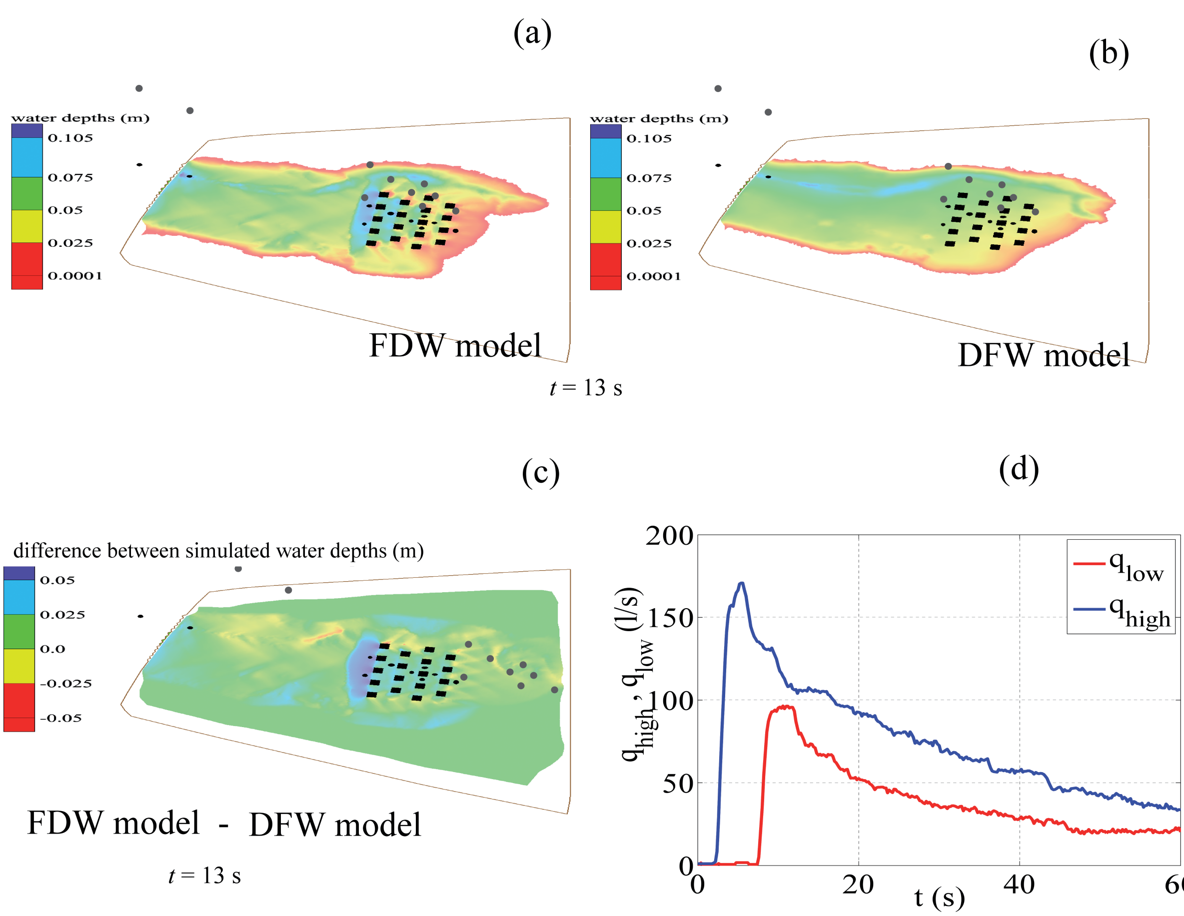

Fig. 5 - Water levels simulated by the FDW (a) and DFW (b) models, differences betweeen the models (c), flood hydrographs used as boundary conditions (d) (from Costabile *et alii, 2017; modified)*

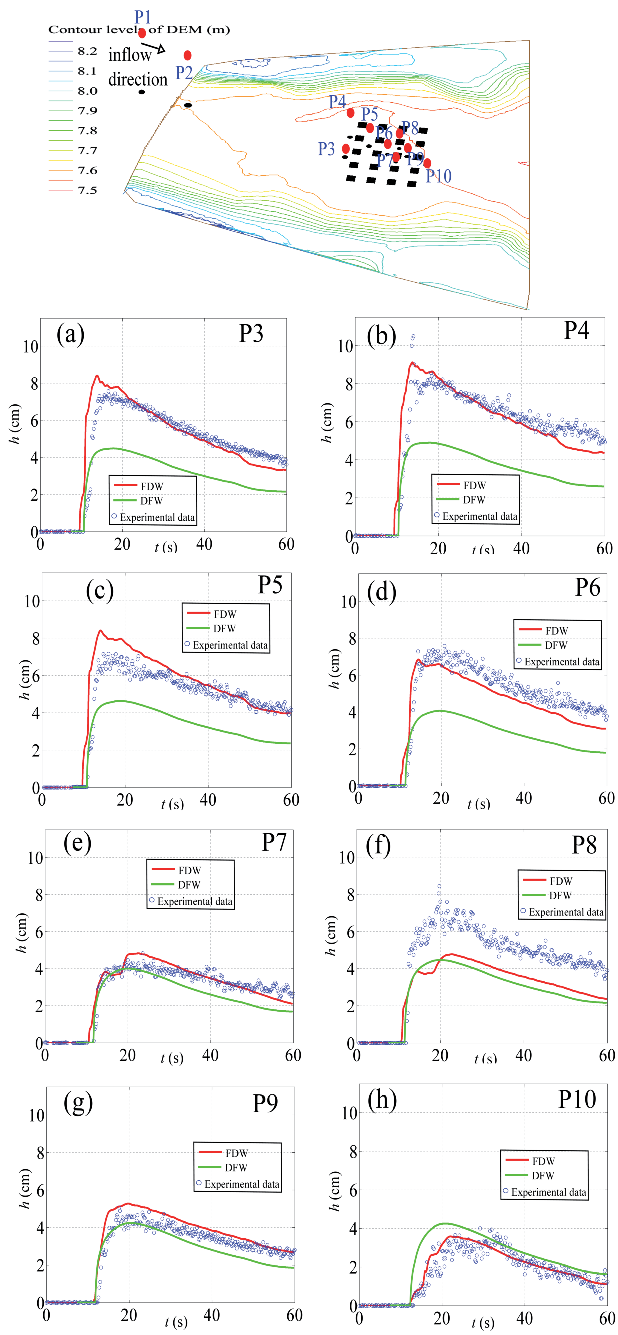

Fig. 6 - Comparison between models results and experimental data in the case of aligned arrangement (from Costabile *et alii, 2017; modified)*

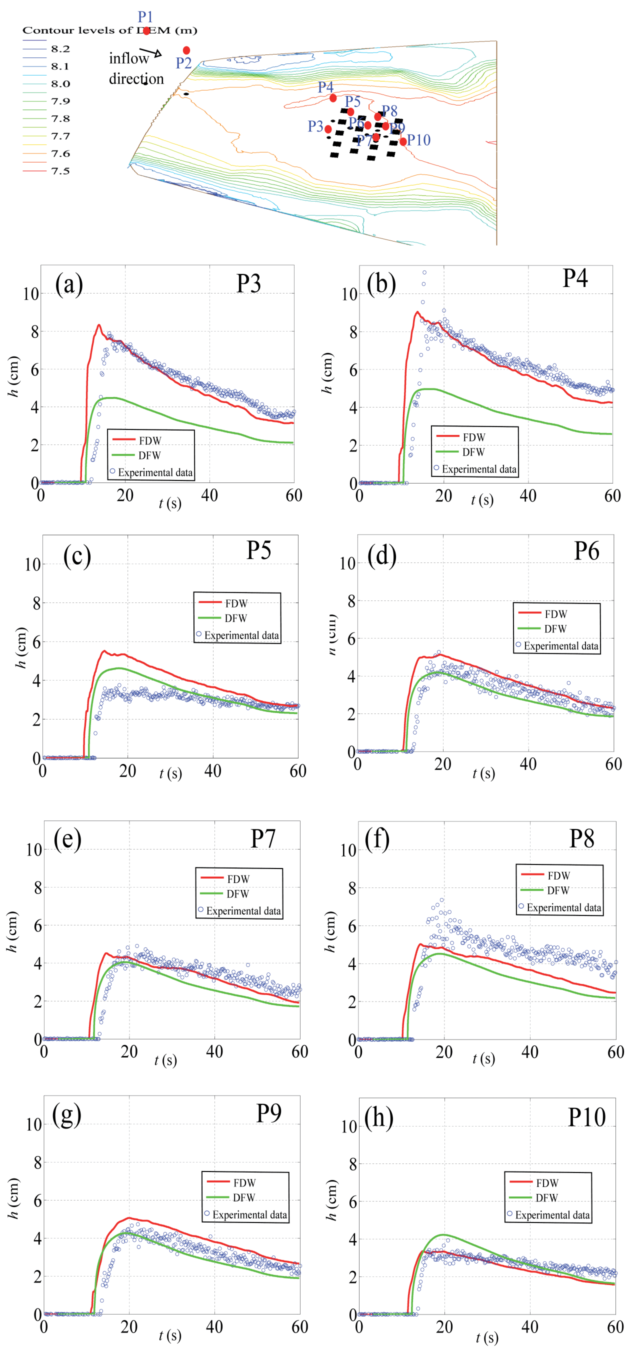

Fig. 7 - Comparison between models results and experimental data in the case of staggered arrangement and high hydrograph (from Costabile *et alii, 2017; modified)*

FLOOD PROPAGATION AT CATCHMENT SCALE

Intense and localized precipitations cause local, sudden floods (often-called flash floods) in small basins. Overland flow is the dynamic component of the watershed reaction to the rain. To model rainfall runoff phenomena, several methods were proposed ranging from linear concentrated models like black box to non-linear physically-based distributed models (Taskinen & Bruen, 2007; Alfieri *et alii*, 2012). As regards the latter family, many simplified hydrodynamic model like diffusive and kinematic wave models can be found in the literature (Lighthill

& Whitham, 1955; Govindaraju, 1988; Tayfur *et alii*, 1993; Di Giammarco *et alii*, 1996; Feng & Molz, 1997; Borah & Bera, 2003; Liu *et alii*, 2004; Jain & Singh, 2005; Howes *et alii*, 2006; Kazezyilmaz-Alhan & Medina, 2007; Gottardi & Venutelli, 2008; Venkata *et alii* 2009; Bates *et alii*, 2010; Lopez-Barrera *et alii*, 2012; Warnock *et alii* 2014). Also in this case, the development of these models have been proposed with the aim of overcoming the complexity of the full SWE, of facing the lack of high-resolution data and reducing the computational times. Nowadays, the importance of these issues is much less significant due to the progress has been built over the last decade. Parallel codes in shallow water 2-D are coming to be more and more usable in computer environments (i.e. Lacasta *et alii*, 2015; Wittmann *et alii*, 2017; Liang *et alii*, 2017). As regards the numerical issues, the application of the methods developed for dam break simulations, proved to be reliable also in the context of overland flow simulation and, therefore, computational dry cells that become wet because of the rainfall input and subsequently dry out because of high bed slopes, the source term computation and the treatment of friction slope terms can now be managed without any problem. Starting from the pioneering models proposed by Esteves *et alii* (2000) and Fiedler & Ramirez (2000), several numerical studies on all these aspects can be found in the literature (Unami *et alii*, 2009; Cao *et alii*, 2010; Yeh *et alii*, 2010; Cea *et alii*, 2010; Mügler *et alii*, 2011; Kim *et alii*, 2012; Caviedes-Voullième *et alii*, 2012; Berardi *et alii*, 2013; Kim & Seo, 2013; Costabile *et alii*, 2013; Yu & Duan, 2014; Simons *et alii*, 2014; Busaman *et alii*, 2015; Cea & Blade, 2015; Singh *et alii*, 2015; Rousseau *et alii*, 2015; Huang *et alii*, 2015; Liang *et alii*, 2015; Bellos & Tsakiris, 2016; Fernández-Pato *et alii*, 2016; Xia *et alii*, 2017; Bermudez *et alii*, 2017). These studies show applications not only in experimental test cases but also in real catchments. An example of these can be found in Costabile *et alii* (2013) in which a numerical model has been applied to simulate a real event, which occurred in a sub-basin or Reno river in Italy (see Fig. 8a). Using net rains, as input for the numerical model, the numerical results show a satisfactory agreement between observed and simulated hydrographs, reproducing not only the peak discharge but also the shape of the observed hydrograph (see Fig. 8b).

The good results obtained by the authors who applied 2-D fully dynamic shallow water equations in overland flow simulations confirm the fact that it can be considered the most advanced physically based approach to deal with these kind of phenomena on large areas (Borah, 2011). In this context, Costabile *et alii* (2009; 2012a) presented a comparative analysis of different overland flow models based on the shallow water equations and relative approximations (diffusive and kinematic models). Numerical results showed that the models performances are similar in very simplified tests where the

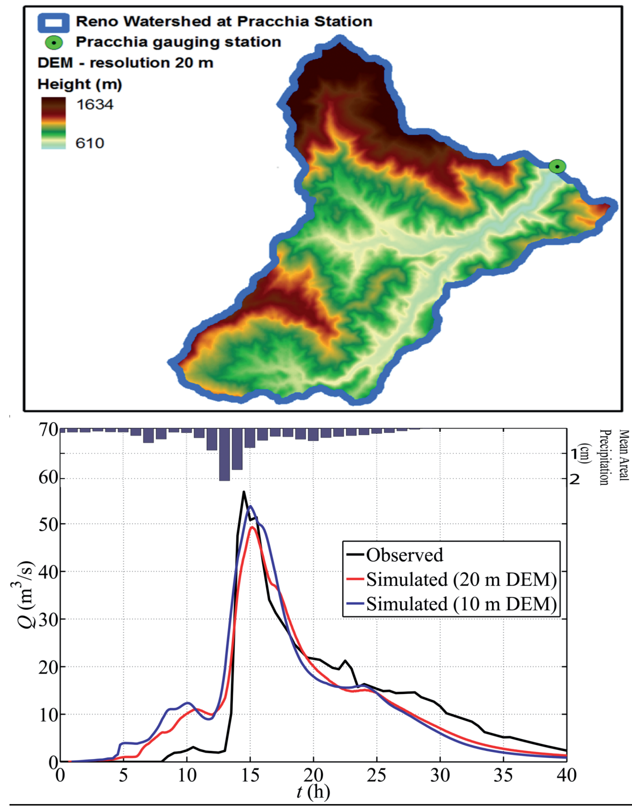

Fig. 8 - Pracchia river basin (a) and comparison between observed and simulated hydrographs (b) (from Costabile *et alii, 2012; modified)*

topography is reduced to a flat surface and the hydraulic phenomena are very far from those occurring during flash floods real events. Indeed, the results coming from the numerical simulation of the experimental test regarding the run off in varying space but leaving constant in time the rainfall intensity over a cascade of three planes, in which the generation of a shock wave occurs, lead to mitigate that conclusion.

Finally, recently, there is an increasing interest in the coupling of soil erosion model and physically based overland flow models (Simpson & Castelltort 2006; Murillo *et alii*, 2008; Heng *et alii*, 2009; Heng *et alii*, 2011; Ali *et alii*, 2013; Kim *et alii*, 2013; Lu *et alii*, 2016; Tian *et alii*, 2017; Lin *et alii*, 2017; Fernández-Pato *et alii 2017*).

Simpson & Castelltort (2006) present a coupled model of overland flow and sediment transport with morphological evolution, based on the SWEs for flow, conservation of sediment concentration and empirical functions for bed friction, substrate erosion and deposition. Fernández-Pato *et alii* (2017) proposed a two-dimensional hydraulic-erosive model based on the fully dynamic approach and on a sediment mass conservation equation combined with several parameters related with the soil erodibility, the catchment slopes and the canopy cover.

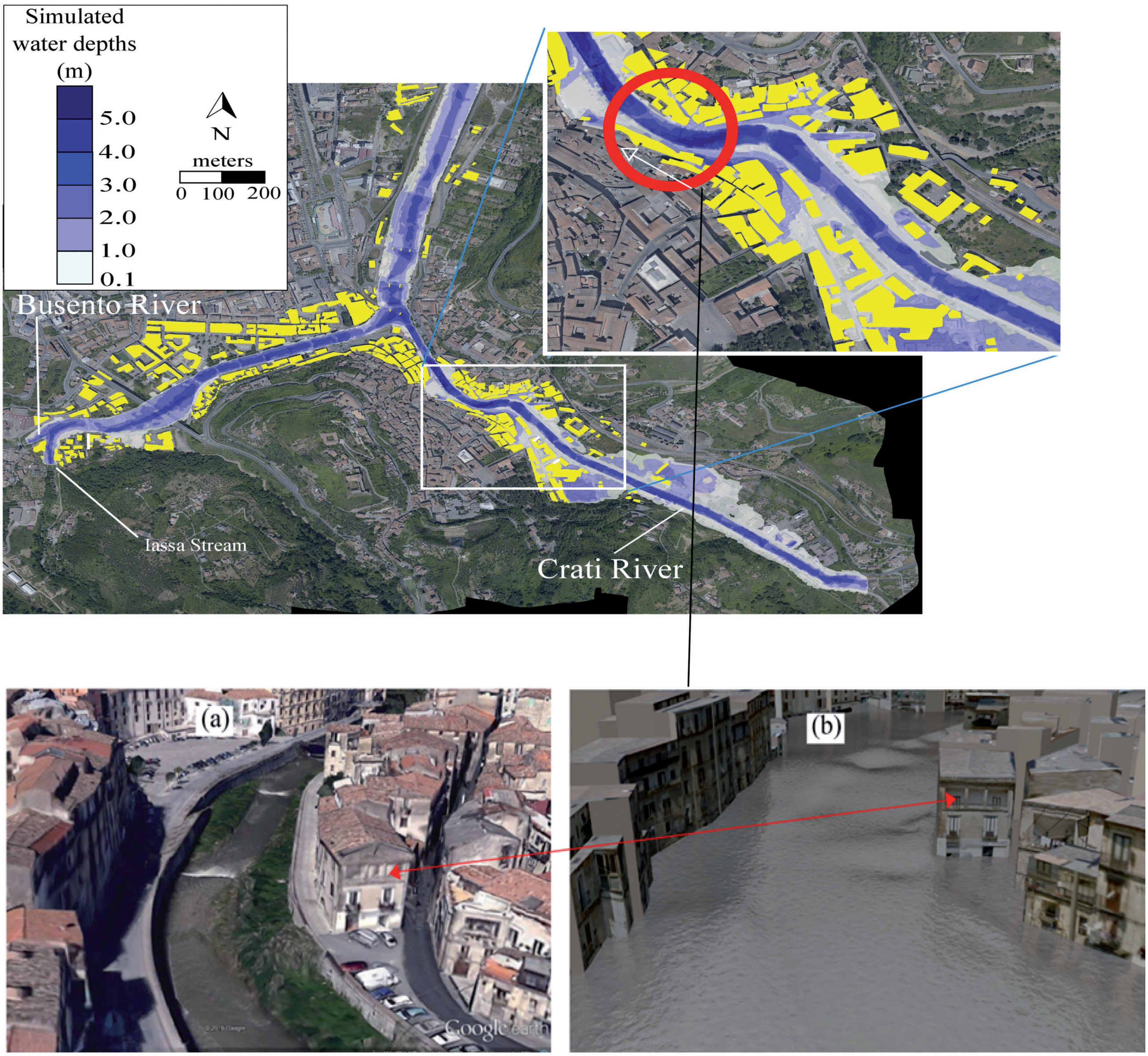

Fig. 9 - 2-D flood map (a) and 3-D representation of a specific aerea without (b) and with (c) simulated water surfaces

CONNECTION BETWEEN 2-D FLOOD SIMULATIONS AND 3-D VISUALIZATION TECHNIQUES FOR FLOOD HAZARD COMMUNICATION

The use of the 2-D fully dynamic modelling has proved to be a reliable approach for obtaining flood hazard maps prescribed by the Directive 2007/60/EC as a key tool for risk management. An example of this has been reported in Fig. 9a in which the flood-prone areas, resulting from two-dimensional numerical modelling, outlined by chromatic shading or contour based method, are represented for the Cosenza old town (Calabria, Italy).

Though technicians and experts in flood risk can easily analyse the 2-D maps, these do not allow a non-scientific audience an immediate understanding of flooding impacts. This last aspect is not of secondary importance because the flood Directive precisely formulated the demand for risk communication with the people at risk. The importance of active involvement of stakeholders in flood risk management has been highlighted in several papers (Voinov & Bousquet, 2010; Arciniegas *et alii*, 2013; Barnaud *et alii*, 2013; Leskens *et alii*, 2014; Hewitt *et alii*, 2014; Maskrey *et alii*, 2016).

Since communication to the public assumes a crucial role in the flood risk management, a basic expertise in this topic should characterize the professional training of hydraulic engineers working on flood hazards. Environmental modellers and technicians working on this field usually neglect this aspect (McInerny *et alii*, 2014, Grainger *et alii*, 2016). So, there is the need of research aimed at finding suitable options to communicate the main results coming from 2-D hydrodynamic simulations by means of specific visualization able to increase flood hazard perception and to influence behaviour of people in emergency and raise risk awareness (Charrière *et alii*, 2012),

Virtual-Reality visualization of 3-D scenarios could allow users to view complex data in a more intuitive and comprehensible way and offers help in communication of scientific knowledge to potentially interested non-expert communities (Saggio & Ferrari, 2012). In this contest, Macchione *et alii* (2016c; 2019) carry out the development of an intentionally simple workflow for the representation of 2-D hydraulic simulations within a 3-D virtual reality environment, using texture-mapping technique. The main goal of this research is to represent realistic flood scenarios with minimum standard formats in virtual environments. Figures 9 b,c shows a 3-D environment without and with flooding. The image without flooding have been taken from Google Earth, in the 3-D view. The results highlight a realistic representation of water depths at neighbourhood's scale by adding more information about interaction between flood and public/private goods, compared to a classic 2-D flood map. Furthermore, this kind of visual risk communication facilitates the emergency planning and preparation, flood damage estimation because the image is vivid and realistic and consequences associated to the flood evolution is easier to perceive.

CONCLUSIVE CONSIDERATIONS

In this paper, attention has been devoted to the importance of the 2D SWEs for the numerical simulation of flood events and hazard mapping. For this reason, typical fields of applications of the fully dynamic modelling have been presented, in order to give a reference framework useful not only for researchers but also for technicians working on this area.

The first aspect analysed is related to dam break simulations. Beside the technical interest in that kind of simulation, dam break numerical modelling represented the reference field of research in which the most reliable numerical schemes have been developed, analysed and compared.

Then attention has been focused on the key role played by the fully dynamic shallow water modelling for flood hazard mapping. Two main aspects have been underlined. The first one concerned the limitations of the one-dimensional modelling highlighted by comparing the results with those obtained by using the two-dimensional approach. The second one dealt with the drawbacks associated to the use of simplified two-dimensional modelling.

The last modelling issue analysed in this work dealt with the application of the 2D fully dynamic modelling at a basin scale, which represents a relatively novel topic in the literature. In fact, due to the increasing availability of LIDAR data and the development of more and more efficient parallel-codes, the application of that modelling seems to be the best choice to achieve reliable results.

Finally, the connection between 2-D flood simulations and 3-D visualizations of the results in the context of flood risk communication has been highlighted. In particular, it has been mentioned the usefulness of virtual-reality scenarios to strengthen people's risk awareness in order to encourage the population at risk to implement preventive actions and to be prepared for an emergency.

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