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Is HEC-RAS 2D accurate enough for storm-event hazard assessment? Lessons learnt from a benchmarking study based on rain-on-grid modelling

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ABSTRACT

Rain-on-Grid (RoG) modelling is an increasingly popular approach within the storm risk management, in which the hydrological and hydrodynamic flood processes are modelled entirely within the 2D hydrodynamic model. Contrarily to what was done in the context of flood propagation in rivers, at the present time no systematic benchmarking study of the software packages implementing this approach is available in the literature. The need of benchmarking studies related to the RoG approach is becoming ever more important for HEC-RAS 2D (HR2D), the use of which has been rapidly increasing in the last few years, as further testified by very recent papers explicitly focussed on this research issue. However, there is still a lack of studies that clearly show the suitability of this software package as a reliable fully integrated hydrologic-hydrodynamic model. Therefore, the novelty introduced by this paper is the benchmarking of HR2D for RoG simulations, analysing several situations representing most of the applications related to "storm-event" hazard assessment. Specifically, after the analysis of ideal cases, which gave the opportunity to carefully assess the accuracy of the numerical schemes for RoG simulations, practical applications were considered to face some challenging issues related to the analysis of rainfall/runoff in urbanized areas and actual basins, including the numerical treatment of buildings and the computation of infiltration losses within hydrodynamic computations. The HR2D results were compared to analytical solutions, when available, experimental data and numerical solutions of a numerical code developed by the authors. The results shown in the paper highlight the potential but also the limitations of this software package, providing evidence to scientists and technicians about those situations for which reliable results are expected but also indications on specific aspects that need improvements so as to increase the model accuracy.

1. Introduction

Understanding the effects of flood inundation in terms of area, depth, velocity and time is a key element for efficient flood risk management. Therefore, the use of suitable mathematical models for flood inundation mapping, differentiated according to characteristics of the flood event, is a major step for the implementation of any flood management strategy.

It is well-known that floods can arise from a variety of causes, but the most common type is the so-called fluvial flooding that occurs when, following intense rainfall and/or melting snow, water levels in rivers rise and the rivers overtop their banks. The general approach for the generation of fluvial flood hazards maps along large rivers is quite consolidated and it is commonly organized into two main steps, requiring the use of two separate models consecutively. In the first one, attention is mainly focused on the computation of a discharge hydrograph, related to single runoff events, using consolidated hydrological rainfall-runoff models. Then, the calculated hydrograph is used as the upstream boundary condition of a two-dimensional (2D) hydrodynamic model.

However, there is a growing awareness of different types of non-fluvial flood events, that show apparent increasing frequency and, due to climate change, are predicted to increase further. They originate from heavy rainfall (storm-event hazard), have different characteristics than fluvial floods, since they occur apart from large rivers, and are often characterized as flash or pluvial floods (Yin et al., 2016; Schanze, 2018). Pluvial flooding can be broadly defined as flooding that results from rainfall-generated overland flow and ponding before the runoff enters any watercourse, drainage system or sewer, or cannot enter it because the network is full to capacity (Falconer et al., 2009). This term is sometimes distinguished from flash flooding, which may also be associated with heavy rainfall but usually arises from a watercourse.

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Rainfall non-fluvial floods are modelled following the approach known as direct rainfall modelling or rain-on-grid (RoG), in which the hydrological and hydrodynamic flood processes are not modelled in two different model systems, but entirely with the 2D hydrodynamic model. This approach is increasingly used to determine the rainfall-runoff processes of watersheds with different sizes (see for example Cea and Bladé, 2015; Fernández-Pato et al., 2016; Bout and Jetten, 2018; Costabile et al., 2019; Ming et al., 2020) and also on an urban scale in which, due to the high relevance of the sewer system, the studies often focus on the concept of dual drainage (Chang et al., 2015; Leandro et al., 2016; Jang et al., 2018; Li et al., 2020a). The aforementioned studies testify the increasing interest for this kind of approach and, in the future, the number of works dealing with this topic are expected to have the same diffusion of those related to fluvial flooding in previous years. In particular, specific attention to the benchmarking of software packages implementing this approach is likely to occur, going through the significant amount of research carried out for fluvial flooding models. In this latter context, this important research activity was motivated by the strong need to provide evidence about the reliable predictions of the flood packages and a data set against which such numerical codes can be evaluated and differentiated in terms of performance and predictive capability. Specifically, 2D software packages may have different features in terms of: 1) the physical processes simulated by the model's mathematical formulation; 2) the approximate numerical method used to solve the mathematical formulation; 3) the configuration of the numerical grid upon which the numerical method is applied. The first rigorous comparison of 2D hydraulic models was carried out by Hunter et al. (2008), comparing six models representing a wide spectrum of fundamental equations and numerical schemes, to simulate surface flooding of a small urban catchment. Then, a great effort was made within the Environment Agency/DEFRA (Department for Environment, Food & Rural Affairs) – UK which faced this issue in several reports. In particular, in a well-known report (Néelz and Pender 2010), 10 benchmark test cases were presented against which 14 2D flood inundation modelling packages were tested and compared. This study was updated in 2013 (Néelz and Pender 2013), taking into account the further development of the already used software packages and the new ones that had become available. Neal et al. (2012) used some of these test cases to benchmark three 2D models that can be broadly defined as simulating diffusive, inertial and shallow water waved in order to understand how much physical complexity a flood inundation model needs for a given problem. The model benchmarking carried out by Néelz and Pender (2013) has been used several times in the literature to check the performance of new models for flood mapping (see for example Leandro et al., 2014; Guidolin et al., 2016; Ayog et al, 2021).

Unlike the fluvial flooding models, at the present time no systematic benchmarking study of the software packages implementing the RoG approach is available in the literature, identifying a clear gap in the literature. It should be recalled that RoG simulations have specific and different features to the traditional 2D fluvial flood computations, due to the very low value of surface runoff that may amplify the common problems related to the management of wet/dry fronts, instabilities due to roughness computations and inaccuracy related to numerical treatment of highly irregular topography (see for example Costabile et al., 2013; Cea and Bladé, 2015). Therefore, in our view, there is the need of benchmarking studies related to RoG modelling, that, along the lines of the research carried out by Néelz and Pender (2010), Néelz and Pender (2013), can provide 1) evidence about the accuracy and reliable predictions of the industrial flood packages and 2) a data set against which such software can be evaluated and differentiated in terms of performance and predictive capability.

This research issue gains much more importance when referred to the most used hydrodynamics models, from both the scientific and technical points of view. In this context, the software HEC-RAS 2D, hereafter HR2D, plays a leading role. A SCOPUS search highlighted that the number of papers per year having HEC-RAS in the article title, abstract or keywords has more than doubled in the last five years, resulting in more than 200 documents in 2020. This significant increase is probably due to the launch of the version 5.0 in 2016, in which several new tools were introduced such as the module for two-dimensional computations. Specifically, the analysis of the related literature highlighted that HR2D was extensively used in flood mapping for estimating: 1) flood magnitude (van der Meulen et al., 2021), urban flood hazard (Yalcin 2019; Rangari et al., 2021), also using probabilistic approaches (Bhola et al., 2020) and analysing the effects of bridges (Trueheart et al., 2020); 2) the influence of the topographic data on flood extent (Farooq et al., 2019; Stoleriu et al., 2020; Li et al., 2020b; Yalcin, 2020; Muthusamy et al., 2021); 3) the performances of commercial and research software (Liu et al., 2019; Pinos and Timbe 2019; Shustikova et al. 2019; Sridharan et al., 2020) and benchmarking of simplified models (Jamali et al., 2019; Afshari et al., 2018), 4) compound flooding (Saleh et al., 2017; Gori et al., 2020; Khanam et al., 2021); 5) potential or historical flooding due to dam/dyke breaching (Albu et al., 2020; Urzică et al., 2021; Feroz Islam et al., 2019; Pilotti et al., 2020) and glacial lake outburst (Kougkoulos et al., 2018; Majeed et al., 2021)

Besides these more traditional issues, it is worthwhile to mention the popularity gained by HR2D in emergent fields of research such as Ecohydraulics (Adeva-Bustos et al.,2019; Juárez et al., 2019; Papaioannou et al., 2020) and the Natural Flood Management (Keys et al., 2018; Pal et al., 2020; Ferguson and Fenner, 2020; Tamagnone et al., 2020).

The widespread use of HR2D within the scientific community is expected to further increase in the near future considering also the new tools available in the just released version 6.0, that allow scholars and technicians to perform more reliable RoG simulations. In particular, this last version was enriched with some options to simulate non-uniform spatial rainfall and to compute infiltration losses in a 2D cell.

This research aims at providing a contribution within the scientific framework described so far. In particular, the paper is motivated by two considerations: the increasing attention devoted to the analysis of non-fluvial risks for which the RoG is the reference approach and the substantial lack of benchmarking studies of widely used software packages, such as HR2D, in situations like these. On the other hand, the need for this line of research has already been highlighted in the very recent literature (David and Schmalz, 2020; Zeiger and Hubbart, 2021). However, though facing a similar general purpose, this work differs from the above-cited papers since it is oriented to assess the accuracy and reliability of HR2D as an integrated hydrodynamic-hydrologic model supporting storm risk management that, therefore, represents the focus and the novelty of this research. To face this challenging issue, an extensive benchmarking is presented, analysing situations representative of most of the applications related to storm-event hazard assessment. Specifically, the paper is organized considering phenomena of increasing levels of trouble, ranging from ideal cases to practical applications, comparing the HR2D results to analytical solutions, experimental data and results obtained by a numerical model specifically developed by the authors for problems like these.

The paper is organized as follows: attention is firstly dedicated to the conceptualization of the work and, particularly, to the rationale used for the identification of the case studies and the description of the numerical benchmark (section 2). The list of the test cases is presented in section 3 while section 4 is devoted to the analysis of the results. Finally, the discussion of the results in the light of recent literature is provided in section 5, followed by the conclusions.

2. Conceptualization and methodological issues

The conceptualization of this research involves essentially three aspects. The first one revolves around the criteria used for the selection of specific test cases able to stress the performances of the HR2D model in

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challenging situations from both purely numerical and practical points of view. The second one is represented by the need of testing the accuracy and the stability of the two numerical schemes, implemented in the last released version of HR2D, for solving fully-dynamic wave equations. Finally, the third aspect relates to the use of a numerical model, the results from which are used for comparative analysis.

2.1. Rationale used for the identification of the case studies

In the style of the benchmarking studies of 2D fluvial flooding models (Fewtrell et al., 2011; Neal et al., 2012; Néelz and Pender, 2013), a series of ideal and real-world test cases are selected. Basically, several idealized tests to check the accuracy and stability of the numerical algorithms implemented in HR2D were simulated. This is a crucial issue from the authors' point of view since, as is well known in the literature, the presence of very shallow depths over complex topography and wet–dry interfaces may lead to several numerical problems when using fully dynamic wave equations. In overland flow simulations, these problems clearly are emphasized by the presence of a great number of computational dry cells becoming wet due to the rainfall input and subsequently dry-out because of high bed slope. So, errors and instabilities come from steep bed slopes, because more water than that actually contained in the wet cell may be computed as flowing in the dry cell, and as a consequence, the negative water depth may induce numerical instability or violation of the mass conservation leading to a gain of mass. Therefore, specific treatments should be implemented in order to manage these situations (see for example, Brufau et al., 2004; Liang and Borthwick 2009; Costabile et al., 2013). Further singularities may arise because of the bed friction term when the water depth becomes very small, something which often occurs in overland flow simulations. In these situations, the bed friction term may dominate other terms of the momentum equation, since it is inversely proportional to the 4/3 power of the water depth. To the author's knowledge, no studies exist that show performances of HR2D in those specific situations and therefore a profound analysis of situations like these is essential in a benchmarking study. So the use of ideal tests, in highly controlled and simplified environments, will help in understanding the inherent properties of the numerical methods implemented in HR2D.

Subsequently, attention is devoted to situations closer to reality. In this context, the runoff simulation in urban areas is a major issue, that gains further importance in a climate change context (Kaspersen et al, 2017; Padulano et al, 2021). Two important aspects are discussed: the first one is related to the modelling approaches able to take into account the effects of buildings on the surface runoff. As is well-known, one of the most used approaches to that purpose is to consider them as holes in the computational grids, imposing solid wall conditions on the boundaries. To the authors' knowledge, this option cannot be used within HR2D. Therefore, the interest here is to test the suitability of this software package in the application of two other modelling strategies. In the first one, known as buildings resistance (BR) method, a large resistance parameter value is arbitrary assigned to cells that fall within the buildings' footprints. In the second scenario, known as the buildings block (BB) method, spatially distributed ground elevation data are raised to the heights of rooftops, so that buildings appear as blocks in the topographic model used for flow simulation. The second situation related to inundations of urban areas analyzed here is represented by the suitability of HR2D to deal with flow originating from different sources (for example a rainfall input applied to the model grid and a point source flow) at relatively high resolution. Such a situation allowed us to assess the capabilities of the model to handle complex topography and the related complex flow structures due to both sources of flows.

Finally, this work is oriented at providing indications about HR2D performance in very challenging situations, such as the rainfall/runoff modelling in natural basins, for which several efforts have been made in the literature to get stable and accurate results. The aim of this part of the research is not only the evaluation of the performances of HR2D using the RoG, that in any case would be a novelty in itself due the lack of studies on this (the works by David and Schmalz, 2020; Costabile et al., 2020a; Zeiger and Hubbart, 2021, are exceptions). The further purpose is to explore the potential of HR2D as an integrated hydrologic/hydrodynamic model in which even the infiltration losses, recently added in version 6.0, are considered in just one modelling tool. In this regard, the applications shown here represent the most challenging ones for the use of HR2D.

Therefore, the analyzes performed here is grouped in four main relevant situations: 1) tests over impervious/permeable planes using steady and uniform rainfall; 2) tests over planes using unsteady or non-uniform in space rainfall; 3) tests in idealized or real-world urban areas; 4) rainfall-runoff simulations in actual catchments considering net rainfall and gross rainfall, so as to consider the effect of the infiltration losses inside the HR2D. Ultimately, the analyzed tests are devoted to covering most of the applications related to "storm-event" hazard assessment except those situations strictly related to urban drainage modelling, in which the description of the interaction with the sewer system makes the application in HR2D quite complex.

All the case studies are presented in section 3.

2.2. Numerical solvers implemented in HR2D

The HR2D model allows the user the choice of three equation sets, namely: 2D Diffusion Wave equations (not considered in this work); Shallow Water Equations (SWE-ELM) with a Eulerian-Lagrangian approach to solving for advection; or a new Shallow Water Equation solver (SWE-EM), that uses a Eulerian approach for advection. The governing equations are not reported here for the sake of brevity and the reader can refer to the user's Hydraulic Reference Manual Version 6.0. As reported in that Manual, the original solver (SWE-ELM) is claimed to be more than adequate for most problems requiring the full momentum equations. The last option (SWE-EM), added only in version 6.0, is claimed to be more momentum conservative but may require smaller time steps and produce longer run times and therefore it is suggested only when the user is interested in very localized phenomena (changes in water surfaces and velocities at and around hydraulic structures, piers/abutments, and tight contractions and expansions). The SWE-EM uses an explicit solution scheme based on a strictly conservative form of the momentum equation. According to the reference manual, SWE-EM solver produces less numerical diffusion than the original SWE-ELM solver if a time step controlled by the Courant number (<1.0) is setup, otherwise instabilities are expected to occur due to the explicit nature of the scheme. Both the numerical schemes will be used here, in order to provide evidence about their accuracy and reliability.

2.2.1. Computational options and tolerance

HR2D model allows the user to set the tolerance on both the 2D water surface elevations and the volume. Basically, if the maximum error is greater than the set tolerance, then the program will iterate to get a better answer. The program will only iterate up to the maximum number of iterations set by the user. Therefore, the maximum iteration allows the solver to solve the equations with the minimum numerical error, which has to be contained in the tolerance value. For further details, one may refer to the 2D Modeling User's manual. As for the simulations shown here, in particular, the tolerances thresholds were setup as small as possible (10–9) since the high degree of accuracy required in the tests case. Since a small tolerance was imposed, the maximum number of iterations settable (40) was set according to the user's manual.

All the tests were run with a pure SWE model, no turbulent model was setup. Moreover, the values of *Theta*, *Theta Warmup* were analyzed. According to the 2D Modeling User's Manual, this is "the implicit weighting factor that is used to weight spatial derivatives between the

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current solution time line and the previously computed time line. Theta of 1.0 (Default), uses only the currently solved time line for the spatial derivatives. This provides for the most stable solution, but possibly at the loss of some accuracy. Theta of 0.6, provides for the most accurate solution of the equations, but tends to be less stable." *Theta Warmup* is used during the model warmup and ramp up periods.

Finally, all the tests were performed using the adjust time step based on Courant. Although the SWE-ELM model can run with a Courant number higher than 1, all the tests were run with a maximum value always less than the unity in order to correctly compare SWE-ELM and SWE-EM. Furthermore, minimum Courant number was set 1/100 of the maximum Courant number.

The influence of all these parameters was checked in all the numerical tests, highlighting negligible variations.

2.3. UniCal benchmark model: Governing equations and numerical schemes

Different benchmarks for HR2D solutions were considered. Depending on features of the specific case study, we used theoretical solutions related to the kinematic wave theory, observed data and numerical solutions obtained from a code developed by the authors at the University of Calabria (Italy) (hereafter UniCal), that proved to be very reliable for simulations like these. The rationale behind this choice is to provide evidence about the accuracy of HR2D in relation to a numerical model, first order accurate in time and space, developed for research purposes. In other words, the UniCal model is not used here to understand which model performs better but to have a reference numerical solution representative to what a reliable SWE numerical model, first order accurate in time and space, can provide in terms of numerical simulations. It should be observed that the reason of important discrepancies between model simulations and observed/theoretical reference solutions can be found in the physics of the governing equations or in some numerical inaccuracy of the solvers. In case of inaccurate solutions generated by HR2D and reliable simulations provided by the UniCal model, the reason cannot be found in the physics of the governing equations but in some deficiencies of the numerical solvers. Therefore, the use of UniCal model aims at certifying the presence of numerical errors in the solution of the numerical solvers implemented in HR2D and its solutions will be shown, in particular, in those cases for which HR2D predictions highlight important discrepancies in respect to the theoretical or experimental solutions.

The UniCal model is based on the 2-D SWE that can be expressed in the following form:

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

where:

$$\begin{aligned} \mathbf{U} &= \begin{pmatrix} h \\ hu \\ hv \end{pmatrix}; \mathbf{F} \\ &= \begin{pmatrix} hu \\ hu^2 + gh^2/2 \\ huv \end{pmatrix}; \mathbf{G} \\ &= \begin{pmatrix} hv \\ huv \\ hv^2 + gh^2/2 \end{pmatrix}; \mathbf{S} \\ &= \begin{pmatrix} r - f \\ gh\left(S_{0x} - S_{fx}\right) \\ gh\left(S_{0y} - S_{fy}\right) \end{pmatrix} \end{aligned} \tag{2}$$

in which: t (s) is time; x (m), y (m) are the horizontal coordinates; h (m) is the water depth; u (m/s), v (m/s) are the depth-averaged flow velocities in x- and y- directions; g (m/s^2) is the gravitational acceleration; r (m/s) is the rain intensity and f (m/s) the infiltration losses; S_{0x} (m/m), S_{0y} (m/m) are the bed slopes in x- and y- directions; S_{fx} (m/m), S_{fy} (m/m) are the friction slopes in x- and y- directions. In equation (2), the source term S in the mass continuity equation is not zero, both the rainfall and the infiltration losses are included. Therefore, acting on the source term, the SWEs have the ability to apply rain directly to a two-dimensional grid, implementing the RoG approach.

The model is developed for unstructured grids, based on irregular triangular elements, to obtain the computational domain. For the numerical integration of system (1), the model is based on finite volume methodology. In particular, the Roe scheme (1981), first order accurate in time and space, is used for the computation of the numerical fluxes. The numerical integration of the shallow water equations in complex topographies requires further specific algorithms to the numerical treatment of the bottom slope, of the friction slope and of the wet-dry fronts. For the sake of brevity, only some key aspects of the model are recalled here: a) in order to ensure the stability of the model, the time steps have been estimated according to the well-known CFL condition; b) an upwind approach inspired by Brufau et al. (2004) is used to discretize the bottom variations; c) a semi-implicit treatment of the friction source term is implemented (Costabile et al., 2013; Cea and Bladé, 2015); d) a robust wet-dry procedure is considered (Costabile et al., 2013). This model was used for several different applications ranging from flood mapping in urban environments (Macchione et al., 2019; Costabile et al., 2020b; Costabile et al., 2021) to runoff simulations at basin scale (Costabile et al, 2020a; Costabile and Costanzo, 2021).

3. Description of the numerical tests and available data

3.1. Runoff over impervious or permeable planes using steady uniform rainfall

Three different tests characterized by geometries from low to high slopes and different values of rainfall input are performed. In Fig. 1, an overall quick view of these tests is given. The first one (Test 1 hereafter) was proposed by Gottardi and Venutelli (1993) and then considered in other works (see for example Jaber and Mothar, 2003), for which the kinematic analytical solution given by Stephenson and Meadows (1986) can be used. The watershed is represented by a plane having these characteristics: low-slope plane (S_L = 0.0005; S_T = 0), 500 m long, Manning roughness coefficients $n_x = n_y = 0.02$ sm$^{-1/3}$. A steady uniform rainfall rate R equal to 0.33 mm/min was set for a duration D equal to 200 mins.

The second test (Test 2 hereafter) was first introduced by Singh (1996) and further used in several papers in the literature (see, for example, Tsai and Yang, 2005; Singh et al., 2015). In this case, a steady and uniform rainfall intensity R, equal to 300 mm/h and duration D of 1600 s, was set to simulate the overland flow over a plane with a length L = 500 m and slopes S_L = 0.01 and S_T = 0. The Manning roughness coefficient was considered equal to 0.02 sm$^{-1/3}$. Also in this case, the kinematic analytical solution can be computed.

The third test (Test 3 hereafter, see Fig. 1 right panel) is an experimental test carried out by Lima (1982), who used a laboratory soil flume 1 m long, 0.5 m wide having a slope equal to S_L = 0.01 (S_T = 0). The soil was a loam. The bottom of the flume consisted of a metallic perforated plate to collect percolation water. The rainfall simulator is able to generate a uniformly distributed rainfall pattern equal to R_0 = 135 mm/h for a duration of D = 15 mins.

3.2. Runoff over impervious planes using unsteady or non-uniform rainfall

In this group of tests, three differentiated situations were considered, one of which is related to an unsteady rainfall and the remaining two are referred to non-uniform rainfalls (see Fig. 2).

The first test of this category (Test 4 hereafter) was proposed by Tsai and Yang (2005). The plane has the following characteristics: length

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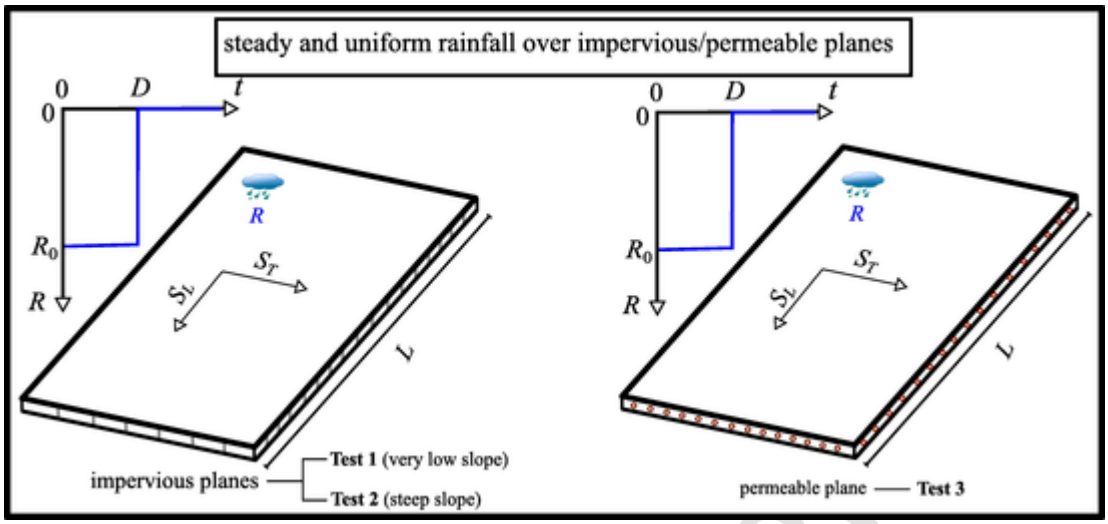


Fig. 1. Sketch of the tests 1, 2 and 3 related to steady and uniform rainfall over impervious planes.

$L = 1000$ m, longitudinal slope $S_L = 0.01$ ($S_T = 0$), Manning's coefficient equal to $n_x = n_y = 0.02$ sm$^{-1/3}$. The unsteady rainfall duration is $D_3 = 4500$ s (see Fig. 2a). From $D_1 = 1500$ s to $D_2 = 3000$ s the rainfall rate is equal to $R_2 = 300$ mm/h, whereas it is equal to $R_1 = 100$ mm/h outside this interval.

The last two tests considered here refer to steady and non-uniform rainfalls. In this context, attention is firstly focused on the experimental tests carried out by Iwagaki (1955). This test (Test 5 hereafter) was used for validation purposes in several papers (Zhang and Cundy, 1989; Feng and Molz, 1997; Fiedler and Ramirez, 2000; West et al., 2017; Ding et al., 2018; Hu and Song, 2018; Aureli et al., 2020). The experiments consist in a rainfall/runoff situation over a cascade of three planes (Fig. 2b). Each plane section was 8 m long, the slopes of which were equal to 0.02, 0.015 and 0.01 in the downstream directions. Each section received a constant rainfall input of 389, 230 and 288 cm/h, respectively. Three rainfall durations were considered in the experiments for which discharge and water depth hydrographs are available. For the sake of brevity, we considered only the durations $D = 10$ s and $D = 30$ s.

Finally, the last application (Test 6 hereafter) considered for this category refers to a well-known test in the literature (see for example Di Giammarco et al., 1996; Kim et al., 2012; Xia et al., 2017; Hou et al., 2018; Shu et al., 2020) and for which an analytical solution is available (Stephenson and Meadows, 1986). It is a V-shaped catchment (see Fig. 3c) having a single slope on both the plane (Sp = 0.05) and the channel (Sc = 0.02). The depth of the channel varies from 1 m at the upstream end to 20 m at the downstream end. The intensity of the rainfall input R_0 is 10.8 mm/h and duration D of 1.5 h. The precipitation does not affect the channel, interesting only the valley side. The assigned values of the Manning's coefficients are 0.05 s m$^{-1/3}$ for the valley side and 0.15 s m$^{1/3}$ for the channel.

3.3. Runoff over idealized and real-world urban areas

Two tests were considered in this group, one of which is represented by an idealized urban area whereas the other one is a real-world situation. Specifically, the first test (hereafter identified as Test 7) refers to the experiments performed by Cea et al. (2010) and considered for validation purposes by several authors in the literature (see for example Fernandez-Pato and Garcia-Navarro 2016; Xia et al., 2017; Su et al., 2019; Caviedes-Voullième et al., 2020). The designed experimental urban catchments were made of three planes each of them with an approximate slope of 0.05 but, once the experiment was set up, the real topography was similar to what is shown in Fig. 3a. Eight different urban configurations were built in the laboratory. The configurations considered in this paper are shown in Fig. 3b and 3c. The horizontal dimensions of the building are 20 cm × 30 cm and the vertical outer walls are 20 cm in height. A steady and uniform rainfall equal to 300 mm/h was set and three different durations (20, 40 and 60 s) were considered in the experiments, even though only the shorter one is considered here.

Following Cea et al. (2010), the Manning coefficient can be assumed equal to 0.016 s m$^{-1/3}$. The only variable measured was the discharge hydrograph generated at the outlet of the basin, located in the valley in the middle of the domain (Fig. 3a), which was used to validate the numerical results.

The second test used for this category (hereafter identified as Test 8) belongs to case studies used in the benchmarking analysis carried out by Néelz and Pender (2013), it is used for assessing the latest generation of 2-D hydraulic modelling tools and widely used in the literature for benchmarking purposes (for the most recent ones, see for example Courty et al., 2017; Hu et al., 2018; Savant et al., 2019; Caviedes-Voullième et al., 2020). It corresponds to a synthetic event on a real topography, located in the urban area of Glasgow (Scotland, UK). The modelled area is approximately 400 × 960 m and a digital elevation model, having a spatial resolution of 2 m, is available (see Fig. 3d). The event was designed to determine the models capability to correctly simulate flooding due to two different sources of water, since the test attempts to mimic a common urban flooding scenario where a rainfall event overwhelms the drainage systems and consequently causes flooding due to a surcharging pipe or stormwater drain. Thus, the flood is assumed to arise from a point time-dependent inflow representing a sewer outflow (Fig. 3e) and a uniformly distributed rainfall (Fig. 3f), applied to the modelled area. The source point location is shown in Fig. 3d together with the 9 observation locations considered for results comparisons. Roughness values were assumed to be variable throughout the domain, since roads and pavements have the Manning's coefficient equal to 0.02 s m$^{-1/3}$ whereas it was assumed 0.05 s m$^{-1/3}$ elsewhere. All domain boundaries are closed and, therefore, no outflow hydrographs are available.

Contrarily to the previous cases, for which HR2D was used for the first time in the literature in this work, this test had already been simulated by Brunner (2018). Despite that, in the author's opinion, it is important to discuss it again in the light of the purposes of this paper, especially in relation to the results obtained by the first order accurate in time and space model user here (UniCal).

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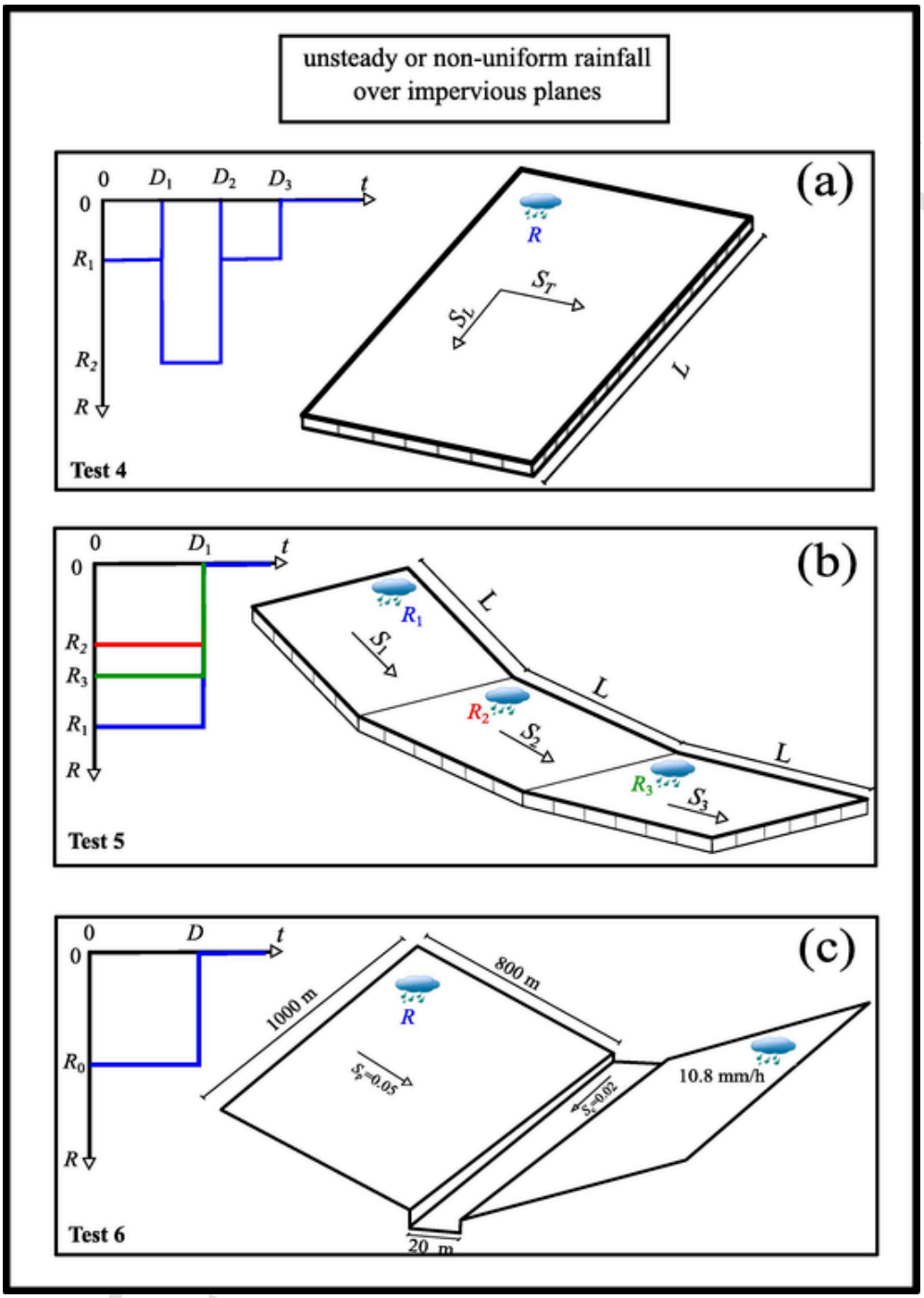


Fig. 2. Sketch of the tests 4, 5 and 6 related to unsteady (a) or non-uniform rainfall (b,c) over impervious planes.

3.4. Runoff over actual catchments

In this group, two possible situations of interest in the rainfall/runoff simulations over actual catchments (see Fig. 4) were considered. The first one is oriented at using HR2D for predictive purposes, in cases for which no observed data related to rainfall, flooded areas and discharge, are available. This is a common situation that characterizes small basins that, very often, are ungauged catchments for which it is not possible to have data for model calibration and validation. As a consequence, "blind" simulations should be performed, for instance using a design net hyetograph as input. The authors feel that in situations like these it is important to assess the performance of a commercial software using a state-of-the-art model, developed for research purposes, as the benchmark solution. Therefore, the benchmark for this test will be thus represented by the solution provided by the UniCal model.

The selected basin, namely AR, shown in Fig. 4a, is a part of the Ardivestra catchment, located in the Lombardia Region (Northern Italy), having an extent approximately equal to 43 km^2, a mean altitude of 423 m above sea level (a.s.l.) and length of the main river equal to 22.4 km. A LiDAR bare ground data was available, from which 1-m DEM was extracted. Following a common approach for technical studies, a Chicago hyetograph was obtained by the available rainfall duration curve corresponding to a return period of 200 years, in which the net rainfall was computed through the SCN-CN method. The roughness coefficient is considered variable throughout the domain according to the available map of soil use.

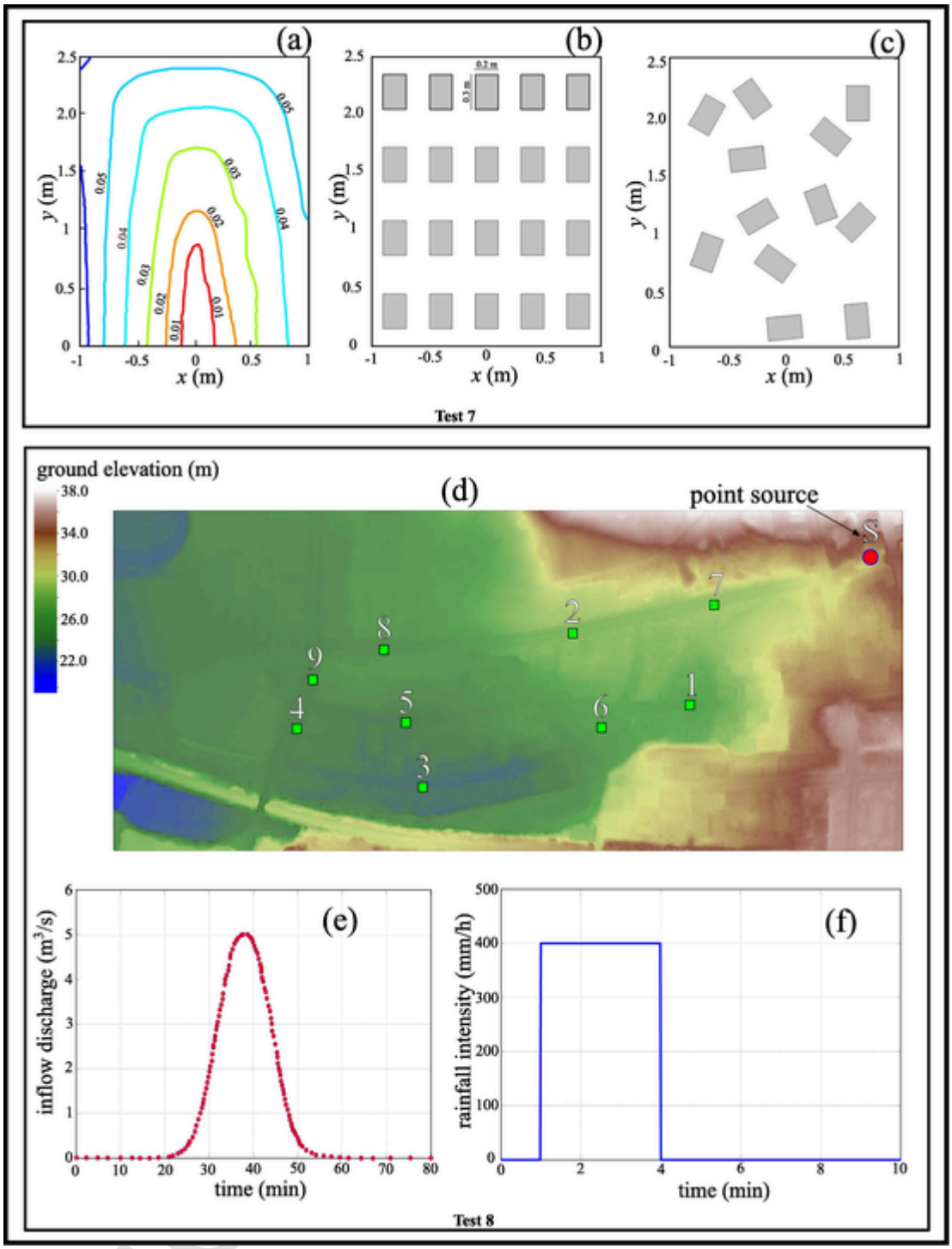


Fig. 3. Tests related to runoff in urban areas (tests 7 and 8). Experimental test: topography (a) and configuration of buildings (b, c). Real-world test with two sources of flow: ground level (d), point source inflow (e) and rainfall intensity (f).

The second test is focused on the reconstruction of an observed event on a small basin. In this case, HR2D will be used for the first time in the literature as an integrated hydrologic-hydrodynamic model at the basin scale, able to be initialized by gross rainfall and in which the computation of the infiltration losses is computed within the model itself. Specifically, we considered the Turbolo catchment, located in the Calabria region (Southern Italy). The area of the basin is equal to 22.5 km^2 with an elevation between 1015 and 112 m above sea level and catchment mean slope of 18.6%. Agricultural and wooded areas represent the dominant land use while urbanization is less than 2% of the total catchment area. A variable roughness was assumed, based on the information related to the map of the soil use. Furthermore, a litho-logic map is available for this basin (Buttafuoco et al., 2012) according to which the parameters of the Green-Ampt model were roughly estimated using the value proposed in Rawls et al. (1983). The observed event, selected for evaluating the performance of HR2D, occurred between the 27th and 28th January 2004. The rainfall data used here was recorded by the rain gauge of the Fitterizzi station, located at 185 m above the sea level whereas the observed discharge refers to a section located downstream at 75 m a.s.l. (Fig. 4b).

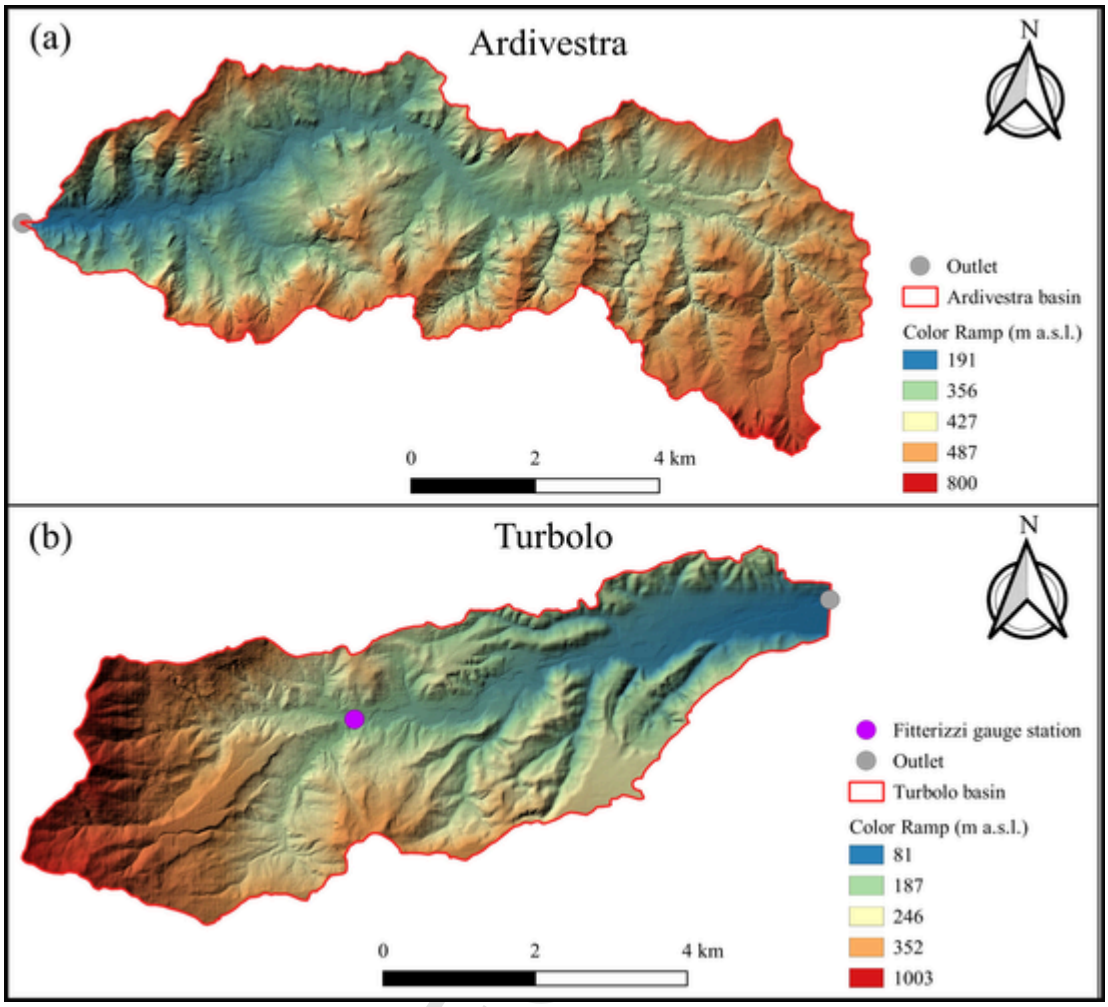


Fig. 4. Catchments used for rainfall-runoff simulations (tests 9 and 10): Ardivestra basin (a) and Turbolo basin (b).

4. Results

4.1. Impervious or permeable planes using steady uniform rainfall

Two benchmarks were used for these tests. The first one is related to the analytical solution of the kinematic-wave modelling, useful to check the overall behaviour of the simulated discharges. Since attention here is focused on the "full momentum" solution provided by HR2D, a second benchmark was also considered, which refers to the simulation obtained by the UniCal model applied to an unstructured triangular grid having almost uniform resolution equal to 25 m^2. The same resolution was used for HR2D, for which the reference grid is made of square elements having sides equal to $L_0 = 5$ m. The minimum and maximum Courant number, for HR2D, was set equal to 0.01 and 0.3 respectively. These values are significantly lower than those recommended in the user's manual. Preliminary tests, not shown here for the sake of brevity, highlighted that the model did not crash using recommended values (for example 1–2 for SWE-ELM option). However, unphysical results and oscillations in the hydrodynamic variables may be generated, confirming that hydrodynamic features of overland flow simulations that are more critical than the traditional flood propagation study.

4.1.1. Test 1 – Impervious plane (very low slope)

Fig. 5a shows the comparison between the simulated discharges obtained by the HR2D model, using both the SWE-EM and SWE-ELM numerical resolution algorithms on the reference grid, and the solutions provided by the two benchmarks. The HR2D solutions are in a good agreement with the analytical one, reproducing the expected shape of the wave. The differences near the peak value can be explained easily, considering the fully-dynamic version of the momentum equation implemented in HR2D. As a proof of this, the simulated hydrograph is very similar to the UniCal solution in this part of the graph, even though the peak value is not exactly the same of that simulated by the two benchmarks.

Though the shape of the rising limb of the hydrograph is fairly well reproduced by HR2D, it can be observed that they are slightly shifted on the left in respect to those obtained by the two benchmarks (see the magenta box in Fig. 5a). Finally, it is interesting to observe the solutions obtained by HR2D in the falling limb of the hydrograph. The simulations are in good agreement with the two benchmarks but a strange behaviour is reproduced approximately around $t = 300$ min, giving an unrealistic shape of the wave not simulated by the benchmarks that are very close together (see red box in Fig. 5a). Therefore, it is likely that a numerical error occurred, probably due to some difficulties in the treatment of drying fronts. In order to check the effect of this inaccuracy as a function of the grid size, three further simulations were performed, halving progressively the side length of the mesh (0.5 L_0, 0.25 L_0, 0.125 L_0 respectively). The results obtained by the two solvers are very similar, so only the simulations obtained using the SWE-ELM numerical solver are shown (see Fig. 5b).

As highlighted in the purple box of Fig. 5b (see also the black arrows), the artificial step-like behaviour simulated by HR2D-EM progressively vanishes, reducing its value and appearing later on the simulation. Only when using a very fine grid (0.125L_0), the solution pro-

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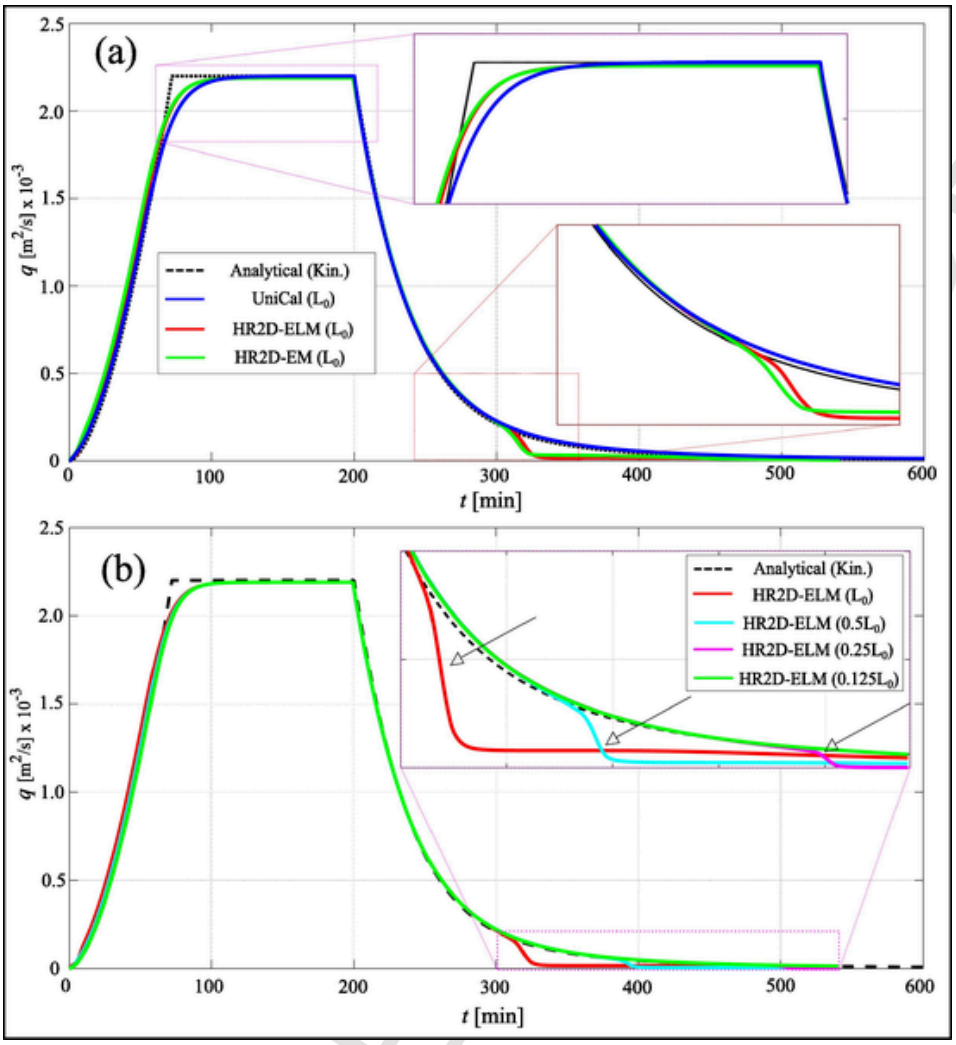


Fig. 5. Test 1: comparison between the hydrographs simulated using the HR2D-ELM and HR2D-EM schemes and the benchmarks (a) and effects of grid resolution on the numerical results (b).

vided by HR2D seems to be not affected by numerical errors and very close to the solution given by the UniCal models shown in Fig. 5b.

4.1.2. Test 2 – Impervious plane (steep slope)

Fig. 6 shows the comparison between the water depth hydrographs simulated by HR2D and the two benchmarks. Using the reference grid (side length L_0 = 5 m), the two numerical solvers implemented in HR2D are not in agreement with each other and gave quite different results from the numerical and analytical benchmarks that, in turn, are practically superimposed (Fig. 6a). The unphysical behaviour observed in the previous test seems to be much more important than what was observed in test 1, providing a quite poor prediction of the recession

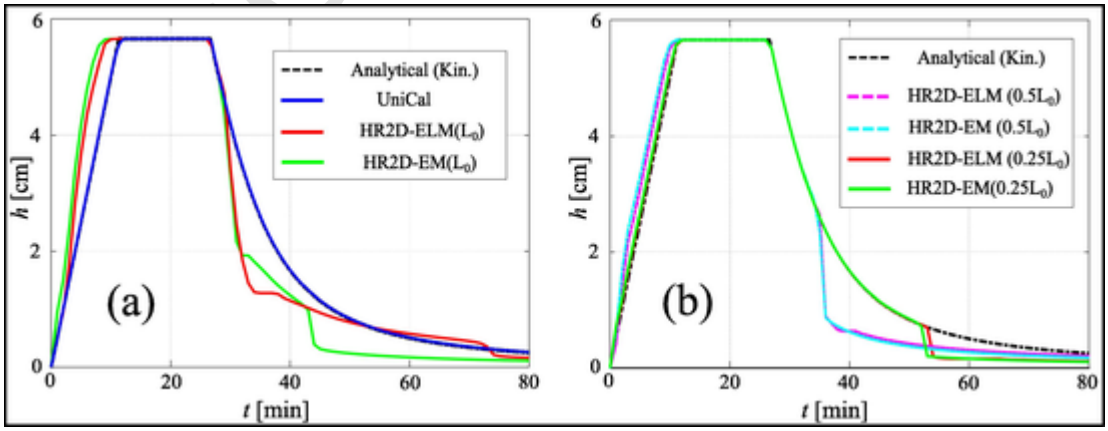


Fig. 6. Test 2: comparison between the hydrographs simulated using HR2D-ELM and HR2D-EM schemes and the benchmarks (a) and effects of grid resolution on the numerical results (b).

limb of the hydrograph (Fig. 6a). In particular, the sudden decrease of the water depth is a clear indication of the presence of numerical inaccuracies that generated poor predictions after the end of the rainfall input.

It is not very simple to detect which numerical scheme implemented in HR2D performs better. The new numerical solver (SWE-EM) seems to perform a little bit worse (SWE-ELM) than the traditional scheme, since some significant discrepancy from the benchmark solutions can be observed also during the rising stage of the hydrograph.

Also in this case, we analyzed the role played by the grid size on the generation of these numerical inaccuracies. As expected, the use of finer grids led to an improvement of the solution. In particular, the sudden decrease of the water levels is reduced and temporally shifted, meaning that the generation of the errors happens later on in the simulation in respect to the reference grid (Fig. 6b). The two numerical schemes converged to the same solution as the grid size decreases, providing a solution closer to those predicted by the benchmark (Fig. 6b). However, despite the use of a finer grid, HR2D performed worse than the UniCal model.

In order to better understand the reasons behind the unphysical solutions given by the numerical solvers implemented in HR2D, in Fig. 7 the comparison between the water depth and velocity profiles simu-

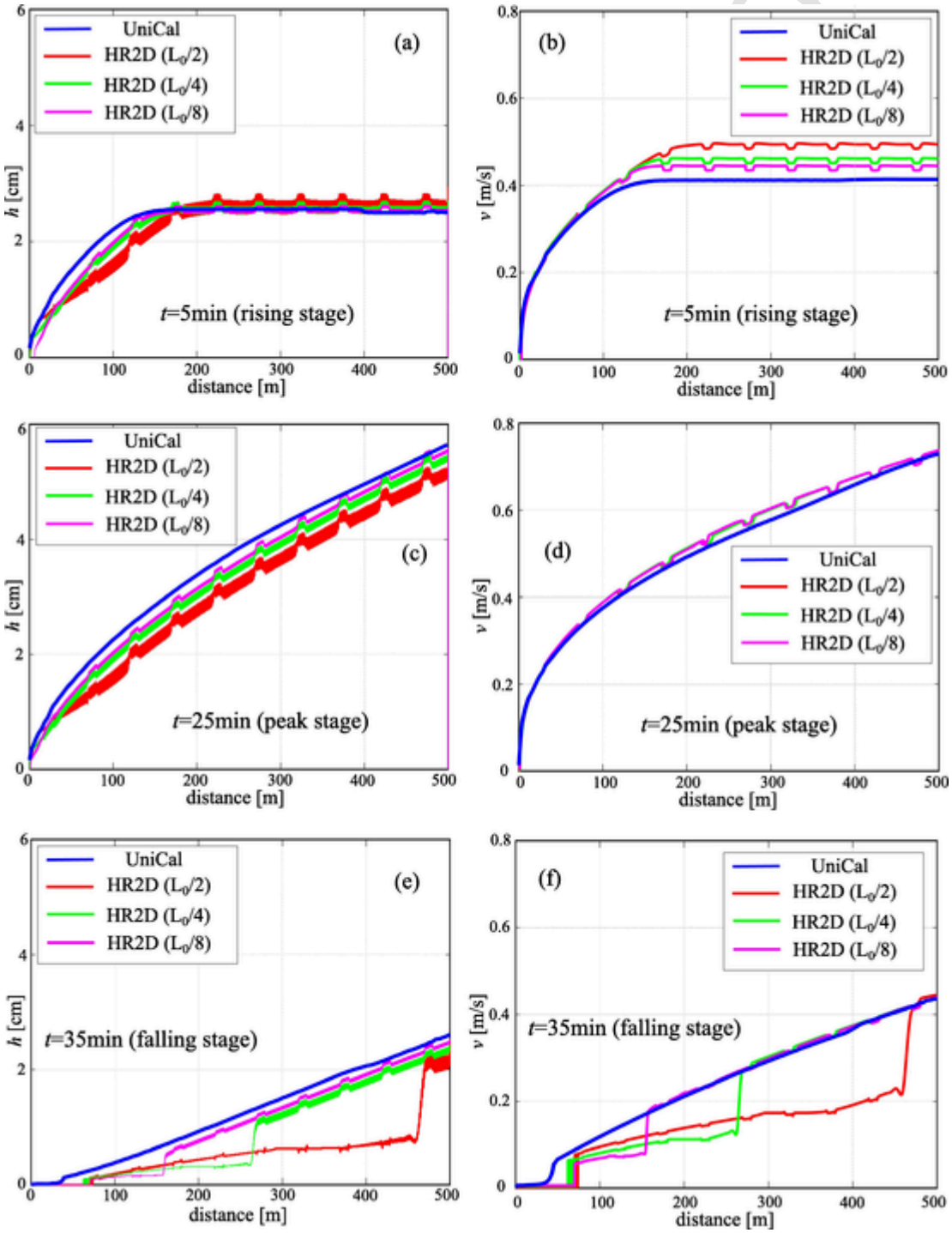


Fig. 7. Test 2: comparison between the water depths simulated by HR2D-ELM, using refined grids, and the UniCal model for instant of times representative of the rising (a,b), peak (c,d) and falling stage of the phenomenon.

lated by UniCal model and HR2D, using the original solver (SWE-ELM), is shown. The grid resolutions used to that purpose were finer than that used for the UniCal model, corresponding to the mesh side equal to $L_0/2$, $L_0/4$ and $L_0/8$. Moreover, three instants of times were considered (t = 5 min, 25 min and 35 min), corresponding to situations representative of the rising limb, time to peak and recession limb of hydrograph.

During the rising stage, the water depths simulated by HR2D show are characterized by significant oscillations, generating predictions quite far from the UniCal solution that, instead, is oscillation-free (Fig. 7a). Reducing progressively the grid size, the simulation provided by HR2D approaches to the UniCal profile, even though some oscillations are still evident. Some oscillations can be observed also in the simulated velocities (Fig. 7b) that led to a generalized overestimation of the predictions performed using the UniCal model. As expected, the reduction of the grid size improved the solutions given by HR2D that tend to be similar to the benchmark. This discrepancy in respect to the UniCal model might be explained by the inaccuracy of the numerical solver used by HR2D in dealing with an initially dry bed condition in presence of very low water depths, as those characterizing overland flow simulations.

During the peak stage (Fig. 7c,d), the simulation provided by HR2D seems to be more similar to that given by the UniCal model, especially in terms of velocity profiles for which the benefits induced by grid refining are quite limited. However, oscillations still occurred in both the profiles. Finally, the analysis of the profiles during the recession stage (Fig. 7e,f) highlighted further important numerical inaccuracy in the solution provided by HR2D that led to unphysical solutions especially for the coarsest grid shown in Fig. 7. Only the use of a very fine grid provided simulations that tended to be similar to that predicted by the UniCal model, which conversely highlighted a convincing hydrodynamic behaviour. The poor prediction in the falling stage, might be explained by the inability of the numerical solver implemented in HR2D in simulating correctly wet-dry fronts especially in the presence of a steep slope. Therefore, this evenience may represent the reason of the unphysical behaviour observed in the water depth hydrograph shown in Fig. 6.

4.1.3. Test 3– Permeable plane

Three simulations were carried out for this test, using the well-known Green-Ampt method for the computation of the infiltration losses. In the first one, based on the ELM solver, the average values for loam according to Rawls et al. (1983), and reported in the reference manual, were used. Therefore, no calibration of the parameters of the Green-Ampt model was performed. In the second simulation, we used the measured and estimated values of saturated soil water content and the hydraulic conductivity after Lima (1989) and the same calibrated values for the capillary suction head and Manning coefficient as in Tügel et al. (2020), selecting the ELM solver as in the previous case. Finally, the last simulation is based on the same set of parameters as in the second simulation but using the EM solver. Since the calibration process was not performed in HR2D but refers to the calibrated values by Tügel et al. (2020) using their 2D SWE model, the HR2D solution should be compared ideally to the simulations shown in that paper.

In Fig. 8, the comparisons between the experimental data and simulated specific discharge are shown. In the first simulation (see blue line in Fig. 8), the surface runoff simulated by HR2D is strongly overestimated, confirming what was already observed by Tügel et al., (2020) using their 2D SWE model. On the contrary, the second simulation (see red line in Fig. 8) provided a fairly good prediction of the phenomenon, since the shape of the simulated hydrograph is very close to the observed one. Some overestimation can be observed in the early stages of the rising limb of the hydrograph, according to other simulations performed in the literature (Lima, 1989; Tügel et al., 2020). The prediction of HR2D is in good agreement with the experimental data, including the recession limb of the superficial runoff. Similar considerations can be made for the third simulation, in which the EM solver provided a very similar solution to the ELM one, except a slightly faster arrival time of the front wave. No oscillations or physical anomalies can be observed in this test, giving a preliminary indication about the suitability of HR2D as an integrated hydrologic-hydraulic model for storm risk management.

4.2. Impervious planes using unsteady or non-uniform rainfall

For the first two ideal cases, two benchmarks provided by the analytical solution and the simulations obtained using the UniCal model

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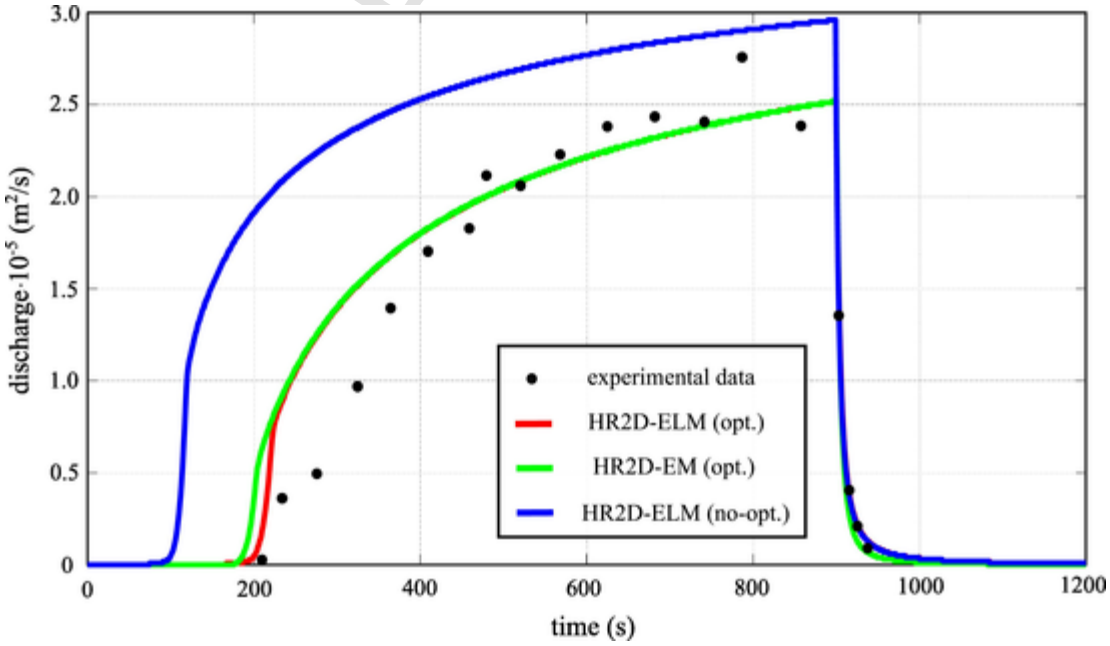


Fig. 8. Test 3: comparison between the hydrographs simulated using the HR2D-ELM and HR2D-EM schemes, using calibrated and uncalibrated values, and the benchmark (experimental data).

were considered again whereas, for the experimental case, both the observed data and the UniCal simulation were used.

4.2.1. Test 4 – Unsteady flow over a plane

Fig. 9 shows the comparison between the simulations performed by HR2D-ELM and HR2D-EM and the benchmarks, considering the same reference computational grid as for the tests 1 and 2. The two benchmarks provided a very similar evolution of the water depths, with the UniCal prediction being practically superimposed on the analytical solution. In this case, the predictions performed by both the solvers implemented in HR2D still suffer from numerical errors. Specifically, the shape of the simulated hydrographs is close to the benchmarks only for the instant of time around the peak values. The errors in both the rising and falling limbs of the water depth hydrographs, already discussed for the test 2, seem to be amplified by the non-uniform rainfall leading to a unphysical solution. This consideration holds regardless of the numerical scheme used to compute the solution. In this regard, the simulation obtained using HR2D-EM is even worse than the original one (HR2D-ELM). This is in contrast to what was reported in the user's manual in which the SWE-EM scheme is presented to be as more reliable than SWE-ELM.

In order to evaluate potential positive effects induced by grid refinement, further simulations were performed, halving progressively the side length of the mesh. For the sake of clarity, only the simulations performed with both the numerical solvers, related to $0.25L_0$, are shown in Fig. 9b.

Though an improvement of the solutions induced by the grid refinement can be observed in both the rising and falling limbs of the hydrographs, the results are still heavily affected by numerical inaccuracy leading, for example, to the unphysical sudden decrease of the water depths just before 6000 s. This anomaly is probably smoothed using the reference grid (L_0). The solutions obtained using the two numerical schemes tend to be closer to each other in respect to the simulations carried out using the reference grid (L_0), suggesting that the source of the errors is not so much in the algorithm in itself (ELM vs EM). Probably, it could be found in the numerical errors generated by an inaccurate treatment of dry-wet fronts, which could have minor impacts on

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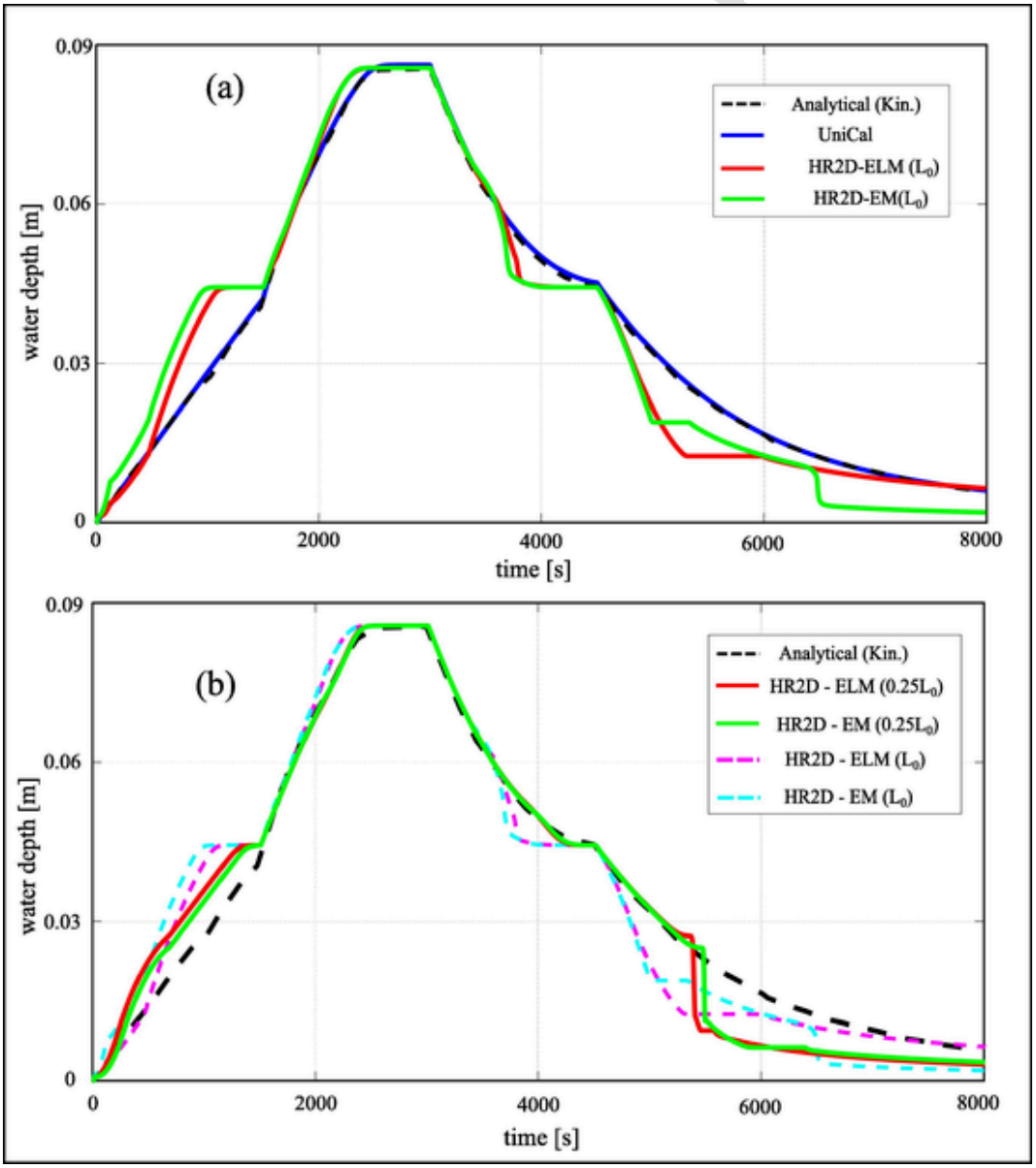


Fig. 9. Test 4: (a) comparison between the water depth hydrographs, simulated using the HR2D-ELM and HR2D-EM schemes, and the benchmarks (Analytical and UniCal solutions) and (b) effects of grid refinement on the HR2D solutions.

HR2D-ELM in respect to HR2D-EM due to the greater diffusion that tends to smooth out unphysical oscillations.

4.2.2. Test 5 – non-uniform rainfall over a cascade of three planes

In order to distribute the three different rainfall inputs on the three successive planes, three separate grids were created and connected to each other. The connection was made by a SA/2D Area Connection option selecting a broad crested weir geometry which has the same height of the DEM elevation between the connected areas and the weir width setup as small as possible (0.1 mm).

The same spatial resolution was used for the UniCal model. Fig. 10 shows the comparison between the discharge and water depth hydrographs computed by HR2D-ELM and HR2D-EM and the two benchmarks, represented by the experimental data and the solution of the UniCal model. All the numerical simulations refer to grids having approximately 0.06 m^2 of spatial resolution since the element side, assumed for HR2D computations, was set equal to $L_0 = 0.25$ m.

Focusing the attention on the overall phenomena observed for both the rain durations, reasonable predictions in terms of water depth and discharge hydrographs were provided by HR2D. However, significant discrepancies not only from the experimental data but also from the UniCal model can be detected. In particular, HR2D showed some difficulties in capturing the shock wave observed for rain duration $D = 10$ s, especially when using HR2D-EM, leading to an overestimation of the simulated discharges in the rising limb of the hydrographs (Fig. 10a, b). Moreover, the recessive part of the hydrograph seems to be more impulsive than the observed one, so that the temporal evolution of the water depths is far from the experimental values (Fig. 10b). Therefore, some important discrepancies in terms of velocities simulated by HR2D are likely to occur. The HR2D predictions seem to be closer to the observed hydrographs when a less impulsive phenomenon is simulated (Fig. 10 c,d), even though some significant underestimations can be detected especially in the water depth hydrograph.

It is important to observe that the limitations observed in the HR2D predictions are not present in the UniCal simulations, which are in close agreement with the observed data for both the rain durations. This may induce us to argue that the numerical errors provided by the HR2D solver, highlighted in previous sections, played an important role also in this case. In order to evaluate the potential benefit due to the grid refinement ($L_0/2$), another simulation was performed using HR2D-ELM but halving the computational element side, so that the spatial resolution is 4 times greater than before. Some improvements in the solution can be observed especially for rain duration $D = 10$ s, in which the sudden rise of the hydrographs is better reproduced, limiting the effects of the numerical diffusion (Fig. 10a,b). The shape of the recession limb of the hydrograph seems to be better reproduced as well. For rain duration $D = 30$ s, the benefits in the solutions are quite limited and, in particular, no improvements can be observed in terms of water depth peak value (Fig. 10 d). Therefore, despite the use of a refined grid, the overall solutions provided by HR2D is still worse than the UniCal ones.

Considering all the simulations shown up to now, HR2D-EM seems not to provide benefits in respect to the HR2D-ELM. This comment holds regardless of the values assumed for the Courant number and all the parameters reported in section 2.2.1. Specifically, several simulations (not shown here for the sake of brevity) were carried out further reducing the Courant number and providing variations in both the tolerance and Theta values because changing in the solution are expected. However, only negligible differences in the solutions were observed.

Therefore, these results seem not to confirm what was reported in the reference manual about the accuracy of the numerical solvers. A possible explanation for this apparent discrepancy may be found in the already recalled specific nature of RoG simulations that makes them more challenging than the traditional simulation of flood propagation. For the sake of brevity, only the results obtained using HR2D-ELM will be shown in the next sections.

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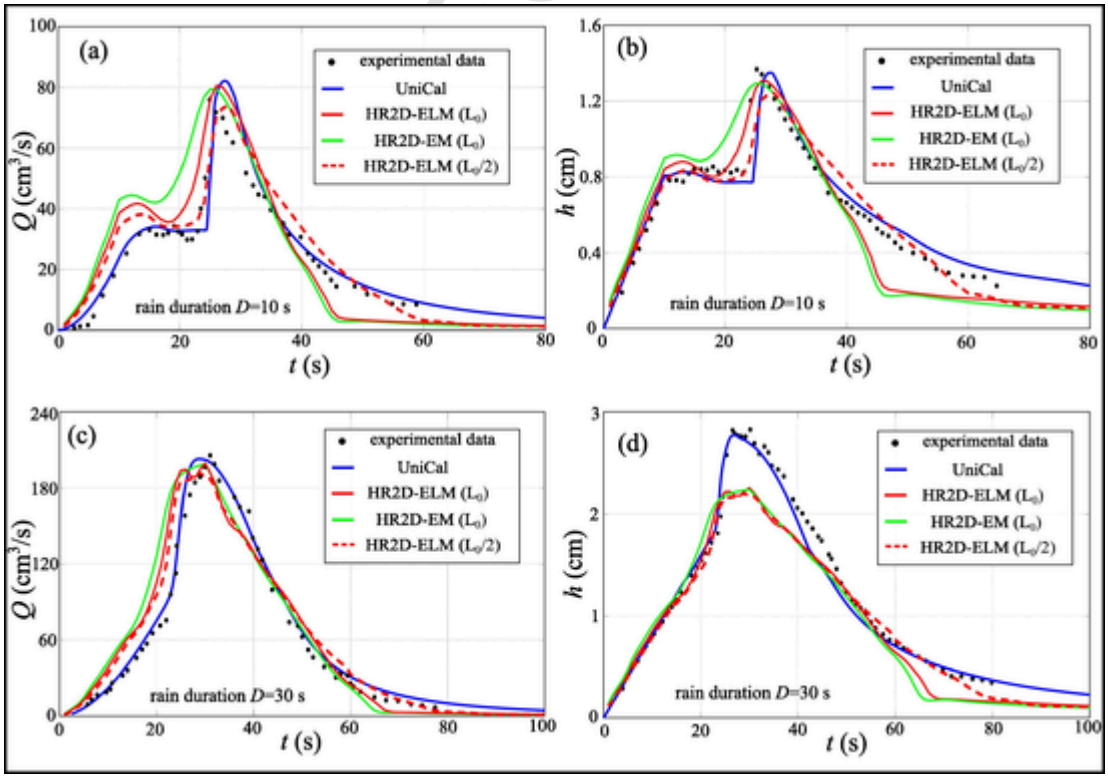


Fig. 10. Test 5: comparison between the discharge and water depth hydrographs simulated by HR2D-ELM and HR2D-EM schemes and the benchmarks (experimental data and UniCal solutions) computed at the channel outlet: rain duration $D = 10$ s (a,b) and 30 s (c,d).

4.2.3. Test 6 – non-uniform rainfall over idealized basin

In order to simulate the vertical wall delimitating the channel, two areas were connected through the SA/2D Area Connection option selecting a broad crested weir geometry which has the same height of the DEM elevation at the end of the planes which was connected directly to the channel bottom.

As regards UniCal computations, a uniform spatial resolution was set everywhere (about 50 m^2), except for a very limited area at the turn of the banks of the channel, where a grid refinement was provided (resolution approximately equal to 5 m^2) to avoid excessive smoothing of the existing steep topographic gradient. A square grid was used for the simulations performed in HR2D, having element side L_0 equal to 5 m.

Fig. 11 shows the comparison between the hydrographs simulated by HR2D and the two benchmarks. The shape of the hydrograph simulated by HR2D is in good agreement with the benchmarks, which are very close to each other, even though a slight delay can be observed in the front arrival times and time-to-peak, probably due to some inaccuracy in dealing with initially dry bed conditions.

Some discrepancies between UniCal and HR2D can be observed in the recession part of the hydrograph. Specifically, a drastic change of the discharge hydrograph derivative occurred after 120 mins (see black circle in Fig. 11a) that has no motivation from a hydrodynamic point of view. This unphysical behaviour could be explained by some numerical inaccuracy in the treatment of wet-dry front during the transition from overland plus channel flow to channel flow only. On the contrary, the UniCal solution is convincing due to the quite smooth shape of the simulated wave. In order to evaluate the effect of the grid size on this kind of situation, other simulations were carried out reducing progressively the grid size ($0.8L_0$, $0.6L_0$, $0.4L_0$) in the channel only. As shown in Fig. 11, the numerical errors progressively vanish leading to a smooth solution like that simulated by the UniCal model.

4.3. Simulation related to runoff over idealized and real-world urban areas

4.3.1. Test 7 – Experimental test

The results obtained using HR2D were compared against the experimental data collected by Cea et al. (2010).

Two kinds of simulation were carried out for the considered buildings arrangements Y20 and A12 (see Fig. 3b and 3c), following the BR and BB approaches described in section 2.1: in the first one (HR2D-BR), the Manning coefficients of the computational elements covering the building footprints were increased by one order of magnitude in respect to the value suggested by Cea et al. (2010) as representative of the experimental test. In the second one (HR2D-BB), the heights corresponding to the roof tops were assigned to the vertices of the computational mesh that fall within the building footprints, while vertices outside them had original terrain heights as in the HR2D-BR simulation. Both the approaches are significantly influenced by the modelling choices: the roughness value (n_0) for BR and the mesh side of the computational mesh (L_0) for BB. In the basic scenario, it was assumed $n_0 = 0.1$ s $m^{1/3}$ and $L_0 = 0.04$ m for the BR and BB respectively. Finally, in order to check the influence of the modelling assumptions for both the approaches, other simulations were carried out. Specifically, the value of n_0 was increased by factors of 1.5 and 2 (0.15 and 0.2 s $m^{-1/3}$) and L_0 was reduced by factors 2 and 4 (element side 0.01 and 0.02 m) for HR2D-BR and HR2D-BB simulations respectively. The value of L_0 was set to 0.02 m for all the BR simulations, but obviously the buildings are not reproduced in the mesh. The HR2D predictions were clearly influ-

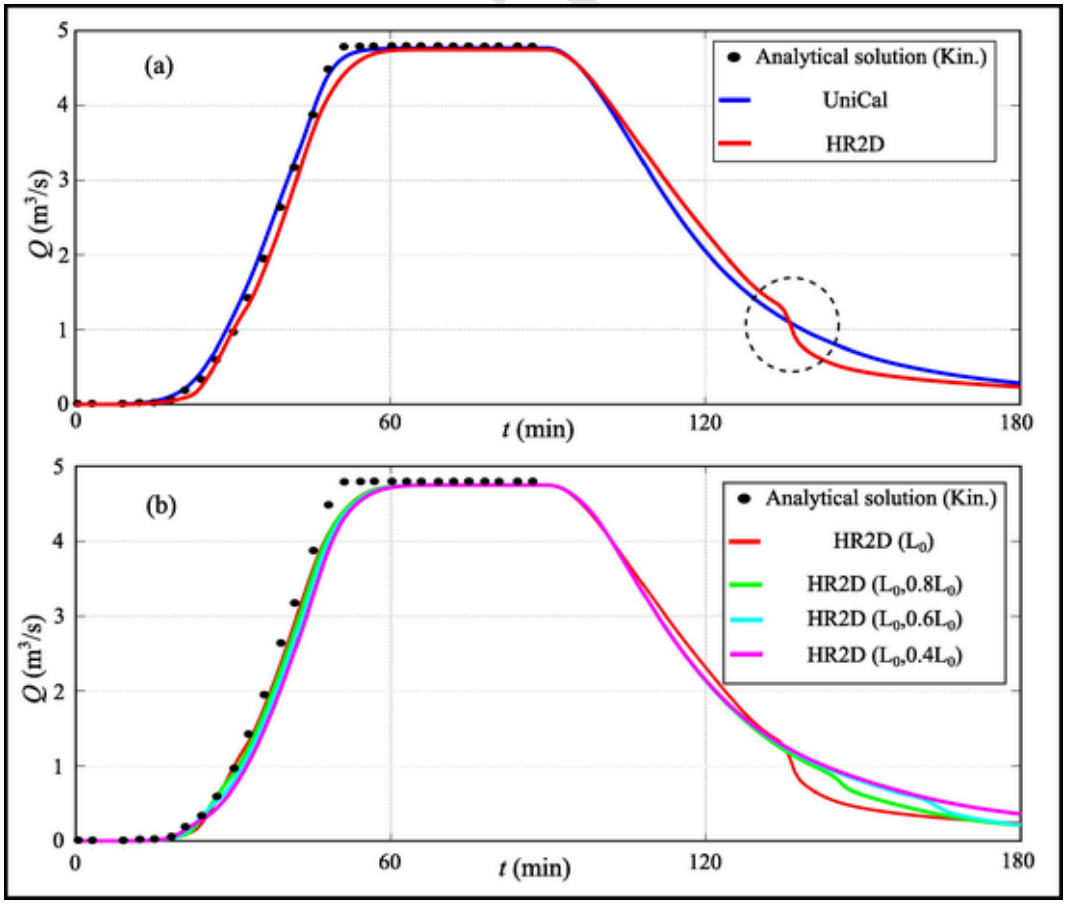


Fig. 11. Test 6: comparison between the hydrographs simulated using HR2D-ELM and HR2D-EM schemes and the benchmarks (Analytical and UniCal solutions) computed at the channel outlet.

enced by the modelling choices and they reflected differently in the results according to the arrangements of the buildings.

Specifically, as regards the HR2D-BB, the choice made for the basic scenario led to a reasonably good agreement between simulated and observed hydrographs for Y20 configuration (Fig. 12 a), for which the peak value is underestimated (about 10 %). The prediction for the A12 arrangement is worse (Fig. 12 c) and the underestimation of the peak value is greater than the previous case (about 30 %). The grid refinement improved the solution for the A12case (Fig. 12c), especially near the peak stage, whereas limited benefits were observed for the Y20 case (Fig. 12a). For both the configurations, all the simulations predicted a faster initiation of outflow in respect to what was observed experimentally, but then the rising stage of the hydrographs is well reproduced. However, some inaccuracy can be detected also during the falling limb of the hydrographs. Similar comments can be made on the HR2D-BR simulations. The value assumed for the basic scenario led to both a good solution for the Y20 case and a significant overestimation for the A12case (almost 20% in terms of peak value). The influence of the Manning coefficient assumed to take into account the buildings did not have a great influence for the Y20 case while it was much more important for the A12configuration (Fig. 12d). It can be observed that the use of the Manning coefficient ranging from 0.15 to 0.2 may provide reasonably good results for both the building configurations. Also for this group of simulations, a faster initiation of outflow was reproduced.

The assessment of best method to use in situations like these goes beyond the purpose of the work. However, both the approaches can be effectively used in HR2D once the calibration of model parameters is carried out.

4.3.2. Test 8 – Rainfall and point source surface flow in urban areas

The spatial grid resolution used for both the numerical models was 4 m^2. For the sake of brevity, only the solutions related to the points 1, 2, 3 and 6 are shown here, as reported in Néelz and Pender (2013) and Cea et al. (2020). In particular, water surface elevations and velocities are discussed for points 2 and 6 while only the water surface elevations are shown for stations 1 and 3 (see Fig. 13). To make the comparison to the other software packages easier, all the panels in Fig. 13 have the same vertical scale used for the y-axis as in Néelz and Pender (2013).

The results obtained by HR2D are free of oscillations, consistent with results produced by other software discussed in Néelz and Pender (2013) and generally close to the UniCal ones. As for the water surface levels, HR2D reproduced the double peak observed in all the other models, caused by the intense rainfall and the inflow discharge. Moreover, it provided practically the same results obtained by UniCal model at points 1, 3 and 2 (see Fig. 13a,b,c) whereas some discrepancies can be observed at point 6 (Fig. 13e).

Due to the hypothetical nature of the event, we have no elements to understand which models provided the most accurate results. However, both the models reproduced substantially the same behaviour simulated by almost all finite volume codes solving the full SWEs shown in Néelz and Pender (2013), considering the expected differences due to the methods used for solving the equations, treatment of wet-dry fronts, different approaches to process topography, etc.

As for the computed water velocities by HR2D, the differences in respect to the UniCal results are higher than those observed for the water surface elevation. As regards point 2 (Fig. 12d), the differences mainly occurred during the recession stage after the two peaks since the peak values are almost the same. The comparison at point 6 (Fig. 12f)

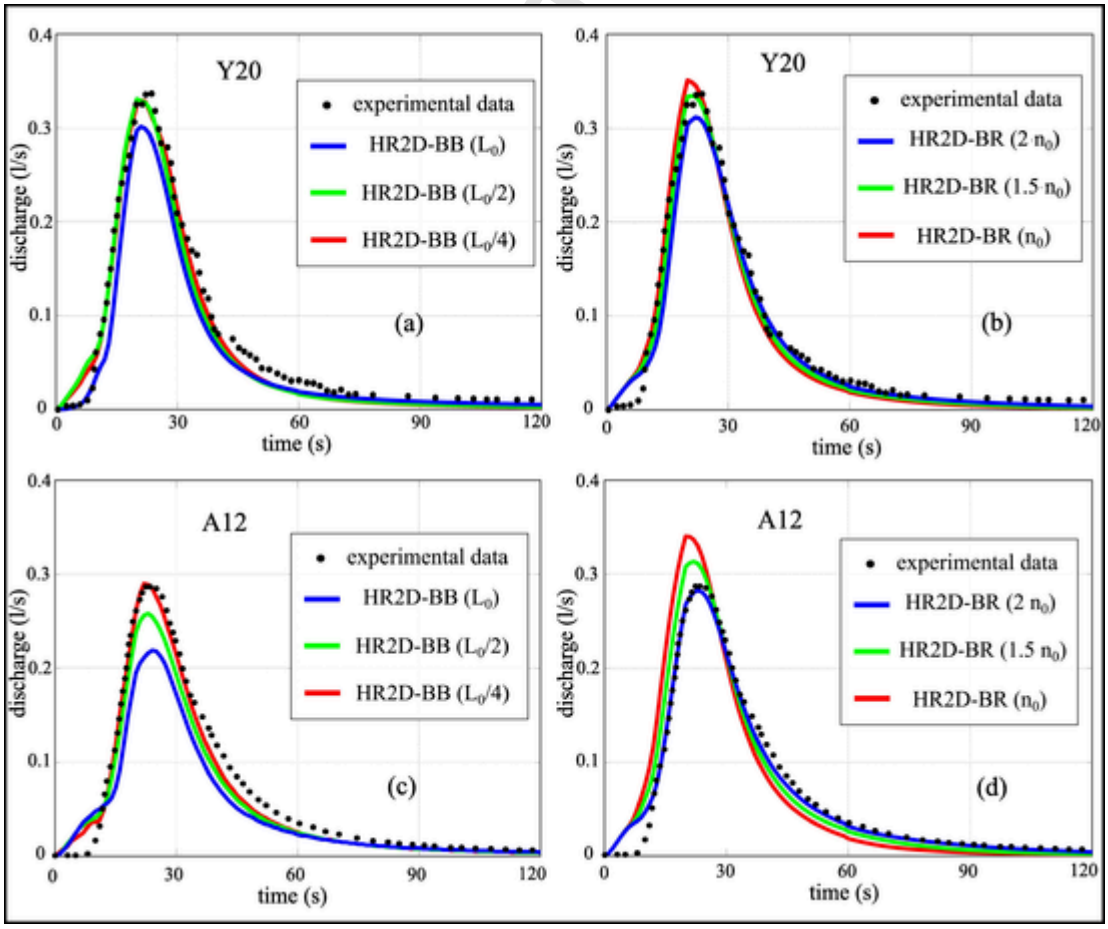


Fig. 12. Test 7: comparison between the observed discharge hydrograph and the simulated one obtained by HR2D according to the BB and BR approaches for the numerical treatment of buildings: Y20 (a,b) and A12 (c,d) configurations.

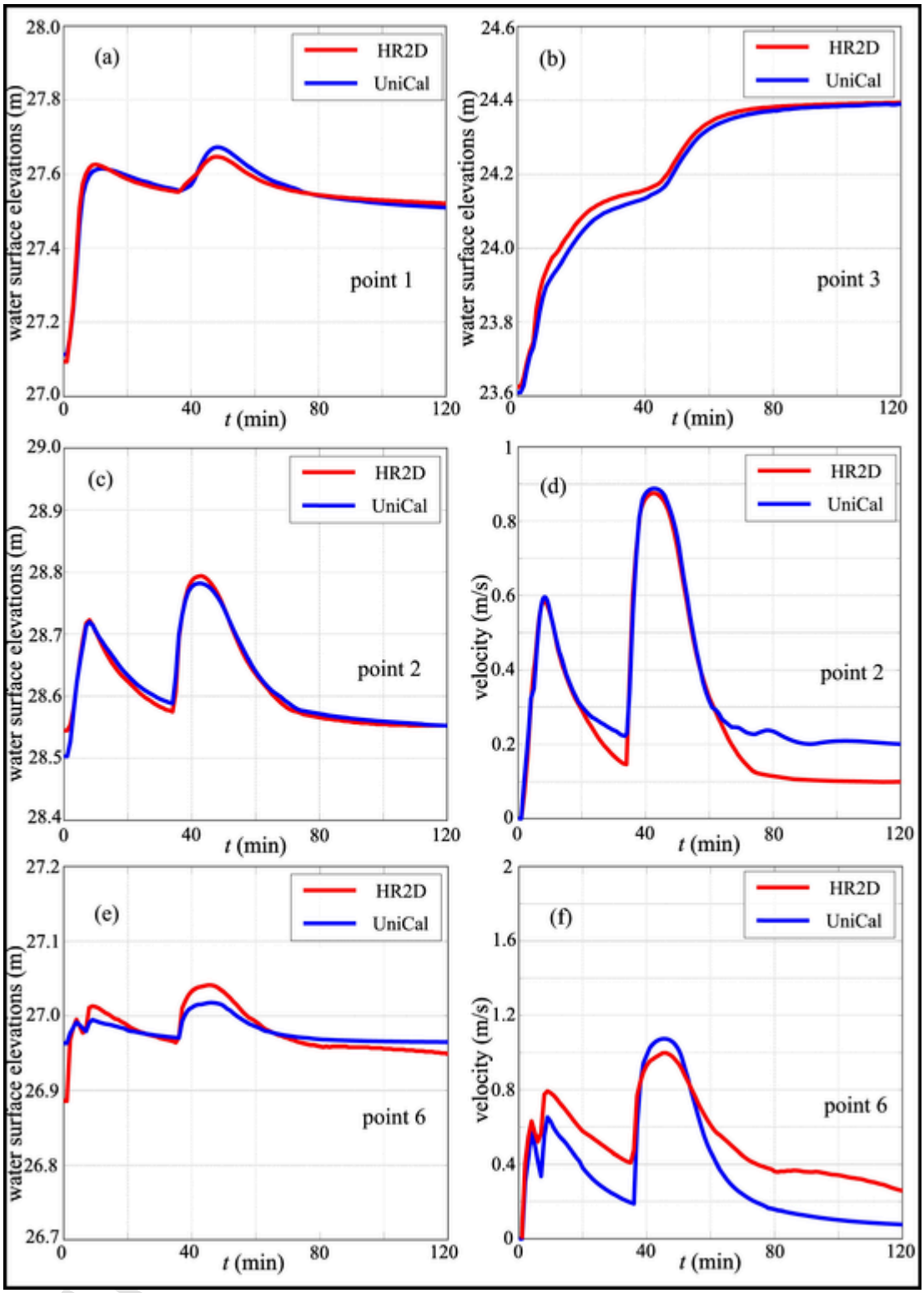


Fig. 13. Test 8: comparison between the simulations performed by HR2D and UniCal models in some reference stations: water surface elevations at points 1,3,2 and 6 (a,b,c,e) and velocities at points 2 and 6 (d,f).

showed higher differences during the first peak and the recession limb after the second peak. However, both the models provided values that fall in the middle of the range described by the models discussed in Néelz and Pender (2013).

The overall solution provided by HR2D can be considered satisfying for this test, considering the close agreement with both other software packages and the UniCal model.

4.4. Runoff over actual catchments

4.4.1. Test 9 – Prediction of the discharge hydrograph starting from a design net hyetograph

Due to very long computational times needed to carry out this simulation, the computational grid used for HR2D simulation is composed of square elements having sides equal to 10 m. In order to ensure similar

conditions in the simulation, the same resolution was used for the UniCal model. Attention will be firstly focused on both the simulated discharges hydrographs at the basin outlet and to the analysis of flooded areas.

Fig. 14a shows a reasonably good agreement between the hydrographs simulated by HR2D and UniCal, even though some differences can be observed. HR2D predicted a slightly slower wave than the UniCal one, with the front wave and peak arrival times a little bit delayed. The difference in terms of peak value is very low (less than 5 %).

Beside the discharge hydrograph at the outlet, one of most important pieces of information for flood hazard assessment is the flooded areas delimitation. For rainfall-runoff simulations at the basin scale, since the rainfall input is applied to each computational cell, it is necessary to define a water depth threshold for the identification of the flooded cells. Fig. 14b shows the comparison between the flooded area extent computed by the two models considering four values of water depth thresholds (5,10,15, 20 cm) used to identify wet cells. The results obtained by the two models are generally in good agreement. The HR2D slightly overpredicts the flooded areas simulated by UniCal, with a maximum discrepancy of 15%, except for the first selected threshold value (0.05 m) in which the total wet area is underestimated (about 20%).

This behaviour could be explained looking at the features of the river network and flow patterns simulated by the two models, shown in Fig. 15. In particular, a quite disconnected river network is generated by HR2D, in which the smaller Horton orders are fragmented and look like a cloud of small areas not connected to each other. This observation can be somewhat related to what was already highlighted by Shustikova et al. (2019), in a traditional flood propagation study, about a certain amount of flooded areas hydraulically disconnected from the main inundated areas. A possible explanation for this might be represented by the approach implemented in HR2D for the distribution of the water within a computational cell, based also on the volume-elevation curve drawn for each cell-face in pre-processing stage. However, more detailed analyzes are required on the specific features of this property, that cannot be found room for in this work.

Finally, it could be of interest to assess the overlapping of the wetted areas for specific water depths. This can be done using several indexes (Sampson et al., 2015). Here we used the so-called Critical Success Index (CSI) defined as in equation (3):

$$\mathrm{CSI} = \frac{A_x \bigcup A_R}{A_x \bigcap A_R} \tag{3}$$

In which A_x and A_R are the wet areas simulated by HR2D and that associated to the reference model (UniCal) respectively. CSI = 0 means no match between model × and the benchmark, CSI = 1 implies a perfect match. The CSI values are substantially equal to 0.75 for all the wa-

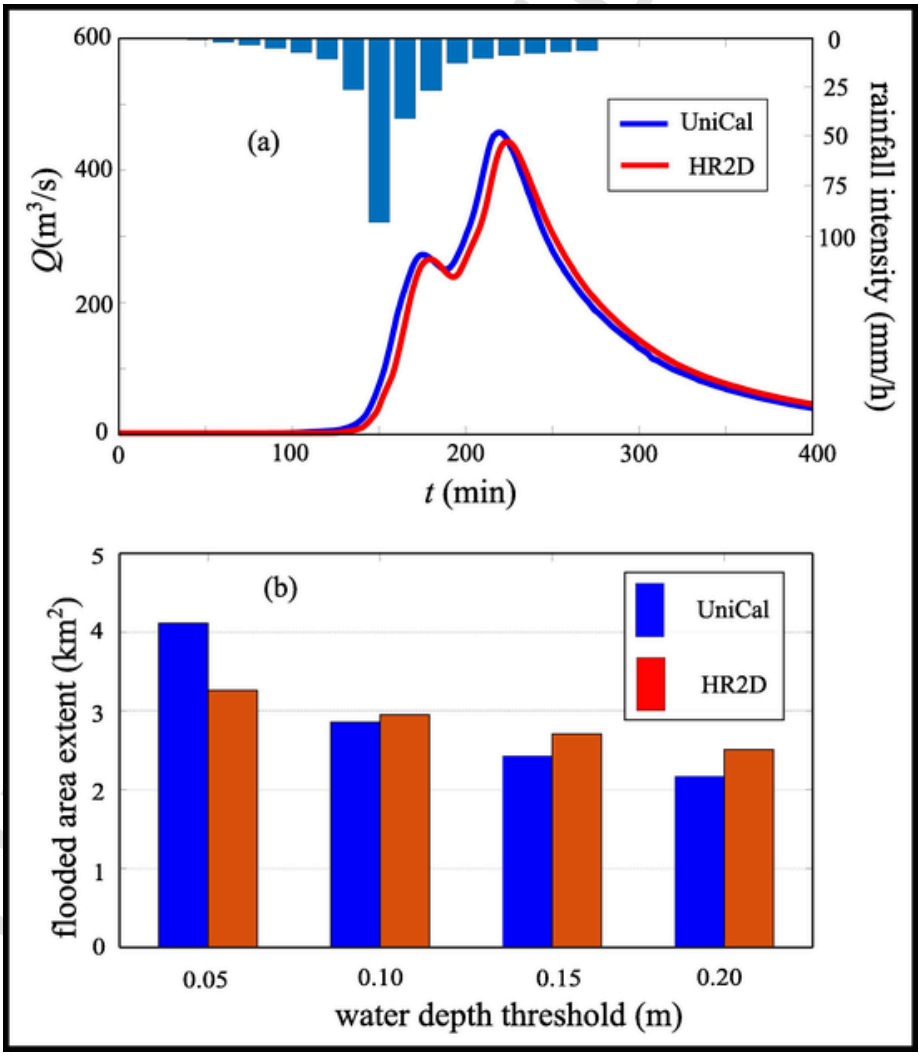


Fig. 14. Test 9: comparison between the simulations performed by HR2D and UniCal models: simulated discharges at the basin outlet (a) and flooded areas extent for specific water threshold (b).

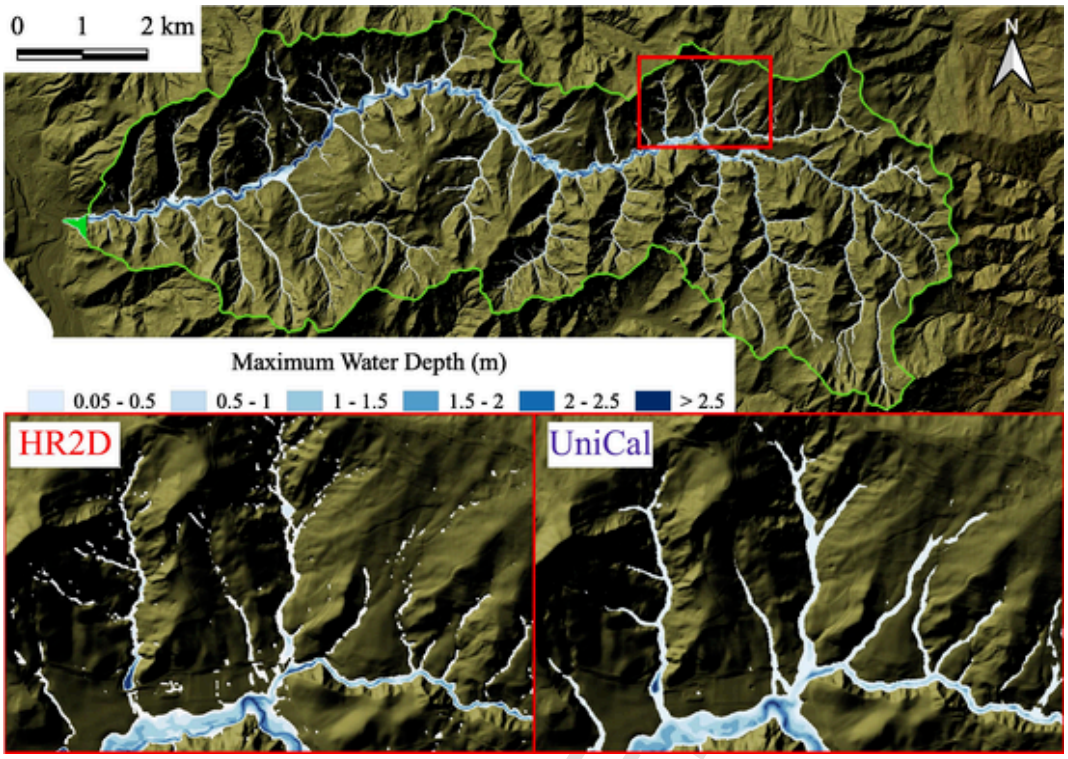


Fig. 15. Test 9: comparison between the hydraulic connectivity of the flooded areas and channels network simulated by HR2D and UniCal models.

ter thresholds falling in the range 0.5 m-2.5 m, highlighting a reasonably good agreement between the two models for higher water depths. However, the CSI value is extremely low (0.15) when the wetted cells are defined using a very shallow water depth threshold (0.05 m), confirming what was previously observed.

4.4.2. Test 10 – Reconstruction of an observed event computing infiltration losses within the hydrodynamic model

This test was the most challenging one due to the specific features, considered intentionally, when this event was selected. Specifically, a very complex event characterized by several closely-spaced peak values was selected, followed by a period in which no rain input was registered. Moreover, several sources of uncertainty exist in the set-up of the modelling inputs. Due to a lack of information, the spatial distribution of the rainfall was not performed. Therefore, the rainfall data recorded at Fitterizzi station (see Fig. 4) was considered as uniformly distributed over the basin. Another important source of uncertainty is in the choice of the parameter values of both the Green-Ampt model and Manning coefficients. No calibration was carried out, intentionally, because the purpose here is to use HR2D in a "blind" mode as a modeller is forced to do for an ungauged basin or in the absence of previous calibration. Considering the available information (lithological and land use maps) mean values of the parameters were selected, according the technical indications reported also in the Hec Ras user's manual. Finally, the total duration of the simulated event, approximately two days, avoided the choice of a fine computational grid in order to reduce the overall computational times, so significant inaccuracy in the geometric description of the channels network and the overall morphometric features of the basin are likely to occur. This choice is also motivated by the absence of any parallelization of the numerical codes implemented in HR2D. So, a square computational grid (element side 10 m) was considered for the computations.

The comparison between the observed and simulated discharges are shown in Fig. 16. From a hydrologic point of view, the overall solutions provided by HR2D are fairly good. In particular, the simulated hydrologic responses to the rainfall inputs B, C and D, highlighted in the green circles in Fig. 16, are very close to the observed ones, even though some important discrepancies can be observed. Specifically, looking at the catchment response to the rain input "B", the first peak is overestimated (see number 1 in Fig. 16) whereas the second and third peaks might be considered comparable since only slight underestimations can be observed (see numbers 2 and 3 in Fig. 16). The response to this part of the event is more impulsive than the observed one, and for this reason all the simulated times-to-peak are lower especially in the case of the first peak. A good agreement can be noted as well also after the rain input "C" (see Fig. 16) for which the shape of the discharge hydrograph is very close to the observed one, providing a slight overestimation of the peak and a comparable time-to-peak. A little bit worse are the results obtained after the rain input "D", since the peak value is underestimated and the shape of the recession limb seems to be not reproduced particularly well. Finally, some significant difference can be observed in the early stage of the simulation, after the rain input "A", for which HR2D response is significant delayed.

Therefore, the differences between observed and simulated discharges were expected due to the lack of a model calibration procedure. Despite that, the overall results can be considered encouraging and in reasonably good agreement with the observations.

5. Discussion

This paper fits into the context of the research field related to the benchmarking of the software packages that, in the last two decades, have drawn significant attention within the fluvial flooding modelling. However, nothing has been done for non-fluvial flood modelling in which the focus is not on the flood propagation starting from an upstream boundary condition (discharge hydrograph) but on the use of 2D hydrodynamic model as an integrated hydrologic-hydrodynamic approach able to be initialized directly from a rain input, as usually done in RoG simulations.

These simulations are very challenging from a numerical point of view because the numerical schemes used for traditional flood propagation need specific treatment not only for appropriate discretization of

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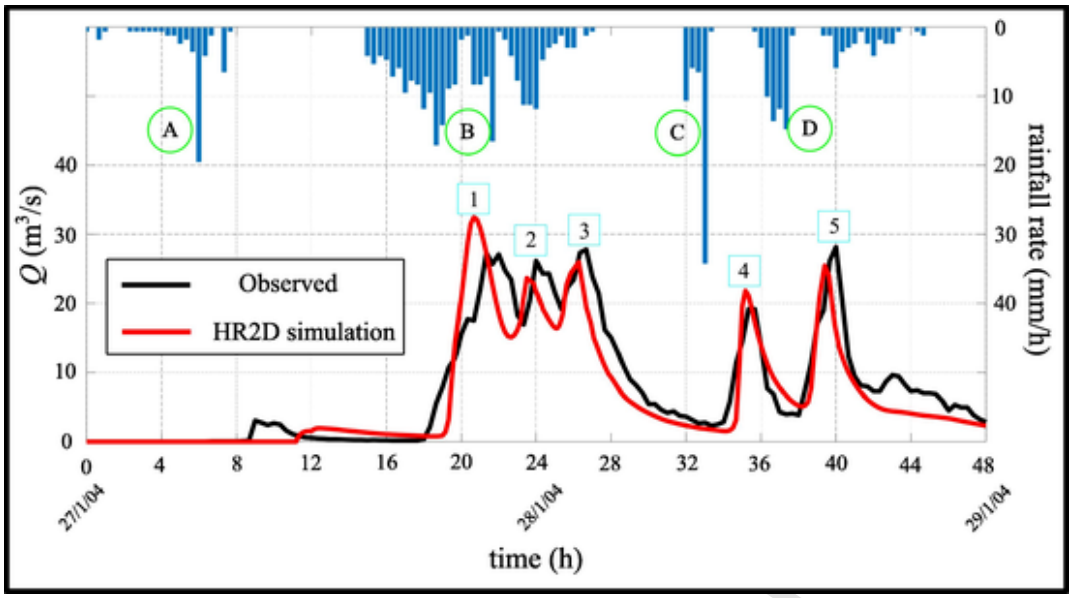


Fig. 16. Test 10: comparison between the predicted and observed discharge at the catchment outlet, using HR2D as a fully integrated hydrologic-hydrodynamic model.

the topography, but also to deal with wet-dry fronts and bed friction in order to avoid instabilities in the solution and unphysical results (Cea and Bladé, 2015). Therefore, the scheme must be accurate and robust to avoid instabilities in the solution due to the presence of highly unsteady wet-dry fronts with water depths of a few millimetres over very rough, complex, and steep terrains. At the same time, the numerical discretization must ensure the conservation of water mass in order to compute properly the shape of the outlet hydrograph (Cea and Bladé, 2015).

In this framework, this paper represents one of the first studies related to the assessment of the accuracy of a software package for RoG simulations, with specific reference to the HR2D model due to its wide popularity even in the scientific community. As far as the authors are aware, this is the first time in which a systematic analysis of HR2D for RoG simulation, ranging from ideal tests to real event simulations, has been presented in the literature but the need for research similar to this has already been recently underlined in the literature. For example, David and Schmalz (2020) compared the performance of HR2D used as decoupled (discharge hydrograph as boundary condition) or integrated (RoG simulation) model. Moreover, Zeiger and Hubbart (2021) assessed the performance of HR2D for RoG simulations in a mixed land-use watershed using effective rainfall simulated by SWAT predictions. Those papers had different purposes from this study but are motivated by the need to understand the potential and limitations of this software package for these specific simulations.

The results of this study enrich and extend the analysis shown in the works cited above because we discuss the HR2D performances for RoG simulation but from a different point of view, explicitly focused on the evaluation of the accuracy of the numerical solvers in a wide range of challenging simulations. Finally, for the first time in the literature, HR2D was successfully used as an integrated hydrologic-hydrodynamic software able to numerically reproduce an observed discharge hydrograph, starting from the recorded rainfall and considering the infiltration losses within the same software package. So, this study is a strong indication about the fact that HR2D can be intended not only as a hydrodynamic model, that needs to be coupled to hydrological models (see among the most recent ones Hankin et al., 2019; Ferguson and Fenner, 2020), but also as a stand-alone approach able to simulate, at least, the basic hydrological process within a 2D hydrodynamic framework. This is a key element for future research, as observed by Tamagnone et al. (2020), according to whom the use of measured hyetographs (or forecast) in a hydraulic freeware, and considering future upgrades in which further hydrological tools will be added, open interesting opportunities for innovative hydrological-hydraulic studies. In this context, this study might become a reference study and has the potential to pave the way for further analysis of the most widely used 2D hydrodynamic/hydrologic models.

Therefore, the results of this work are expected to have several impacts in pluvial/urban flood risk management (Schanze, 2018; Muthusamy et al., 2019) in its broader sense.

However, besides the accuracy features discussed in this work, it should be underlined that a good hydraulic simulator cannot be fully evaluated without an extensive efficiency analysis. As reported in the 2D modelling reference manual, the HR2D computational module was developed from the ground up with parallel processing in mind. The HEC-RAS 2D computations will use as many CPU cores as there are available (which is the default mode for running). Therefore, an efficiency comparison with other numerical models, for example running on GPU architecture, may be performed but it is hard to show here because it requires a paper in itself, representing a potential future development of this research.

6. Conclusions

The RoG approach is considered to be the most suitable numerical strategy for the implementation of an accurate storm risk management. Consequently, several software packages and industrial codes are now available to perform studies like these. Therefore, there is the need of benchmarking studies, especially for the most popular software packages implementing this approach like HR2D, the use of which has been rapidly increasing in the last few years.

Motivated by these considerations, this paper is one of the first researches specifically focused on the benchmarking of HR2D for RoG simulations.

The experience gained in this benchmarking study can be summarized as reported below:

1) the performance related to the runoff simulations over planar impervious surfaces, using steady and uniform rainfall, cannot be considered satisfying. Though the shape and peak value of the hydrographs are substantially reproduced, unphysical results were observed in the solution due to some inaccuracy of the numerical schemes used to solve the governing equations. Specifically, the

most critical situation was detected in the simulation of the recession limb of the hydrograph, in which important oscillations were observed, probably induced by the inability of the numerical schemes to deal with wet-dry fronts, which in turn led to a meaningless solution from a hydraulic point of view. This behaviour, that seems to be much more important for higher slopes, was not observed in the simulations performed using the UniCal model. Moreover, it was highlighted that the HR2D solution approaches the UniCal solution only using computational cells of one order of magnitude, as a further proof of the numerical inaccuracy in dealing with wet-dry interfaces. However, these effects were not observed in the simulation related to the experimental permeable plane in which, for the first time in the literature, HR2D is used considering also the infiltration losses. In particular, the results are in good agreement with the experimental data when using calibrated parameters of the Green-Ampt model according to what is in the literature;

2) the use of unsteady rainfall, over planar impervious surfaces, exacerbated the numerical errors already discussed in the case of steady rainfall. In this situation, the refinement of the grid provided only limited improvements in the solution of the HR2D that showed important differences in respect to the analytical and numerical benchmarks;
3) the simulations related to non-uniform rainfall in the domain are challenging tests for HR2D, for which no other works can be found in the literature. The approach proposed here seems to provide encouraging results but further analyses are required in order to check the reliability of the solutions in the areas close to the discontinuity of the rainfall;
4) contrarily to what was reported in the user's manual about the accuracy of the numerical solvers of the fully dynamic wave equations, HR2D-EM does not provide benefits in respect to the HR2D-ELM, at least for the RoG simulations. The reason for this apparent contradiction may be found in the specific nature of RoG simulations that makes them more challenging than the traditional simulation of flood propagation;
5) the simulations related to idealized and real-world urbanized areas highlighted the good performances of HR2D. Specifically, the two techniques used to take into account the effects of the buildings, increase of roughness and topographical variation, provided fairly good results, even though the first approach is less influenced by the grid resolution contrarily to the second method. Moreover, the real-world test case allowed us to assess the reliability of HR2D, even considering two contextual different sources of water;
6) the simulations related to the runoff computation in actual basins, starting from the net rainfall in order to avoid the computation of infiltration losses within HR2D, highlighted a very good agreement with the predictions performed by the UniCal model in terms of discharge hydrograph at the outlet of the catchment. No important discrepancies were observed in the water depth values throughout the basin, except when considering very shallow water depths. However, HR2D confirmed the tendency to simulate a quite disconnected river network and inundation patterns, as already observed in the literature;
7) the simulation of a rainfall/runoff event on the Turbolo catchment, carried out without any calibration of the parameters, provided encouraging results since the observed discharge hydrographs are reproduced reasonably, considering all the simplified assumptions and the several sources of uncertainty. The analysis of this event is, in itself, a novelty in the literature because, for the first time, the performances of HR2D, as an integrated hydrologic-hydraulic model for discharge hydrograph computation and flood mapping, are shown and discussed.

The generalization of the results presented in this work requires further analysis and applications. However, they may be useful to underline, on one hand, the need of further improvements in the numerical algorithms used, probably in the treatment of the wet-dry fronts, and furthermore to consider the performances of HR2D as very promising for simulations of real events in which the RoG approach is essential.

Uncited references

Fernández-Pato and García-Navarro (2016), Ferraro et al. (2020), Jaber and Mohtar (2003), Ongdas et al. (2020).

CRediT authorship contribution statement

Pierfranco Costabile: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Formal analysis, Supervision. **Carmelina Costanzo:** Methodology, Investigation, Software, Validation, Resources, Writing – review & editing. **Domenico Ferraro:** Methodology, Investigation, Software, Validation, Formal analysis, Writing – review & editing. **Pierfrancesco Barca:** Software, Validation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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