Prof. Paolo Tarolli,

Editor of Natural Hazards and Earth System Sciences

09/10/2019

Re: Manuscript nhess-2019-132

Thank you for your comments regarding our manuscript entitled “A methodology based on numerical models for enhancing the resilience to flooding induced by levee breaches in lowland areas” by A. Ferrari, S. Dazzi, R. Vacondio, and P. Mignosa. We have now updated the manuscript following the suggestions of the Reviewers after their analysis of the paper and the comment of Dr. Olumide Abioye. Moreover, according to your suggestions, we have provided a colour legend in Figure 6, and we have carefully revised the manuscript deserving attention to the English language.

Please find attached to this letter a description of changes and our replies to each comment along with an updated manuscript.

We hope that all the points raised by the Reviewers have been satisfactorily addressed. We wish to kindly thank the referees for their careful reviews and invaluable comments and hope to hear from you again on the status of the manuscript.

Yours sincerely,

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RESPONSE TO REFEREE #1:

The authors gratefully acknowledge the positive and constructive review of the anonymous Referee. In this document the comments provided by the Referee are reported in italic, whereas the authors' response and indications about the original paper modifications are marked in bold fonts.

I enjoy reading the paper by Ferrari and co-authors. It presents a method aimed at improving the resilience of lowland areas that are subject to flooding caused by possible levee failures. The method is simple, as it consists of composing a database of flooding dynamics caused by a (large) number of simulated levee breaches a priori, which allows knowing with good accuracy the flooding dynamics in case of a real levee failure by choosing the simulated event that is most similar in terms of breach locations (and possibly flood magnitude). I can confirm from my experience that such an information could be extremely useful for civil protection purposes. I am thinking of the case of a town that ten years ago was completely flooded about a day and a half after the occurrence of a levee failure, without undertaking significant countermeasures due to the lack of knowledge about flooding propagation in that area.

The authors wish to thank the anonymous Referee for his positive overview about the manuscript.

The text is clear and generally well written. The English could be slightly improved in term of readability with a careful proofreading.

We thank the Reviewer for his suggestion. The entire manuscript has been carefully revised.

It could be worth adding some discussion on the role of the drainage network that typically dissects rural anthropogenic lowlands. Drainage networks, which comprise ditches and channels of gradually increasing size, as well as small obstructions, were proven to affect the flow dynamics at a local scale, encompassing flood formation, the speed of the submerging wave and the flow direction (Hailemariam et al., 2014; Viero et al., 2014; Viero and Valipour, 2017). On the other hand, it must be recognized that the present study deals with the simulation of major flood events, as those caused by levee breaches generally are, and it is reasonable to assume that relatively small landscape features produce negligible effects in such cases.

We thank the Referee for this comment and we agree that drainage networks and microtopography (i.e. tillage feature, ditches) influence the flood dynamics at a local scale, for example by defining preferential pathways. However, as already pointed out by the Referee, the maximum discharge through the breaches here considered (in the order of 10^2 m^3/s) largely exceeds the discharge capacity of the drainage systems. It is also relevant to notice that most of the minor channels are equipped with gates that are kept closed at the passage of huge flood waves in the river, and hence they do not contribute to the drainage of the flooded volume until the end of the event. Even the possible presence of pumping stations

is not relevant during the event, considering the extension of the inundations modelled here. As a result, these networks are not expected to significantly contribute to the flood dynamics, and hence they were neglected in the terrain description to avoid the excessive increase in the number of computational cells. In fact, the riverbed, the levees, the main artificial embankments and channels were described with the maximum resolution (5 m), whereas the description of the remaining lowlands with small channels would have led to an 80% increase in the number of cells. In addition to this, most of these micro-features would have required an even finer resolution (e.g. 1 m), which would have further increased the computational time.

In the revised paper, we have clarified the reasons for neglecting the drainage network by adding the following text (Sect. 4, line 33 (page 12) - line 5 (page 13)):

"Still focusing on topographic information and spatial resolution it is relevant to notice that drainage networks with relatively narrow channels were not described in detail in the computational grid. In fact, even though microtopography (i.e. tillage feature, ditches) determines preferential pathways for very shallow flows (Viero and Valipur, 2017; Hailemariam et al., 2014), the maximum discharge through the breaches here considered (in the order of 10^2 m^3/s) largely exceeds the discharge capacity of the drainage systems. Moreover, most of the minor channels are equipped with sluice gates that are kept closed during river floods, preventing the drainage of the flooded volume until the end of the event. As a result, these networks were not expected to contribute to the flood dynamics significantly, and hence they were neglected in the terrain description."

Finally, I suggest stressing that such a database should be updated when significant modifications affect the landscape and, particularly, the topography of the floodable area, particularly for embankment construction and/or removal, as they can change the flood dynamics dramatically and, often, in unexpected fashions (e.g., Viero et al,, 2019).

We thank the Referee for this comment. Therefore, in the discussion section (Sect. 4, lines 6-8 (page 13)), we have added the following sentence:

"Finally, it must be stressed that the database should be updated periodically to take into account possible significant changes to the landscape (i.e. construction/removal of relevant embankments) that are expected to affect the flood dynamic (Viero et al., 2019)."

ADDITIONAL REFERENCES

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Viero, D.P., Roder, G., Matticchio, B., Defina, A., Tarolli, P., 2019. Floods, landscape modifications and population dynamics in anthropogenic coastal lowlands: The Polesine (northern Italy) case study. Sci. Total Environ. 651, 1435–1450. doi:10.1016/j.scitotenv.2018.09.121

RESPONSE TO REFEREE #2:

The authors gratefully acknowledge the positive and constructive review of the anonymous Referee. In this document the comments provided by the Referee are reported in italic, whereas the authors' response and indications about the original paper modifications are marked in bold fonts.

The paper presents an interesting contribution to the journal, offering a novel approach to improving resilience to flooding and increasing preparedness to face levee breach-induced inundations. However, I have some major concerns related to the current version of the manuscript. Overall, some parts lack clarity, and this might cause some confusion while reading the article. Also, English needs polishing before the paper is ready for publication.

We thank the Reviewer for his comment. The entire manuscript has been carefully revised.

As the paper deals with lowlands and human modifications (levees), it should be important to include some contextual works on the role of levees and embankments to contributing to flooding (i.e. Black 2008; Munoz et al., 2018) and on the importance of the artificial drainage network and landscape changes in contributing to floods (i.e. Wohl 2019a,b; Pijl, Brauer, Sofia, Teuling, & Tarolli, 2018; Sofia et al., 2019). The discussion of the results should also be framed into this wider context. Currently, it is much focussed on the technical domain (computer requirements, time for simulation etc), but the paper would benefit a wider audience if the results were framed into the larger picture of lowlands and flood risk.

We agree that flooding events represent a crucial task for different research branches. Therefore, we have reworded the text in Section 1 (lines 22-27) to better explain the "levee-effect" problem, which actually represents one of the main reason to study levee breach-induced flooding, as follows:

"Among the possible causes of flooding, levee breaching deserves special attention. Due to the well-known "levee-effect" phenomenon, structural flood protection systems, such as levees, determine an increase in flood exposure. In fact, the presence of this hydraulic defence creates a feeling of safety among people living in flood-prone areas, both resulting in the growing of settlements, and in the reduction of preparedness, hence in the increase of vulnerability in those areas (Di Baldassarre et al., 2015). As a result, more people are exposed to less frequent but more devastating floods, for which the statistical frequency is difficult to assess, due to the historical changes in river systems (Black et al., 2008)."

Moreover, in the discussion section (Sect. 4, line 28 (page 11) - line 3 (page 12)) we have added the following sentence to briefly recall the ecological and socio-economic consequences related to the building of structural protection systems:

“Due to climate change and population growth, structural protection systems such as levees have been often adopted to increase protection against floods. However, this kind of defence presents several ecological (e.g. hydraulic decoupling between the river and its floodplain, loss of biodiversity, change in groundwater levels, increase in greenhouse gas emission) and socio-economic consequences (Auerswald et al., 2019).

Focusing on the “levee-effect” phenomenon and on the issue of adequately considering the residual flood risk related to levees, the main goal of this paper was to define a methodology based on the use of numerical models to enhance the resilience of lowland areas in case of levee breach occurrence.”

As regards the drainage network, we have added some discussion about the fact that the drainage networks only influence the flood dynamics at a local scale, for example by defining preferential pathways. However, the maximum discharge through the breaches here considered (in the order of 10^2 m^3/s) largely exceeds the discharge capacity of the drainage systems. Finally, it is also relevant to notice that most of the minor channels are equipped with gates that are kept closed at the passage of huge flood waves in the river, and hence they do not contribute to the drainage of the flooded volume until the end of the event. As a result, these networks are not expected to significantly contribute to the flood dynamics, and hence they were neglected in the terrain description to avoid the excessive increase in the number of computational cells.

In the revised paper, we have clarified the reasons for neglecting the drainage network by adding the following text (Sect. 4, line 33 (page 12) - line 5 (page 13)):

“Still focusing on topographic information and spatial resolution it is relevant to notice that drainage networks with relatively narrow channels were not described in detail in the computational grid. In fact, even though microtopography (i.e. tillage feature, ditches) determines preferential pathways for very shallow flows (Viero and Valipur, 2017; Hailemariam et al., 2014), the maximum discharge through the breaches here considered (in the order of 10^2 m^3/s) largely exceeds the discharge capacity of the drainage systems. Moreover, most of the minor channels are equipped with sluice gates that are kept closed during river floods, preventing the drainage of the flooded volume until the end of the event. As a result, these networks were not expected to contribute to the flood dynamics significantly, and hence they were neglected in the terrain description.”

Finally, in order to better stress that significant landscape changes, which can impact on the flood dynamics, have to be taken into account once the database of simulations is created, we have added the following sentence in the discussion section (Sect. 4, lines 6-8 (page 13)):

“Finally, it must be stressed that the database should be updated periodically to take into account possible significant changes to the landscape (i.e. construction/removal of relevant embankments) that are expected to affect the flood dynamic (Viero et al., 2019).”

A greater concern emerges for the paper structure. In my opinion, the paper structure is very confused, and the chapters are currently disorganized proposing a mixture of literature review, method description, and results altogether. There are a lot of references to what should or should not be done, according to a literature review, rather than a focus on the novelty of the proposed approach, and this makes the text hard to follow. The paper should at first describe what the RESILIENCE project is (beginning of chapter 3) and then describe the methodology proposed in this paper (i.e. ParFlood and why it is novel/Accurate), and further proceed to describe the setting for the current simulation. Currently, much of the description is about previous works and all possible approaches, but this ‘distract’ from the description of the actual method proposed. The authors should consider rewording the text, so that it is clear what are the novelties and strengths of this work, as compared to past ones.

We appreciate this suggestion and accordingly we have changed the structure of the paper in order to better mark the novelties of the work. Particularly, we reworded the text in order to distinguish among the literature review, the presentation of the RESILIENCE project, and its application to the study area. Therefore, in Sect. 2, the novel methodology is presented, and general guidelines concerning choice of the numerical model, topographic data, hydrological scenarios, levee breaches locations, and outputs are discussed.

Following the Reviewer suggestion, in the “numerical model” subsection (Sect. 2.1) we have initially pointed out the strength and weakness of some current numerical models used to model free surface flows, particularly levee breach-induced flooding, and then described the advantages of the PARFLOOD model here used.

Moreover, in order to stress that the proposed methodology is general and that it can be potentially applied to any leveed river, general guidelines concerning the RESILIENCE project are provided in Sect. 2, whereas the application to a pilot area in Northern Italy (e.g. description of the input parameters, analysis of the results) is presented in Sect. 3.

Within the methods, also, a lot of parameters are case-specific and it is not clear how they should be ’tuned’ for further application of this approach in different study areas. For example, it is not clear what the ‘hydrological scenario’ are. Do they come from simulated flows? do they come from actual data? if they come from simulated flows, how are these accomplished? Also, the choice of the return period for inflows A and B is not clear. Was this return period previously analyzed and identified? how? [this latter confusion probably *emerge from some lack of clarity in the manuscript]. Should the parameters be optimized for future studies, if so how?*

We thank the Referee for this useful comment that allows us to clarify some further aspects of the proposed methodology. In the revised paper, also by separating the sections concerning the description of the methodology (Sect. 2) and its application to the chosen pilot area (Sect. 3), we have better stressed that the methodology is general and that it can be applied to any leveed river.

Moreover, we have reworded Sect. 2.3 in order to clarify the role of the hydrological scenarios in the creation of the database of flooding scenarios, as follows:

"Discharge hydrographs with a specific return period are assigned as upstream boundary condition. Sometimes these hydrographs are already available from previous hydrological studies, and can be provided by local River Basin Authorities; otherwise, they can be derived from rainfall-runoff modelling or from statistical analyses of recorded discharge hydrographs (e.g. Tomirotti and Mignosa, 2017).

For the purpose of this study, multiple hydrological conditions should be considered, in order to cover possible configurations characterized by different breach triggering mechanisms, flood volumes, etc. At least two different discharge hydrographs should be considered for each breach location, even though the simulation database can be extended with more hydrological inputs if needed. The first case ("inflow A") corresponds to the condition for which the water surface elevation reaches the levee crest somewhere along the river, thus generating overtopping. The second configuration ("inflow B") concerns a flood event with a lower return period, for which the levee is never overtopped, but other mechanisms might induce the levee collapse. In fact, earthen levees can also experience breaching for piping and internal erosion processes, even when water levels remain below the levee crest. Besides, the dens of burrowing animals (e.g. porcupine, badger, nutria) were recently identified as another possible cause for breach triggering (Viero et al., 2013; Orlandini et al., 2015). Incidentally, the collapse of an embankment during a flood event with a relatively low return period can be very threatening for human lives because the highest warning thresholds may not be reached, and population can be unprepared to face flooding.

The choice of the return period for inflows A and B is river-dependent, because it is influenced by the design return period of the levee system, by the presence of other flood control structures, etc. In general, preliminary simulations of the propagation of flood waves with different return periods (e.g. 10, 20, 50, 100, 200, 500 years) for each river should be performed, and the event that corresponds to incipient overtopping can be identified as inflow A. Then, a higher frequency hydrograph can be selected as inflow B, in order to consider levee collapses due to piping or other mechanisms during a flood event that does not induce overtopping (for example, when a specific freeboard is guaranteed).

The discharge hydrographs thus obtained are imposed as upstream boundary condition for the levee breach scenarios."

A further issue is that the authors state that 'Compared to previous studies on flooding induced by levee breaches, the proposed methodology benefits from the adoptions of an accurate and fast numerical model and of high-resolution meshes', but the manuscript does not present any actual comparison with previous studies, but it only showcases a literature review on them.

The Referee is right. The paper does not compare the results of the RESILIENCE methodology with those of previous studies, and the sentence "compared to previous studies ..", which in the original manuscript was adopted to refer to the literature studies, has been removed in the revised paper.

I believe addressing these issues would add value to the paper, and would make this work useful to a wider scientific audience.

The authors wish to thank the anonymous Referee for his positive overview about the manuscript.

References

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Sofia, G., Ragazzi, F., Giandon, P., Dalla Fontana, G., Tarolli, P., Fontana, G. D., & Tarolli, P. (2019). On the linkage between runoff generation, land drainage, soil properties, and temporal patterns of precipitation in agricultural floodplains. Advances in Water Resources, 124, 120–138. https://doi.org/10.1016/j.advwatres.2018.12.003

Wohl, E., 2019a. Forgotten Legacies: Understanding and Mitigating Historical Human Alterations of River Corridors. Water Resources Research. Available at: http://dx.doi.org/10.1029/2018wr024433.

Wohl, E., 2019b. Forgotten Legacies: Understanding Human Influences on Rivers. Eos, 100. Available at: http://dx.doi.org/10.1029/2019eo127853.

RESPONSE TO SHORT COMMENT: Dr. Olumide Abioye

The authors gratefully acknowledge the positive comment of Dr. Olumide Abioye. In this document the comment provided by Dr. Olumide Abioye is reported in italic, whereas the authors' response and indications about the original paper modifications are marked in bold fonts.

The study proposed a methodology to create a database of numerically simulated flooding scenarios with embankment failures with the objective of improving resilience to flooding and increasing hazard preparedness in lowlands with levee breach-induced inundations.

The study is well worth investigating and the paper was well written. The application of the proposed model may have significant implications for hazard preparedness. Here are my concerns:

Although the authors briefly mentioned that optimization techniques have been implemented (see lines 29 and 30 of the manuscript) they have failed to cite recent relevant studies that have applied mathematical modeling and optimization strategies. It is important that the authors emphasize this more in this study. The following are some critical references:

1) Dulebenets, M. A., Pasha, J., Abioye, O. F., Kavoosi, M., Ozguven, E. E., Moses, R., Boot, W., Sando, T. (2019). Exact and heuristic solution algorithms for efficient emergency evacuation in areas with vulnerable populations. International Journal of Disaster Risk Reduction.

2) Trivedi, A., Singh, A.. (2017). A hybrid multi-objective decision model for emergency shelter location-relocation projects using fuzzy analytic hierarchy process and goal programming approach, Int. J. Proj. Manag., 35 (5), pp. 827-840

3) Pel, A., Bliemer, M., and Hoogendoorn, S. (2012). A review on travel behaviour modelling in dynamic traffic simulation models for evacuations, Transportation, 39, pp. 97-123.

We thank Dr. Olumide Abioye for his comment. In Sect. 4 (page 12, lines 10-14) we have added the following text:

"Besides these emergencies, the results of each simulation, also combined for global considerations, allow for an improvement of evacuation and defence system planning. In this context, advanced optimization-based tools and algorithms (Dulebenets et al., 2019a,b) can be exploited to create emergency evacuation plans that efficiently minimize individuals travel time during a natural hazard."

The comparison between the original paper and the revised one is shown in the following pages. Since the manuscript has been completely reworded according to the Reviewer' suggestions, several parts have been moved or changed. As a result, the track-changed manuscript is not clear, and we would kindly suggest to refer to the revised manuscript.

A methodology based on numerical models for enhancing the resilience to flooding induced by levee breaches in lowland areas

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With the aim of improving resilience to flooding and increasing preparedness to face levee breach-induced inundations, this paper presents a methodology to create a wide database of numerically simulated ~~inundation~~flooding scenarios due to embankment failures, applicable to any lowland area protected by river levees. The analysis of the detailed spatial and temporal flood data obtained from these hypothetical scenarios is expected to contribute both to the development of civil protection planning, and to immediate ~~action~~actions during a possible future flood event (comparable to one of the available simulations in the database), for which ~~a~~ real-time ~~simulation~~modelling may not be feasible. The most relevant criteria concerning the choice of ~~the~~ mathematical model, ~~the~~ grid resolution, ~~the~~ hydrological conditions, ~~the~~ breach parameters and locations are discussed in detail. ~~Results of the application of the~~The proposed methodology, named RESILIENCE, is applied to a 1,100 km^2-pilot area in Northern Italy ~~are presented~~. The creation of a wide database for the study area is made possible thanks to the adoption of a GPU-accelerated shallow water numerical model, which guarantees a ~~great~~remarkable computational efficiency (ratios of physical to computational time up to 80) even for high-resolution meshes (2.5-5 m) and very large domains~~.~~ (> 1,000 km^2).

1 Introduction

Flood events adversely affect communities living in flood-prone areas, causing huge damages in terms of economic losses and human lives. Recent studies identified a rising trend in flood frequency and affected population in the past few decades (Kundzewicz et al., 2013; Paprotny et al., 2018), and suggested that global warming will determine a growing occurrence of extreme flood events (Alfieri et al., 2015) and the related damages (Dottori et al., 2018) ~~can be expected~~ in the future~~, due to the global warming~~.

Among the possible causes of flooding, levee breaching deserves special attention. ~~The presence of a~~Due to the well-known “levee-effect” phenomenon, structural flood protection systems, such as levees, determine an increase in flood exposure. In fact, the presence of this hydraulic defence ~~system~~ creates a feeling of safety ~~in river~~among people living in flood-prone areas, both resulting in the growing ~~settlement~~ of ~~people~~settlements, and in the ~~accumulation~~reduction of ~~economic assets~~preparedness, hence ~~increasing~~in the increase of vulnerability in those areas (Di Baldassarre et al., 2015). ~~This phenomenon is known as the “levee-effect”.~~ As a result, more people are exposed to less frequent but more devastating floods, for which the statistical frequency is difficult to assess, due to the historical changes in river systems (Black et al., 2008).

Moreover, the presence of levees ~~constrains the river, thus resulting in~~ causes a reduced flood ~~lamination~~attenuation, which in turn increases the damages when a breach occurs (Heine and Pinter, 2012). ~~Even if the adoption of the best available techniques for~~ Despite all the efforts adopted in embankment design, maintenance and monitoring ~~can reduce the probability of occurrence of these events~~, the residual risk associated with levee breach flooding in the surrounding highly exposed areas cannot be neglected, and its evaluation is hence gaining attention worldwide (Huthoff et al., 2015~~).~~; Pinter et al., 2016).

Nowadays, mathematical models for flood simulation, which solve physically~~-~~-based equations ~~describing the motion of the fluid~~for hydrodynamics (Teng et al., 2017), represent an essential instrument for flood hazard and risk assessment (e.g. Apel et al., 2004; Qi and Altinakar, 2011~~). Moreover, new methodologies for probabilistic flood hazard mapping are able~~), including the residual risk due to ~~include dike~~levee breaches ~~in the analysis~~ (Vorogushyn et al., 2010~~), and~~). Numerical modelling can contribute to ~~the development of~~draw up flood risk management plans ~~and to the comparison of different mitigation strategies (Di Baldassarre et al., 2009; Pinter et al., 2016).~~

~~In this context, flood risk management plans should provide~~with prevention and protection measures to reduce flood-related damages ~~by enhancing~~and enhance resilience~~, which for lowland rivers can be~~ (defined as the ability of the system to recover ~~(return to the normal situation/development)~~ from flooding in flood-prone areas ~~(~~, De Bruijn, 2005). ~~Particularly, the availability of numerical models capable of providing~~The accurate predictions of inundation scenarios ~~can~~provided by numerical simulations can also be useful for assessing civil protection and adaptation strategies (Jongman et al., 2018) and emergency planning during flood events (Tarrant et al., 2005; Dulebenets et al., ~~2019).~~ 2019a,b).

For civil protection purposes, real-time numerical modelling is the most suited solution when dealing with large river basins whose flood events last several days, considering that simulation time (a few hours) is usually much smaller than the physical duration of the flood. Moreover, hydrologic inputs or water level measurements from ~~the~~ upstream river sections ~~of the river~~ can be ~~exploited~~used as boundary conditions to predict the flood propagation along the river. Conversely, in small/medium river basins with short-lasting floods (less than one day), ~~the performance of~~ real-time simulations ~~is prevented by the difficulty in having reliable upstream boundary conditions (~~are much more challenging, because: (i) they have to be based on rainfall-runoff models and weather forecast ~~systems~~, which are characterized by high uncertainties~~)~~, and ~~also by the fact that~~(ii) their computational and physical times are characterized by the same order of magnitude. ~~Finally~~Focusing on levee failures, the real-time prediction of possible ~~levee~~ breach locations is very difficult in the practice, due to the complexity of the breaching process and to the uncertainties in the embankment material characteristics (often heterogeneous, and with unknown local discontinuities), especially for small rivers. Considering all these limitations, the creation of an off-line database of hypothetical flooding scenarios constitutes an alternative solution to real-time forecasting based on integrated hydrologic-hydraulic modelling.

This paper presents a methodology for assessing the flooding scenarios induced by levee breaches with the purpose of increasing resilience in lowland ~~rivers. The~~areas. For a given exposed area, the RESILIENCE project (REsearch on

Scenarios of Inundation of Lowlands Induced by EmbaNkment Collapses in Europe) aims at the creation of a wide database of high-resolution numerical simulations, concerning several ~~hypothesized~~hypothetical flood scenarios, each one characterized by ~~different~~a specific breach ~~locations~~location and ~~hydrological conditions in~~ an ~~exposed area, which will be available for emergency planning during a possible future event~~upstream discharge hydrograph with assigned return period. While previous studies combined the results of different scenarios in order to create probabilistic flood hazard and flood risk maps (Di Baldassarre et al., 2009; Vorogushyn et al., 2010), in this work breach scenarios are not associated with their probability of occurrence. In fact, the focus of this study is not on flood hazard mapping, but on the evaluation of flood dynamics, arrival times, maximum water depths and velocities, required for the definition of civil protection strategies, which should be equally effective regardless of the event probability, breach failure mechanism, etc~~. Moreover, compared~~.. Accurate simulation results are obtained thanks to ~~previous studies on flooding induced by levee breaches,~~ the ~~proposed methodology benefits from the adoptions of an accurate and fast numerical model and of~~ adoption of high-resolution meshes~~.~~ and of a robust and efficient numerical model, named PARFLOOD (Vacondio et al., 2014, 2017).

The ~~proposed~~ methodology is applied to a study area in Northern Italy, ~~in particular to the region~~ bounded by the Po River and by its two tributaries Secchia and Panaro, which was affected by levee breach flooding in the past (Vacondio et al., 2016). General guidelines for the application of the ~~methodology~~procedure and details ~~of~~on the criteria adopted for the pilot area are reported. Moreover, a few examples of simulation results are provided, and their possible practical use is discussed.

The paper is organized as follows: in Sect. 2, the RESILIENCE project is presented, and the most important features ~~that a numerical model for the simulation~~and requirements of ~~floods induced by levee breaches should have~~the methodology are ~~discussed~~described in detail~~, and the PARFLOOD model is briefly presented.~~. Sect. 3 illustrates the ~~RESILIENCE project and its~~ application to the pilot area, together with some examples of the results. The assumptions, the advantages and the implications of the methodology are discussed in Sect. 4, and concluding remarks are finally outlined in Sect. 5.

2 Flooding scenarios induced by levee breaches: the RESILIENCE project

The RESILIENCE project aims at defining a new methodology for mapping flood scenarios due to levee breaches, which can be helpful for improving preparedness and supporting the development of technical and scientific tools for emergency planning and management, consistently with EU Flood Directive 2007/60/CE. Several breach locations along a leveed river are preliminarily identified, and multiple discharge hydrographs, characterized by different return period, are considered. Each combination of breach position and upstream boundary condition corresponds to a simulated flood scenario. In this way, a large database describing different hypothetical real levee breach events in that area is created. The results of these simulations, made available to public administrations, can be fundamental not only for emergency planning, but also for civil protection immediate action during real flood events.

In the following sections, the most important assumptions of the methodology concerning model selection, spatial resolution, hydrological conditions, breach locations and modelling are discussed thoroughly. Moreover, the most relevant simulation outputs and their usefulness for civil protection purposes are described.

2 Which model should be used?

2.1 (Coupled or uncoupled) 1D-2D models vs. fully 2D models

2.1 Numerical model

2.1.1 Background

Free-surface flows are traditionally described by means of the shallow water equationsShallow Water Equations (SWEs), i.e. depth-averaged mass and momentum conservation laws (Toro, 2001), thatwhich can be written either in one-dimensional (1D) or in two-dimensional (2D) form. In the past, the high computational effort required to perform fully 2D simulations led to the development of 1D-2D models, which separate the river, described by means of a 1D model, and the flood-prone area, where a 2D model is adopted because in this region no preferential flow direction can be determined *a priori*.

IfHowever, the two models areadoption of either 1D-2D uncoupled, the 1D model computes the discharge hydrograph at the breach location treating the breach as a lateral weir; then, the hydrograph is used as boundary condition for the 2D model (Di Baldassarre et al., 2009; Masoero et al., 2013; Mazzoleni et al., 2014) or coupled (e.g. Gejadze and Monnier, 2007; Morales-Hernandez et al.,). This approach reduces the computational time and allows the modeller to exploit the available river sections surveys. However, the separation between the two numerical2013; Bladé et al., 2012) models may lead to inaccurate results, as in. In the former case of, backwater effects near the breach location, which can reduce the outflow discharge, or even reverse the flow. In many real cases, due to the presence of embankments or to the natural ground elevation, the total head of water accumulating in the flood-prone area can induce a flow reversal at the breach location after some time, and part of the flood volume can flow back into the river through the breach itself.

To overcome these limitations, other authors introduced coupling between 1D and 2D models (e.g. (Gejadze and Monnier, 2007; Morales-Hernandez et al., 2013). In general, coupling can be performed either by adding a source term to the continuity equation and an internal boundary condition, such as the weir flow equation, or by properly discretizing the numerical fluxes at the boundary to ensure mass and momentum conservation (Bladé et al., 2012). The former approach is often preferred for lateral connections, as for levee breach simulations (Liu et al., 2015): in this case, the breach evolution in time is included in the internal boundary formulation, and influences the outflow discharge (Vorogushyn et al., 2010; Viero et al., 2013; Huthoff et al., 2015; Ahmadian et al., 2018). Significant speed-ups can be achieved in comparison with fully 2D models (Morales-Hernandez et al., 2013), but the necessity), are not captured, whereas in the latter case the need of defining the coupling location *a priori* makes the 1D-2D model less flexible than a fully 2D modelsmodel. Besides, the flow field becomes markedly 2D after the breach opening, both inside and outside the river region, and a 1D model cannot predict the outflowing discharge accurately~~ due to the presence of an abrupt deviation of the streamlines and to the fact that the discharge downstream of the breach can fall close to zero or even reverse right after the occurrence of the breach~~.

~~**2.2 Simplified vs. complete numerical schemes**~~

~~Different numerical methods are available to discretize~~Focusing on the 2D-SWEs~~. Among these, simplified~~, several models ~~like~~adopt a diffusive approach to simplify the original formulation (e.g. LISFLOOD~~ (~~, Horritt and Bates, 2002~~), which adopts a diffusive approach, are worth mentioning due to their widespread use for practical flood simulations. Despite their reduced computational time, simplified models do~~). However, this does not always guarantee an overall accuracy comparable to that obtained from models which solve the full SWEs, particularly when supercritical flows and hydraulic jumps need to be modelled (Hunter et al., 2008; Neal et al., 2012~~). If~~; Costabile et al., 2017), as often occurs when a breach opens. On the other hand, if the complete equations are written in conservative form, explicit finite volume (FV) schemes can be adopted (Toro, 2001). These~~ robust and accurate~~ methods have the advantage of reproducing both subcritical and supercritical flows, ~~and~~ of incorporating the propagation of shock-type discontinuities automatically~~. The discretization~~ , and of ~~slope and friction source terms should guarantee that the *C-property* (i.e. the ability to preserve steady states at rest) is satisfied (e.g. Audusse et al., 2004; Aureli et al., 2008a;~~ including robust treatments of wet/dry fronts and irregular topography (Liang and Marche, 2009~~), especially for flood simulations over an irregular bathymetry. Moreover, the treatment of wet-dry fronts must be robust in order to reproduce the flood propagation accurately (e.g. Bradford and Sanders, 2002; Liang and Marche, 2009).~~).

~~**2.3 Serial vs. parallel models**~~

~~Until a few years ago, the wide adoption~~The high computational cost of fully 2D models ~~for the simulation of large areas was~~based on complete SWEs has prevented ~~due~~ the extensive use of these models to ~~the long computational time required. Recently, the advances in~~simulate large domains (> 100 km^2) with high resolution meshes (5-10 m) until a few years ago, when parallelization techniques ~~opened up new perspectives in this field.~~ started being applied to SWE models (Sanders et al~~. (~~., 2010~~) achieved significant CPU time savings by developing a parallel 2D shallow water model based on Message Passing Interface (MPI) communication, which on the other hand requires large and~~). Nowadays, expensive supercomputers~~. A more feasible and cheap alternative is the code parallelization on~~ are not even required, since the use of Graphics Processing Units (GPUs) (Brodtkorb et al., 2012; Lacasta et al., 2014; Vacondio et al., ~~that~~2014, 2017; Conde et al., 2017) limits hardware requirements to a standard workstation equipped with a video card. ~~A number of works about 2D SWE models implemented on GPUs have been presented in the literature (Castro et al., 2011; Brodtkorb et al.,~~ The execution time of a GPU-parallelized code can be reduced~~2012; Lacasta et al., 2014; Vacondio et al., 2014, 2017). All the cited papers report that the GPU parallel implementation of the code entails reductions~~ up to two orders of magnitude ~~in execution time~~ compared to the CPU serial version of the same code (Castro et al., 2011; Vacondio et al., 2014~~). Morales-Hernandez et al. (2014) show that a 2D GPU model may even outperform a 1D-2D coupled model in terms of execution time. Moreover, the~~

~~implementation of optimization techniques, such as the local time stepping strategy (Dazzi~~; García-Feal et al., 2018~~), and the development of codes able to exploit the multi-GPU architecture typical of High Performance Computing (HPC) clusters (Turchetto et al., 2018; Ferrari et al., 2018) can further enhance the efficiency.~~).

2.1.2~~.4~~ The PARFLOOD model

Following this discussion, a GPU-accelerated fully 2D model, such as PARFLOOD (Vacondio et al. 2014, 2017), is considered best suited for the purposes of this work~~,~~ and is adopted for the present application. The model solves the complete 2D SWEs written in integral form (Toro, 2001):

$$\frac{\partial}{\partial t}\int_A \mathbf{U}\,\mathrm{d}A + \int_C \mathbf{H}\cdot\mathbf{n}\,\mathrm{d}C = \int_A\left(\mathbf{S}_0 + \mathbf{S}_f\right)\mathrm{d}A \tag{1}$$

where t is the time, A and C are the area and boundary of the integration volume, respectively, $\mathbf{U}$ is the vector of conserved variables, $\mathbf{H} = (\mathbf{F},\mathbf{G})$ is the tensor of fluxes in the x and y directions, $\mathbf{n}$ is the outward unit vector normal to C, while $\mathbf{S}_0$ and $\mathbf{S}_f$ are the bed slope and friction source terms, respectively. In order to obtain a well-balanced scheme, the terms $\mathbf{U}$, $\mathbf{F}$ and $\mathbf{G}$, $\mathbf{S}_0$ and $\mathbf{S}_f$ are defined according to the formulation of Liang and Marche (2009), as follows:

$$\mathbf{U} = \begin{bmatrix} \eta \\ uh \\ vh \end{bmatrix},\quad \mathbf{F} = \begin{bmatrix} uh \\ u^2h + \frac{1}{2}g(\eta^2 - 2\eta z) \\ uvh \end{bmatrix},\quad \mathbf{G} = \begin{bmatrix} vh \\ uvh \\ v^2h + \frac{1}{2}g(\eta^2 - 2\eta z) \end{bmatrix},$$

$$\mathbf{S}_0 = \begin{bmatrix} 0 \\ -g\eta\dfrac{\partial z}{\partial x} \\ -g\eta\dfrac{\partial z}{\partial y} \end{bmatrix},\quad \mathbf{S}_f = \begin{bmatrix} 0 \\ -gh\dfrac{n_f^2 u\sqrt{u^2+v^2}}{h^{4/3}} \\ -gh\dfrac{n_f^2 v\sqrt{u^2+v^2}}{h^{4/3}} \end{bmatrix} \tag{2}$$

where h is the flow depth, z is the bed elevation, and $\eta = h + z$ is the water surface elevation; moreover, u and v are the velocity components along the x and y directions, respectively, g is the acceleration due to gravity, and n_f is Manning's roughness coefficient.

Equations 1 and 2 are discretized using an explicit FV scheme, and both first- and second-order accurate approximations in space and time ~~are available.~~can be selected in the PARFLOOD model. The adoption of a depth-positive MUSCL extrapolation at cell boundaries (Audusse et al., 2004) with the *minmod* slope limiter, and the second-order Runge-Kutta method ensures the second-order accuracy in space and time, respectively. Flux computation is performed using the HLLC approximate Riemann solver (Toro, 2001), and the correction proposed by Kurganov and Petrova (2007) to avoid non-physical velocity values at wet/dry fronts is applied. Finally, the slope source tem is discretized by means of a centered approximation (Vacondio et al., 2014), while for the friction source term the implicit formulation proposed by Caleffi et al. (2003) is adopted.

The computational grid can be either Cartesian or Block Uniform Quadtree (BUQ, see Vacondio et al., 2017), that is a non-uniform structured mesh.

With the aim of reducing the computational times, the code is written in Compute Unified Device Architecture (CUDA) language ~~that is~~, i.e. a framework for GPU-based parallel computing introduced by NVIDIA™. This high-level language allows for the exploitation of both hardware resources: the CPU (the host) and the GPU (the device). The good computational performance of this code for field applications was assessed in previous works (Vacondio et al., 2016; Dazzi et al., 2018, 2019; Ferrari et al., 2018, 2019).

2.2 Topographic data and spatial resolution

When levee breach-induced floods in lowland areas are modelled, a high-resolution mesh is often necessary to describe the relevant terrain features typical of man-made landscapes (e.g. roads, railways, channels, embankments). High-resolution topographic information for large areas can be obtained from new remote sensing techniques, such as Light Detection and Ranging (LiDAR) and Shuttle Radar Topography Mission (SRTM), which provide raw data for the generation of digital terrain models (DTMs). LiDAR-based DTMs are nowadays available to public access for most flood-prone areas in Europe, and meshes derived from these data (even coarsened) often provide the most accurate results for flood modelling (Ali et al., 2015).

DTM grids can include billions of cells; however, the amount of cells (and thus the runtimes) can be decreased by performing a moderate downsampling (e.g. reducing the grid size from 0.5-1 m to 2-5 m) and by adopting non-uniform meshes, either unstructured (Liang et al., 2008; Saetra et al., 2015) or structured (Vacondio et al., 2017). In fact, in urban and suburban areas, the presence of road and railway embankments can influence the flood dynamics significantly, and the bathymetry near these elements should be at high resolution (2-5 m). On the other hand, for uniform rural areas a lower resolution (e.g. 10-50 m) can be used without impairing the overall accuracy.

It is relevant to notice that high-resolution DTMs can be exploited thanks to the availability of parallel 2D codes; until a few years ago, traditional 2D and 1D-2D models usually adopted a low resolution in the order of 50-100 m for flood-prone areas in order to reduce the computational times (Aureli and Mignosa, 2004; Aureli et al. 2006; Vorogushyn et al., 2010; Masoero et al., 2013; Mazzoleni et al., 2014; Huthoff et al., 2015).

2.3 Upstream/downstream boundary conditions

Discharge hydrographs with a specific return period are assigned as upstream boundary condition. Sometimes these hydrographs are already available from previous hydrological studies, and can be provided by local River Basin Authorities; otherwise, they can be derived from rainfall-runoff modelling or from statistical analyses of recorded discharge hydrographs (e.g. Tomirotti and Mignosa, 2017).

For the purpose of this study, multiple hydrological conditions should be considered, in order to cover possible configurations characterized by different breach triggering mechanisms, flood volumes, etc. At least two different discharge hydrographs should be considered for each breach location, even though the simulation database can be extended with more hydrological inputs if needed. The first case ("inflow A") corresponds to the condition for which the water surface elevation reaches the levee crest somewhere along the river, thus generating overtopping. The second configuration ("inflow B") concerns a flood event with a lower return period, for which the levee is never overtopped, but other mechanisms might induce the levee collapse. In fact, earthen levees can also experience breaching for piping and internal erosion processes, even when water levels remain below the levee crest. Besides, the dens of burrowing animals (e.g. porcupine, badger, nutria) were recently identified as another possible cause for breach triggering (Viero et al., 2013; Orlandini et al., 2015). Incidentally, the collapse of an embankment during a flood event with a relatively low return period can be very threatening for human lives because the highest warning thresholds may not be reached, and population can be unprepared to face flooding.

The choice of the return period for inflows A and B is river-dependent, because it is influenced by the design return period of the levee system, by the presence of other flood control structures, etc. In general, preliminary simulations of the propagation of flood waves with different return periods (e.g. 10, 20, 50, 100, 200, 500 years) for each river should be performed, and the event that corresponds to incipient overtopping can be identified as inflow A. Then, a higher frequency hydrograph can be selected as inflow B, in order to consider levee collapses due to piping or other mechanisms during a flood event that does not induce overtopping (for example, when a specific freeboard is guaranteed).

The discharge hydrographs thus obtained are imposed as upstream boundary condition for the levee breach scenarios. The downstream boundary condition also deserves special attention. In fact, downstream of the breach location, the discharge may reduce or even fall to zero and reverse, but the water depth does not necessarily reduce accordingly. Hydraulic gradient and inertia can play a significant role, and the stage-discharge relationships at downstream sections may be characterized by a strong loop effect (D'Oria et al., 2015). This leads to the suggestion that, if a single-valued rating curve is imposed as outflow boundary condition, it should be assigned at the farthest possible section downstream from the breach location.

2.4 Levee breaches location and modelling

Several breach locations must be identified along the river levees, so that a real event can be associated with one of the simulated scenarios. The distance between two consecutive breach positions should be selected considering the river dimensions, the presence of urban settlements, the flood-prone area topography, and the possible presence of roads and embankments influencing the inundation dynamics.

The description of the gradual opening of the levee breach must be somehow included in the 2D modelling, since the hypothesis of instantaneous break is not realistic for river embankments. Among the available approaches in the literature, which also include the coupling of the SWEs with a sediment transport model (Faeh, 2007), or with an erosion law (Dazzi et al., 2019), the simple "geometric" approach is selected in this work for two reasons. First, the uncertainties about the geotechnical parameters of the embankment and the complexity of the breaching process (three-dimensionality, interactions between erosion, infiltration, and bank stability, etc.) can be neglected. Second, this method was successfully applied to a real test case (Vacondio et al., 2016), and a similar approach is often adopted for 1D-2D coupled models, especially in the context of flood hazard assessment (e.g. Vorogushyn et al., 2010; Mazzoleni et al., 2014). Thus, in the RESILIENCE project the breach evolution is modelled by varying the local topography in time, assuming a trapezoidal opening that widens and deepens in time, from the crest of the embankment to the ground elevation, while the breach geometric dimensions (i.e. width) and opening time are imposed as input parameters.

The two breach parameters should be set consistently with historical data, if available (e.g. Nagy, 2006; Vorogushyn et al., 2010; Govi and Maraga, 2005), or hypothesized according to the river and embankment characteristics. A breach final width in the order of tens to hundreds of meters is often assumed in the literature (Apel et al., 2006; Kamrath et al., 2006). As for the breach development time, very few field observations are available, and values in the range 1-3 h are often reported (Apel et al., 2006; Alkema and Middelkoop, 2005). The impact of the parameters uncertainty on the results should be evaluated for at least one hydrological scenario, by means of a probabilistic treatment (Apel et al., 2006; Vorogushyn et al., 2010; Mazzoleni et al., 2014) or a sensitivity analysis (Kamrath et al., 2006; Huthoff et al., 2015).

For each breach location and return period, the triggering time for breach opening should be selected after preliminary simulations and corresponds to the moment when either overtopping or the peak water surface elevation is observed at the breach location.

Finally, simulations must be extended in time long enough to capture the flooding evolution in the lowland, which is actually the goal of the presented methodology. The selection of this temporal interval should be guided by considerations on the flood duration in the river, on the inundation dynamics, and on the fact that drainage operations and/or breach closure would start at some point.

2.5 Outputs

The outcomes of the modelled scenarios could help the civil protection activities for emergency planning and/or at the occurrence of an event similar to one of those already modelled. Arrighi et al. (2019) recently presented a framework that integrates hydrologic/hydraulic modelling with human safety and transport accessibility evaluations, applied to a small municipality near Florence (Italy), and confirmed the usefulness of detailed spatial and temporal flood data provided by numerical modelling for civil protection purposes. Thus, the first mandatory output concerns spatial and temporal information about the flood dynamics in the lowland area, which can be visualized as an animation of the inundation pattern or as a sequence of frames at selected times.

Other useful indicators for evaluating the flood severity for each scenario include the maps of arrival times of the wetting front, maximum water depths (and/or water surface elevations), maximum velocities, and of a hazard index which combines simultaneous water depth and velocity. In general, these maps can be opened in a GIS environment and overlapped with layers of data (e.g. about population, transportation, buildings, critical and vulnerable structures, etc.) to analyse the possible flood impacts on the territory, with the aim of increasing the resilience in the area. First, information about the maximum water depth allows for the definition of the affected areas, as well as the identification of escape routes and safety zones where assembly points can be organized. On the other hand, in areas where only shallow water levels can be expected, people can simply be instructed to protect their homes with anti-flood barriers to prevent water from damaging their property. Besides, analysis of the inundation dynamics can reveal possible service interruptions and disturbance to road accessibility, which can also prevent rescue operations; in this way, alternative routes can be identified.

Moreover, the maximum flow velocity map should not be neglected, because high velocities can reduce the stability of vehicles and pedestrians, increasing the hazard for human lives (Milanesi et al., 2015). In general, the most important results for quantifying the hazard for human lives are the maximum simultaneous water depth and velocity, which can be represented in terms of Froude number, total head, total force and/or total depth. This last indicator, which represents the water depth at rest *D* whose static force is equivalent to the total force of the flow, is evaluated as follows (Aureli et al., 2008; Ferrari at al., 2019):

$$D(t) = h(t)\sqrt{1 + 2Fr^2(t)} \qquad (3)$$

where $h(t)$ represents the water depth and $Fr(t)$ the Froude number at time t.

Finally, the map of the arrival times of the wetting front can be useful for early warning and for establishing the timeline for the evacuation procedures, in particular for vulnerable people (older adults, hospitalised patients, etc.). The off-line analysis of the simulation results, on the other hand, can help in the identification of possible strategies to reduce the damages, as for example the adoption of movable defence systems (e.g. flood barriers) to preserve lowland urban settlements from flooding or other emergency interventions to drain water (e.g. pumping, relief cuts). Selected strategies can also be tested numerically to verify their effectiveness.

~~3 Flooding scenarios induced by levee breaches: the RESILIENCE project~~

~~The RESILIENCE project aims at defining a new methodology for mapping flood scenarios due to levee breaches, which can be helpful for improving preparedness and supporting the development of technical and scientific tools for emergency planning and management, consistently with EU Flood Directive 2007/60/CE. Several breach locations along a leveed river are preliminarily identified, and multiple hydrological events, characterized by different frequency, are considered. 2D numerical simulations of the flood scenarios resulting from each combination of breach position and upstream boundary condition are performed, in order to create a large database of simulations covering any potential real levee breach event in that area in the best possible way. The results of these simulations, made available to public administrations, can be fundamental not only for emergency planning, but also for civil protection immediate action during actual flood events.~~

~~The~~3 Application of the RESILIENCE project to a pilot area ~~for this~~in Northern Italy

In this section, an example of application of the proposed methodology is presented. The pilot area for the RESILIENCE project (Figure 1) is at the boundary of two regions (Emilia-Romagna and Lombardia~~,~~), in Northern Italy~~)~~.. This territorial unit is about 1,100~~-~~ km^2 wide, and is delimited by the Po River (North) and by its two right tributaries Secchia (West) and Panaro (East). The city of Modena ~~restricts~~bounds the area to the South. This lowland area can be potentially affected by flooding events caused by breaches from the 83 km-long right levee of the Secchia River ~~(along the considered 83 km-long reach)~~ and/or from the 67 km-long left levee of the Panaro River ~~(along the modelled 67 km-long reach).~~ .

~~The pilot~~This study area was selected for several reasons. First, the latest report of the Italian Institute for Environmental Protection and Research (ISPRA, 2018) showed that Emilia-Romagna is the Italian region with the highest level of exposed population (up to 2.7 million exposed inhabitants out of 4.3), buildings and areas for both high (return period of 20-50 years) and medium (return period of 100-200 years) flood ~~hazard levels.~~frequency. Moreover, the middle-lower basin of the Po River was subject to levee breach-induced floods several times in the last 150 years, either from the main river levees or from its leveed tributaries (e.g. Di Baldassarre et al., 2009; Masoero et al., 2013; D'Oria et al., 2015; Dazzi et al., 2019), often with devastating consequences. ~~The~~Finally, the Secchia and Panaro rivers experienced levee breach events in the past, even without overtopping and during the occurrence of floods with low/medium return periods. In particular, the most recent event that occurred in ~~the pilot~~this area was the flood originated by a bank failure on the Secchia River in 2014 (Vacondio et al., 2016), which caused roughly 500 million euros losses. This event raised awareness of the huge damages caused by flooding and of the necessity of increasing flood preparedness in both public administrations and population.

~~In the following sections, the most important assumptions of the methodology concerning the spatial resolution, the hydrological conditions, the breach locations and modelling are discussed thoroughly. For each topic, both general guidelines and specific assumptions for the pilot area are provided. Moreover, the most relevant simulation outputs and their usefulness for civil protection purposes are described.~~

3.1 ~~Spatial resolution and~~ Setup

The computational ~~In the context of levee-breach induced flood modelling, a low resolution in the order of 50-100 m was usually assumed for flood-prone areas (~~domain was built based on the available 1 m-resolution DTM of the riverbeds and of the floodable lowlands derived from LiDAR surveys carried out in the years 2008, 2015 and 2016. In~~Vorogushyn et al., 2010; Masoero et al., 2013; Mazzoleni et al., 2014; Huthoff et al., 2015), due to the computational cost associated with traditional 2D and 1D-2D modelling. To date, however, both the parallelization of 2D codes (see Sect. 2.3) and the development of new remote sensing techniques, such as Light Detection and Ranging (LiDAR) and Shuttle Radar Topography Mission (SRTM), which provide raw data for digital terrain model (DTM) generation, allow the modellers to perform high-resolution simulations for large areas. A fine mesh is often necessary to describe all the relevant terrain features typical of man-made landscape (e.g. roads, railways, channels, embankments) in detail.~~

~~Several works investigated the influence of topographic data sources (e.g. Sanders, 2007; Cook and Merwade, 2009) and of the spatial resolution (Marks and Bates, 2000; Gallegos et al., 2009; Huthoff et al., 2015) on flood modelling, and showed that LiDAR-based DTMs (even coarsened) often provide the most accurate results (Ali et al., 2015).~~

~~Nowadays, high-resolution DTMs of most flood-prone areas are available to public access, representing a powerful tool for accurate flood modelling. In particular, the whole study area is covered by LiDAR surveys carried out in the years 2008, 2015 and 2016. The bathymetry here adopted was hence built based on the available 1 m-resolution DTMs of the riverbeds and of the floodable lowlands. However, in~~ order to avoid the excessive memory requirements and heavy computational costs (even for a fast GPU-parallel model), related to the adoption of a uniform 1 m mesh (which would require billions of cells), the DTM was downsampled to a resolution of 5 m. This operation did not affect the crest elevation of the artificial embankments. In fact, each 5×5 m cell crossed by an embankment was identified, and its elevation was set equal to the maximum value among the original 25 points belonging to that cell; otherwise, its elevation was simply computed as the average of the 25 terrain data comprised in that cell. For other urban features that were not captured correctly~~ captured~~ by the LiDAR survey, additional corrections were introduced manually.

~~In order to further decrease~~Then, the ~~amount~~study domain was discretized by means of ~~computational cells and thus the runtimes (still retaining the same level of accuracy), the adoption of non-uniform meshes, both unstructured (Liang et al., 2008; Saetra et al., 2015) and structured (Vacondio et al., 2017), should be taken into consideration. In urban and suburban areas, the presence of road and railway embankments can influence the flood dynamics significantly, and the bathymetry near these elements should be at high resolution. On the other hand, for uniform rural areas a lower resolution can be used without impairing the overall accuracy. Therefore,~~ a non-uniform BUQ grid~~ with the finest resolution equal to 5 m was adopted in this work. The~~: the maximum resolution (5 m) was forced along the riverbed, the levees, the main artificial embankments and channels, and at the breach location, whereas for rural areas it gradually decreased up to 40 m according to the algorithm presented by Vacondio et al. (2017). The resulting computational grid~~, which is shown in~~ (Figure 2~~, consists of roughly 13·10^6 cells, and the number of cells is reduced by approximately 70% compared with a uniform 5 m-mesh. This~~), whose spatial resolution is considered suitable for the detailed modelling of the river and the lowland area, consists of roughly 13·10^6 cells, and the number of cells is reduced by approximately 70% compared to a uniform 5 m-mesh. ~~However, the~~The study area also includes several urban settlements: Modena, with ~~around~~about 185,000 inhabitants, is the most populated one, and its old city centre comprises narrow streets, which cannot be accurately described with a 5 m resolution. Therefore, limited to the few scenarios concerning the flooding of Modena, simulations were performed ~~by increasing the resolution~~using a finer mesh (up to 2.5 m) in the town~~ up to 2.5 m~~, and ~~by describing~~ the urban layout ~~in detail~~was modelled according to the "building hole" method (Schubert and Sanders, 2012), in order to capture the flow field inside the urban area correctly.

Buildings were explicitly resolved only for the city of Modena, whereas, according to previous findings (Vacondio et al., 2016), the presence of the other (smaller) settlements was taken into account by means of a higher resistance parameter ("building resistance" method, Schubert and Sanders, 2012). In particular, the roughness coefficient for the urban areas was calibrated based on the event occurred in 2014 (the flood arrival times at selected locations were known), and was set equal to 0.14 m$^{-1/3}$ s, while for rural areas a Manning coefficient of 0.05 m$^{-1/3}$ s was chosen. In the absence of data for calibration concerning past flooding events, land use maps can be exploited to assign standard roughness values from the literature.

As for the river roughness, the calibration for the Secchia River was performed in previous works (Vacondio et al., 2016), based on the water levels recorded at the available gauging stations during recent flood events. A Manning coefficient equal to 0.05 $m^{-1/3}$ s provided the best results. The roughness of the Panaro River was also subject to calibration with a similar procedure, and the value 0.04 $m^{-1/3}$ s was selected.

3.2 Hydrological scenarios

As regards the selection of the hydrological

For the purpose of this study, multiple hydrological conditions should be considered, in order to cover possible configurations characterized by different breach triggering mechanisms, flood volumes, etc. The hydrological information is concentrated into inflow hydrographs with assigned frequency for each river. In the present application, only the two scenarios were modelled, but the simulation database can be extended with more hydrological inputs, if needed. The first case ("inflow A") corresponds to the condition for which the water surface elevation reaches the levee crown somewhere along the river, thus generating overtopping. The second configuration ("inflow B") concerns a flood event with a lower return period, for which the levee is never overtopped, but other mechanisms might induce the levee collapse. In fact, earthen levees can also experience breaching for piping and internal erosion processes, even when water levels remain below the levee crown. Besides, the dens of burrowing animals (e.g. porcupine, badger, nutria) were recently identified as another possible cause for breach triggering (Orlandini et al., 2015). Incidentally, the collapse of an embankment during a flood event with a relatively low return period can be very threatening for human lives because the highest warning thresholds may not be reached, and population can be unprepared to face flooding.

The choice of the return period for inflows A and B is river-dependent, because it is influenced by the design return period of the levee system, by the presence of other flood control structures, etc. For the rivers considered in this study, the inflow hydrographs with assigned return period, the Synthetic Design Hydrographs (Tomirotti and Mignosa, 2017) were provided by the Po River Basin Authority, and were assigned as upstream boundary condition. Preliminarywith assigned return periods were considered. After preliminary simulations of the propagation of these hydrographs were performed for both rivers. Results showed that inflow A corresponded to, inflow A (overtopping-induced flooding) was identified as the 50 years-return period hydrograph for the Secchia River, and toas the 100 years-one for the Panaro River. As for inflow BThen, the inflow hydrograph with 20 years-return period was selected as inflow B for both rivers, in order to consider an event with high hazard level. higher frequency. These discharge hydrographs were assumed as upstream boundary conditions during the simulations.

The downstream boundary condition could be affected by the opening of a levee failure, and deserves special attention. In fact, downstream of the breach location, the discharge may reduce or even fall to zero and reverse, but the water depth does not necessarily reduce accordingly. Hydraulic gradient and inertia can play a significant role, and the stage-discharge relationships at downstream sections may be characterized by a strong loop effect. This leads to the suggestion that, if a

~~single-valued rating curve is imposed as outflow boundary condition, it should be assigned at the farthest possible section downstream from the breach location. For all the considered scenarios, the~~The downstream section was located at the confluence (of the Secchia and Panaro rivers, respectively) into the Po River, and a constant water level in this (much larger) river, which did not affect the breach outflow even for the most downstream breach location, was assumed as boundary condition.

~~3.3 Levee breaches location and modelling~~

~~Several breach locations were identified along the two~~As mentioned before, the pilot area can be flooded by hypothetical failures occurring along the Secchia and Panaro rivers~~, so that a possible actual event can be associated to the closest simulated scenario. The pitch between two consecutive breach positions should be selected considering the river dimensions, the presence of urban settlements, the flood-prone area topography, and the possible presence of roads and embankments influencing the inundation dynamics. In the present study, the breach locations were assumed at~~. Assuming a distance of about 2 km from ~~each~~ one breach to the other, ~~approximately. As a result,~~ 30 breach ~~positions~~locations were ~~selected on~~identified along the right levee of the Secchia River (for the flooding scenarios related to this river), ~~while~~and 26 ~~were identified~~ones along the left levee of the Panaro River. Figure 1 reports all the 56 simulated breach sites. Among these, 8 breach scenarios on the Secchia River and 4 on the Panaro River involve the city of Modena. Based on past observations, the breach final width was assumed equal to 100 m for all scenarios, while the opening time was set equal to 3 or 6 h for inflows A and B, respectively.

~~The hypothesis of instantaneous break is not realistic for river embankments; hence,~~All the ~~description of the gradual opening of the levee breach must be somehow included in the 2D modelling. Among the available approaches in the literature, which also include the coupling of the SWEs with a sediment transport model (Faeh, 2007), or with an erosion law (Dazzi et al., 2019), the "geometric" approach is selected in this work. The breach opening is described by varying the local topography in time, assuming a trapezoidal shape and imposing the breach geometric dimensions and failure time as input parameters. This method was successfully applied to a real test case (Vacondio et al., 2016). A similar approach is often adopted for 1D-2D coupled models, especially in the context of flood hazard assessment (e.g. Vorogushyn et al., 2010; Mazzoleni et al., 2014). Given the uncertainties about the geotechnical parameters of the embankment and the complexity of the breaching process (three-dimensionality, interactions between erosion, infiltration, and bank stability, etc.), this simple "geometric" approach can be considered adequate for the purpose of this study.~~

~~The breach model parameters should be consistent with historical data, if available (e.g. Nagy, 2006; Vorogushyn et al., 2010; Govi and Maraga, 2005), or otherwise they should be identified according to the river and embankment characteristics. A breach final width in the order of tens to hundreds of meters is often assumed in other works (Apel et al., 2006; Kamrath et al., 2006), and the uncertainty in its value is sometimes considered with a probabilistic treatment (Apel et al., 2006; Vorogushyn et al., 2010; Mazzoleni et al., 2014) or a sensitivity analysis (Kamrath et al., 2006; Huthoff et al., 2015). As for the breach development time, very few field observations are available, and often values in the range 1-3 h are assumed~~112 simulations (56 breach locations and 2 hydrological scenarios) (Apel et al., 2006; Alkema and Middelkoop, 2005). In this work, based on past observations, each breach was modelled with a trapezoidal shape that widened and deepened in time, from the crest of the embankment to the ground elevation, reaching a 100 m maximum width after 3 or 6 h for inflows A and B, respectively.

For each breach location and return period, the trigger time for breach opening was selected after preliminary simulations, and corresponded to the moment when either overtopping or the peak water surface elevation was observed at the breach location.

In general, simulations must be extended in time long enough to capture the flooding evolution in the lowland, which is actually the goal of the presented methodology. The selection of this temporal interval should be guided by considerations on the flood duration in the river, on the inundation dynamics, and on the fact that drainage operations and/or breach closure would start at some point for an actual event. For the rivers in the pilot area here considered, all simulations were prolonged for 72 h (3 days), because at that point the outflow from the breach was almost null, the flooded area had reached its maximum extension, and no significant change in the flow dynamics couldcan be observed.

3.4 Results 2 Outcomes

In this Section, some results of the application of the RESILIENCE methodology to the pilot area are presented. Since 56 breach locations and 2 hydrological scenarios were considered, the database for this area currently includes the results of 112 simulations. As already discussed, the outcomes of these scenarios could help the civil protection activities for emergency planning and/or at the occurrence of an event similar to one of those already modelled. Arrighi et al. (2019) recently presented a framework that integrates hydrologic/hydraulic modelling with human safety and transport accessibility evaluations, applied to a small municipality near Florence (Italy), and confirmed the usefulness of detailed spatial and temporal flood data provided by numerical modelling for civil protection purposes. Thus, the first mandatory output concerns spatial and temporal information about the flood dynamics in the lowland area, which can be visualized as an animation of the inundation pattern or as a sequence of frames at selected times. An example of video showing the flooding evolution for one scenario on the Secchia River will be provided as additional material.

Other useful indicators for evaluating the flood severity for each scenario include the maps of flood arrival times, maximum water depths (and/or water surface elevations), maximum velocities, and of a hazard index which combines simultaneous water depth and velocity. Figure 3 shows an example of these results for one scenario on the Secchia River. In general, these maps can be opened in a GIS environment and overlapped with layers of data (e.g. about population, transportation, buildings, critical and vulnerable structures, etc.) to analyse the possible flood impacts on the territory, with the aim of increasing the resilience in the area. First, information about the maximum water depth allows for the definition of the affected areas, as well as the identification of escape routes and safety zones where assembly points can be organized. For example, the water depth mapFigure 3 shows an example of the results for one scenario on the Secchia River. The maps of maximum water depths shown in Figure 3a reveals that the flooding involves the northern portion of the domain, partially affecting some urban settlements (S. Possidonio, Mirandola), while villages at east are safe from this inundation and could temporarily host the evacuated population. The maximum~~On the other hand, in areas where only shallow water levels can be expected, people can simply be instructed to protect their homes with anti-flood barriers to prevent water from damaging their property. Besides, analysis of the inundation dynamics can reveal possible service interruptions and disturbance to road accessibility, which can also prevent rescue operations; in this way, alternative routes can be identified.~~

~~Moreover, the maximum flow velocity map should not be neglected, because high velocities can reduce the stability of vehicles and pedestrians, increasing the hazard for human lives (Milanesi et al., 2015). In the study area, the~~ velocity magnitude (Figure 3b) remains below 1 m s^{-1}, except for the surroundings of the breach, and close to some road embankments that are overtopped by water (see detail in Fig. 3b), where drivers can be in grave danger. ~~In general, the most important results for quantifying the hazard for human lives are the maximum simultaneous~~ The combination of water depth and velocity~~, which can be represented in terms of Froude number, total head, total force and/or total depth. This last indicator, which represents the water depth at rest *D* whose static force is equivalent to the total force of the flow, is evaluated as follows (Aureli et al., 2008b; Ferrari at al., 2019):~~

$$D = h\sqrt{1 + 2Fr^2} \qquad (3)$$

~~where *h* represents the water depth and *Fr* the Froude number. For this scenario~~ (Figure 3c~~),~~) highlights that lowland areas are mostly affected with low (green, 0 ≤ D < 0.5 m) and medium (yellow, 0.5 m ≤ D < 1 m) total depth values, even if higher values (orange, 1 m ≤ D < 1.5 m, ~~-~~and red, D ≥ 1.5 m) are reached where high water depths are observed.

~~Finally, the~~The map of flood arrival times~~ can be useful for early warning and for establishing the timeline for the evacuation procedures, in particular for vulnerable people (older adults, hospitalised patients, etc.). For instance, the map~~ in Figure 3d shows that, for this scenario, approximately 45% of the flooded area is affected 24 h after the breach opening (purple contour line), guaranteeing a considerable amount of time for emergency activities. It is relevant to notice that also during the levee breach occurred in 2014 on the Secchia River (Vacondio et al., 2016) one of the most affected villages was flooded the day after the opening, but no countermeasures were taken at that time, since *a priori* knowledge of the ~~flooding dynamics was not available.~~ inundation dynamics was not available. Finally, a video showing the flooding evolution for this scenario is provided as additional material.

~~The off-line analysis of the simulation results, on the other hand, can help in the identification of possible strategies to reduce the damages, as for example the adoption of movable defence systems (e.g. flood barriers) to preserve lowland urban settlements from flooding or other emergency interventions to drain water (e.g. pumping, relief cuts). Selected strategies can also be tested numerically to verify their effectiveness.~~

In addition to the maps representing specific hydraulic indicators for each scenario, further information can be obtained by analysing the results of the whole database. In particular, the most affected parts in the pilot area and those never hit by flooding can be investigated. Therefore, for both inflows A and B, the maps of the inundated ~~area~~areas were combined in order to quantify the number of scenarios affecting each computational cell in the domain. ~~An example of~~Figure 4 shows the resulting map for inflow B~~ is shown in Figure 4:~~: in this case, about 50% of the pilot area is affected by at least one breach scenario. In particular, two areas can be identified as most affected by the possible flooding induced by levee breaching, since up to 21 breach scenarios (from both the Secchia and the Panaro River) involve these ~~areas~~regions. On the other hand, it can be observed that there is a large zone, in the middle of the pilot area, that is not affected by any of the considered breach scenarios thanks to the favourable terrain topography~~,~~; hence, it is potentially recommended for evacuation purposes (e.g. organization of assembly points).

4 Discussion

~~The~~Due to climate change and population growth, structural protection systems such as levees have been often adopted to increase protection against floods. However, this kind of defence presents several ecological (e.g. hydraulic decoupling between the river and its floodplain, loss of biodiversity, change in groundwater levels, increase in greenhouse gas emission) and socio-economic consequences (Auerswald et al., 2019).

Focusing on the “levee-effect” phenomenon and on the issue of adequately considering the residual flood risk related to levees, the main goal of this paper was to define a methodology based on the use of numerical models to enhance the resilience of lowland areas in case of levee breach ~~occurrences~~occurrence. The procedure, which requires the numerical simulation of ~~a large number of~~many scenarios with different breach locations and hydrological inputs, is applicable to~~ other~~ lowland areas protected from flooding by river levees, which can be inundated in case of embankment collapse.

In the context of emergency planning, the creation of a large database of scenarios represents the main alternative solution when real-time simulations cannot be performed (e.g., when weather forecast systems or direct measurements are missing or simply cannot provide reliable predictions of the incoming flow hydrograph in small river basins). This means that, when a flooding event occurs, the results of the closest simulated ~~scenarios~~scenario can be accessed in order to predict the inundation pattern and to better organize the civil protection activities and take timely countermeasures. Besides these emergencies, the results of each simulation, also combined for global considerations, allow for an improvement of evacuation and defence system planning. In this context, advanced optimization-based tools and algorithms (Dulebenets et al., 2019a,b) can be exploited to create emergency evacuation plans that efficiently minimize individuals travel time during a natural hazard.

Moreover, ~~these tools~~the simulation results can be useful for updating the alert systems, as well as for the dissemination of the correct behaviour to local inhabitants. In the framework of adaptation management, recently, the LIFE PRIMES project (Life Primes, 2019) contributed to building resilient communities in other areas in the Emilia Romagna region, by raising their awareness and proactive participation in the operations of early warning.

In this framework, the availability of high-resolution ~~meshes~~DTMs, which can describe the local terrain features in detail, represents a relevant tool. ~~Moreover~~Focusing on numerical modelling, the adoption of a fully 2D-SWE model was claimed not only for capturing the complex hydrodynamic field near the breach, but also the wet/dry fronts propagation over an irregular topography. The only drawback of this kind of models, which is the long computational time, was overcome by taking advantage of a parallelized code, such as PARFLOOD. Simulations were performed using a NVIDIA® Tesla® P100 GPU. Runtimes range approximately between 1 and 5 h, depending on the extent of the flooded area. The ratio of physical time to computational time is between 15 and 80, and confirms the high efficiency of GPU-accelerated codes for flood simulation, even for large high-resolution domains. If HPC clusters equipped with 20 to 50 GPUs could be exploited, the simulation of the whole database of 112 scenarios would only require 18 to 9 h of computation, assuming an average runtime of 3 h.

With reference to the assessment of flooding scenarios involving urban settlements, the use of a fully 2D model and a high-resolution mesh is required. In particular, a grid size in the order of 2-3 m becomes crucial when dealing with historical towns. Evidence of this requirement is shown in Figure 5 as regards the potential flooding of the city of Modena, whose urban layout was modelled with a 2.5 m-resolution mesh using the "building hole" approach. The backwater effect caused by buildings and the high flow velocities (>1 m s^{-1}) along some streets can be observed. Near the historical centre, streets are very narrow, and the complex hydrodynamic field could hardly be captured using a coarser mesh.

Still focusing on topographic information and spatial resolution it is relevant to notice that drainage networks with relatively narrow channels were not described in detail in the computational grid. In fact, even though microtopography (i.e. tillage feature, ditches) determines preferential pathways for very shallow flows (Viero and Valipur, 2017; Hailemariam et al., 2014), the maximum discharge through the breaches here considered (in the order of 10^2 m^3/s) largely exceeds the discharge capacity of the drainage systems. Moreover, most of the minor channels are equipped with sluice gates that are kept closed during river floods, preventing the drainage of the flooded volume until the end of the event. As a result, these networks were not expected to contribute to the flood dynamics significantly, and hence they were neglected in the terrain description.

Finally, it must be stressed that the database should be updated periodically to take into account possible significant changes to the landscape (i.e. construction/removal of relevant embankments) that are expected to affect the flood dynamic (Viero et al., 2019).

Further considerations are required about the assumptions concerning the levee breach locations and dimensions for the simulated scenarios. First, focusing on the selection of the breach position, a distance of about 2 km between two consecutive sites was chosen. This pitch represents a compromise between the number of simulations to be performed (not so much for reducing the computational time, as for achieving a "manageable" number of scenarios for output analysis) and the possibility of capturing all the inundation patterns. In fact, while two close breaches often generate similar flooded areas, sometimes the flooding evolution may change dramatically even for relatively close breaches. As an example, Figure 6 compares the inundated areas for two breach scenarios on the Secchia River, which are remarkably different: in the first case, the lowland area towards the east is involved, whereas due to the terrain morphology for the breach site immediately downstream, the flooding moves northwards. due to the terrain morphology. This phenomenonbehaviour confirms that the levee breach locations should be carefully considered.

As regards the geometrical parameters assumed for the breach evolution, a sensitivity analysis on the breach final width and opening time was carried out, and the results for a given breach location on the Secchia River (see Fig. 3) are reported in Table 1 for inflows A and B. Maintaining the reference opening time *T* (3 h for inflow A and 6 h for inflow B), additional tests were performed by varying the assumed final width *L* (100 m) by ±30% (*L* = 70, 130 m). As regards the opening time, ±50% variations were explored (i.e. *T* = 1.5, 4.5 h for inflow A, and *T* = 3, 9 h for inflow B), considering a fixed value for the breach width (*L* = 100 m). ~~The sensitivity analysis aimed at investigating the effects of the values assumed for these two parameters on the flooding of lowland areas. Therefore, the~~The total volume flowing out of the breach and the extent reached by flooding at fixed times (24, 48 and 72 h after the breach opening) were used for comparing the different configurations. As expected, the results show that a larger breach, as well as a reduced opening time, slightly increases the flooded volume and area. However, the relative differences against the baseline simulation remain always below 10%: this confirms that the flooding scenarios are only marginally (less than linearly) influenced by the values assumed by these parameters.

Moreover, considering constant breach parameters (*L* = 100 m, *T* = 3 h), data reported in Table 1 also give an idea about the influence of the inflow condition on flooding results for this scenario: unsurprisingly, the total flooded volume for inflow B is 22% lower compared to inflow A, but the final flooded area is only 10% smaller. This means that breaching during a flood event with higher return period generates a more severe inundation on the lowland (i.e. higher water depths), while the affected area may be somewhat less influenced due to the terrain morphology and to the possible presence of obstacles that limit the flood propagation. This outcome is encouraging for the purpose of this work, because even for an actual flood event, whose inflow hydrograph can be quite different from the design hydrograph with assigned return period used for creating the database, at least the area possibly hit by flooding may be identified reasonably.

In this study, scenarios are not associated to their probability of occurrence, i.e. all breach locations are considered equally probable. This is consistent with the purpose of the methodology. However, if the same database of simulations had to be exploited for flood hazard (or even flood risk) assessment in the same area, information about the failure probability of the levee for each scenario would be required. This probability can be estimated by means of "fragility curves" for different levee failure mechanisms (Apel et al., 2006; Vorogushyn et al., 2010; Mazzoleni et al., 2014; Pinter et al., 2016), sometimes called "levee failure functions", which depend both on the water level in the river and on the levee geometrical and geotechnical characteristics (often unknown). This analysis is beyond the scope of this paper, and is left to future developments.

5 Conclusions

With the aim of enhancing the resilience of lowland ~~rivers~~areas in case of levee breach ~~occurrences~~occurrence, this paper defined a methodology for creating a database of hypothetical flood scenarios obtained from 2D numerical modelling, associated with different hydrological configurations and breach locations. The procedure, named RESILIENCE, was applied to a pilot area of about 1,100 km^2 in Northern Italy, but it can be extended to any other leveed river. The computational efficiency ensured by the adoption of the PARFLOOD parallel code allowed for the use of a high-resolution mesh (up to 2.5-5 m), while ratios of physical to computational time up to 80 were reached for some simulations. The application of numerical models to predict the flood dynamics provides useful data for emergency planning and management, and represents a fundamental tool for civil protection purposes and for increasing flood preparedness. Future developments of the methodology include: the expansion of the current database for the pilot area (e.g. other hydrological inputs, breaching along the Po River, multiple breach openings), the identification of the most probable failure locations, and the application of the RESILIENCE procedure to other rivers and lowland areas. Finally, support and assistance will be provided to public administrations for the correct interpretation and employment of the simulation results during civil protection planning.

6 Acknowledgments

This work was financially supported by the Territorial Safety and Civil Protection Agency of Emilia-Romagna Region (Agenzia per la ~~sicurezza territoriale~~Sicurezza Territoriale e la ~~protezione civile) of~~Protezione Civile della Regione Emilia~~-~~Romagna~~ region.~~). The Interregional Agency for the Po River (Agenzia Interregionale per il fiume Po) and the Po River Basin Authority (Autorità di Bacino distrettuale del fiume Po) are gratefully acknowledged for providing data for the Secchia and Panaro Rivers. ~~This research benefits from the HPC (High Performance Computing) facility of the University of Parma.~~ The publication of this paper is financially supported by the Center for Studies in European and International Affairs (CSEIA) of the University of Parma under the OPEN-UP (Outgoing Publications, Essays and Networks) call. This research benefits from the HPC (High Performance Computing) facility of the University of Parma. This work was partially supported by Ministry of Education, Universities and Research under the Scientific Independence of young Researchers project, grant number RBSI14R1GP, CUP code D92I15000190001.

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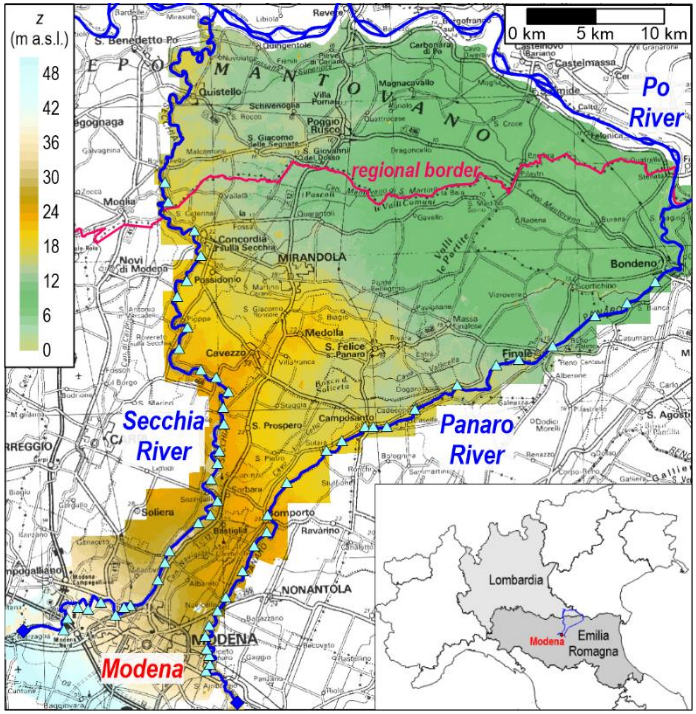


Figure 1. Map of the pilot area (Emilia-Romagna and Lombardia regions, Northern Italy): rivers are represented in blue; the breach locations along the Secchia and Panaro Rivers are indicated as triangles in cyan~~, while the blue diamonds identify the flood control reservoirs~~; the terrain elevation contour map is also depicted in background.

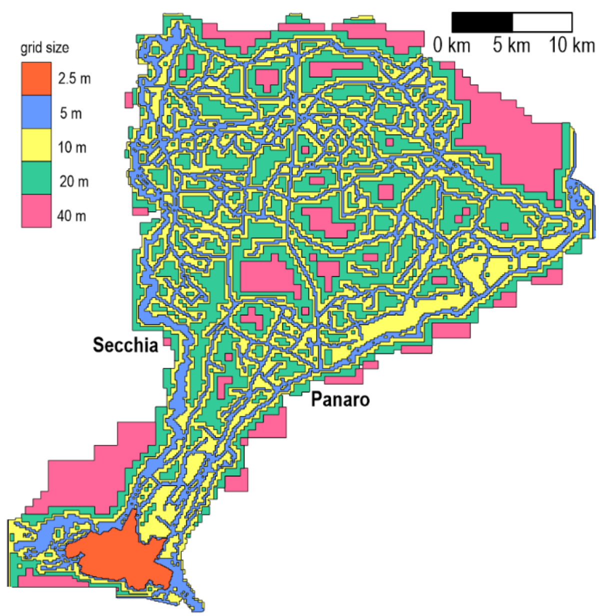
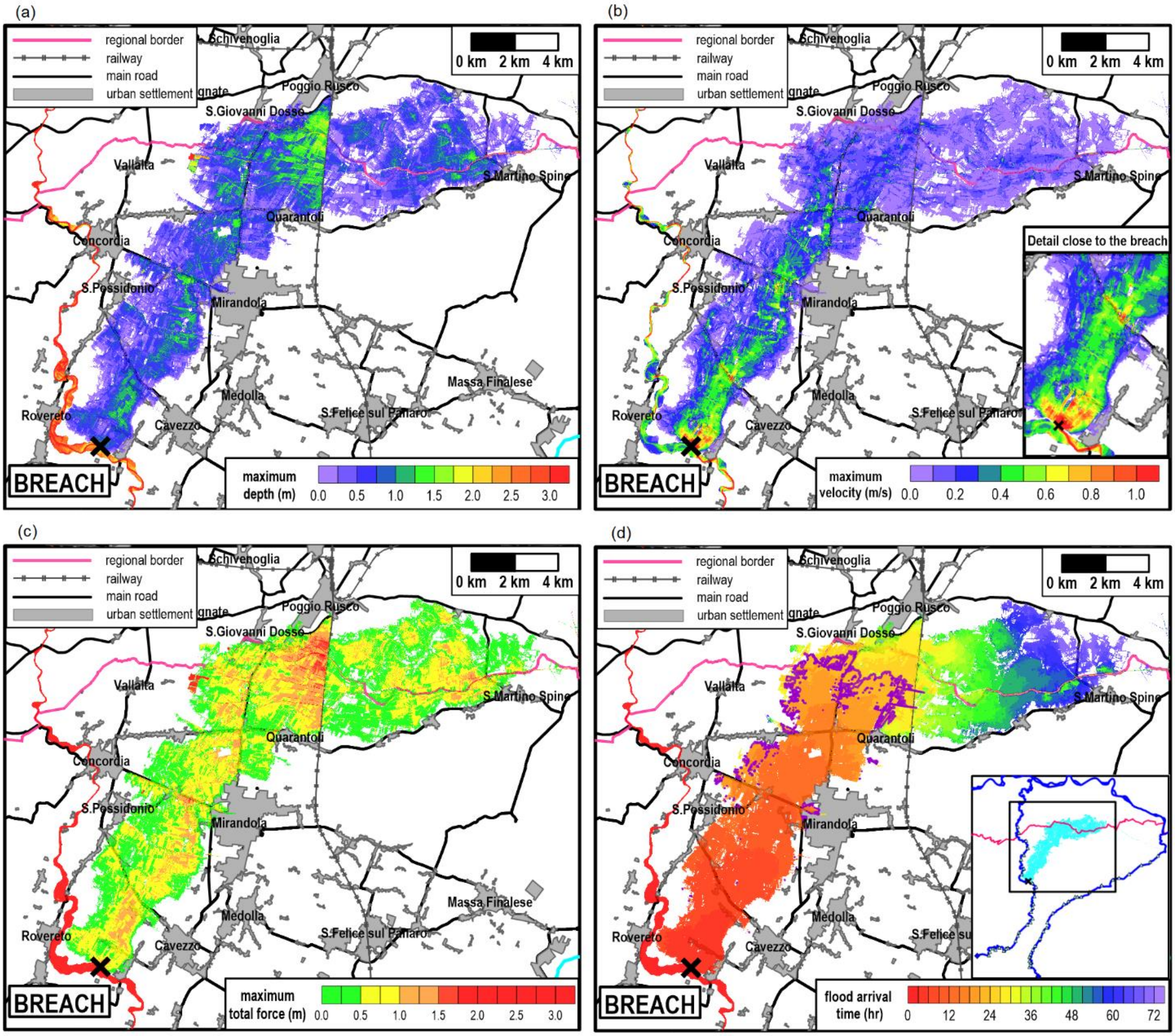


Figure 2. Multiresolution computational grid for the pilot area.


(a)
regional border
railway
main road
urban settlement
0 km 2 km 4 km
Schivenoglia
Poggio Rusco
S.Giovanni Dosso
Vallalta
S.Martino Spino
Quarantoli
Concordia
S.Possidonio
Mirandola
Massa Finalese
Medolla
S.Felice sul Panaro
Rovereto
Cavezzo
BREACH
maximum depth (m)
0.0 0.5 1.0 1.5 2.0 2.5 3.0
(b)
Detail close to the breach
maximum velocity (m/s)
0.0 0.2 0.4 0.6 0.8 1.0
(c)
maximum total force (m)
0.0 0.5 1.0 1.5 2.0 2.5 3.0
(d)
flood arrival time (hr)
0 12 24 36 48 60 72

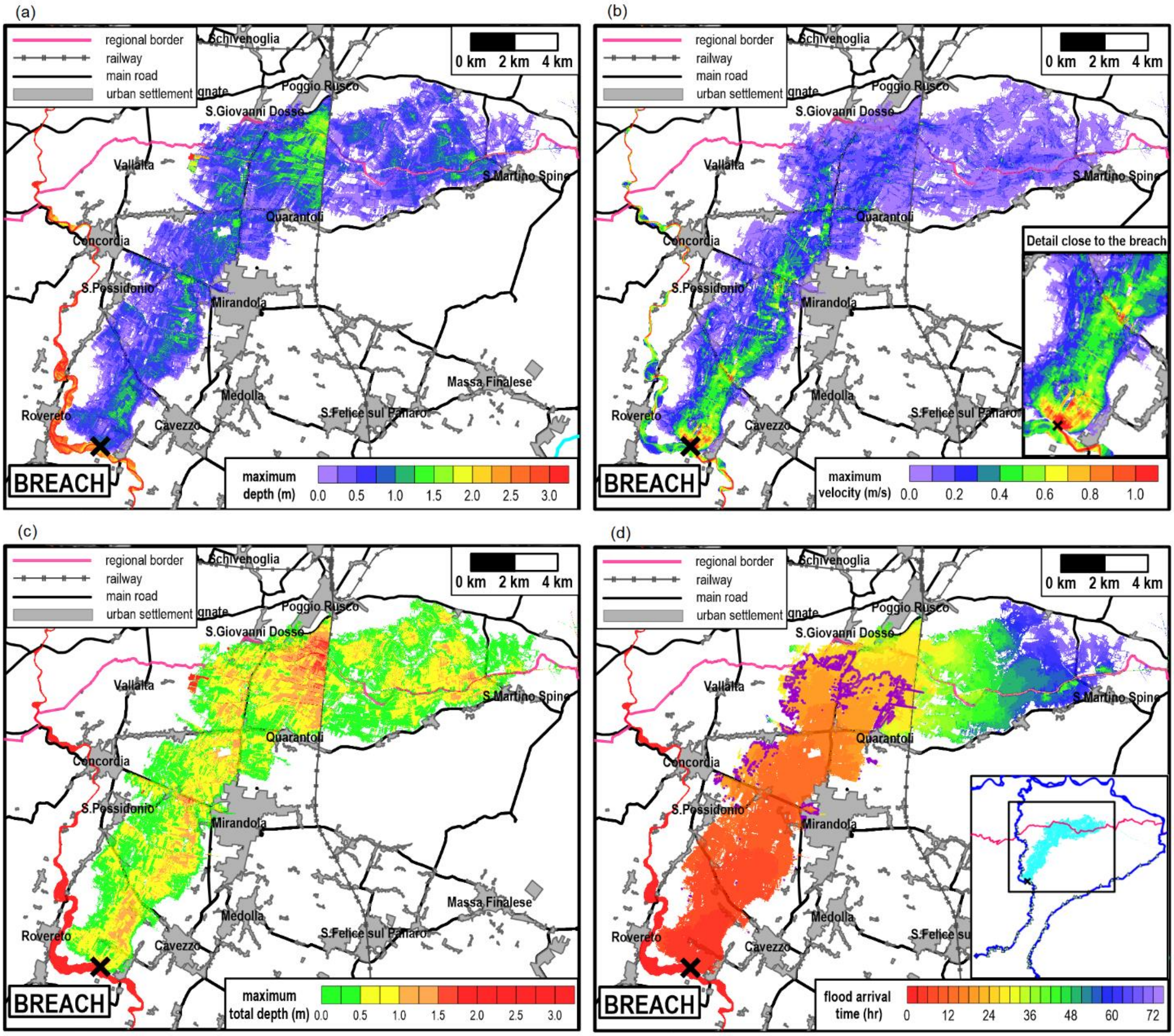


Figure 3. Example of the resulting maps concerning the maximum (a) water depth, (b) velocity, (c) total ~~force~~depth and (d) flood arrival time for a given scenario on the Secchia River with inflow B. The main roads, railways, and urban settlements are identified, and the breach location is indicated with a black cross.

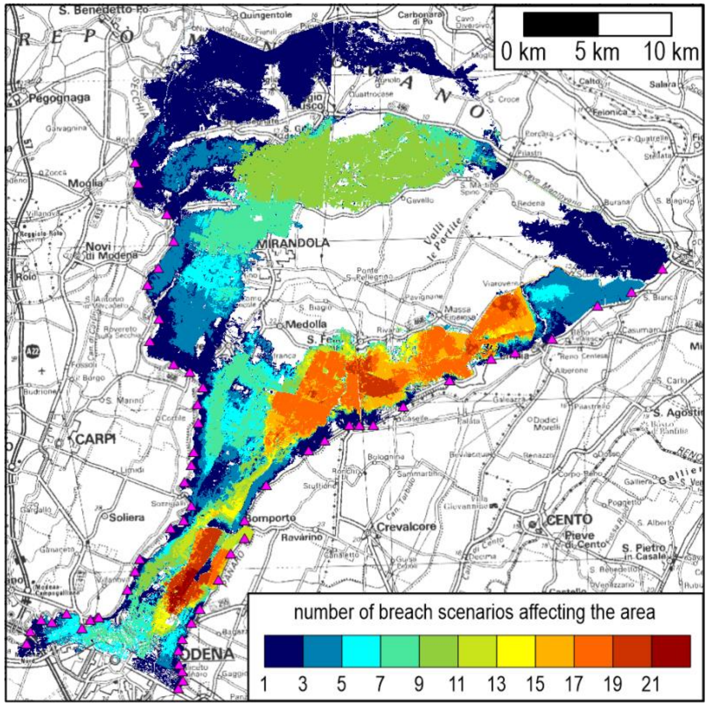


Figure 4. Number of flooding scenarios affecting each cell of the pilot area with inflow B. Two portions of the domain (in red) are flooded for 21 scenarios (from either the Secchia or the Panaro River), while the uncoloured zones are never inundated.

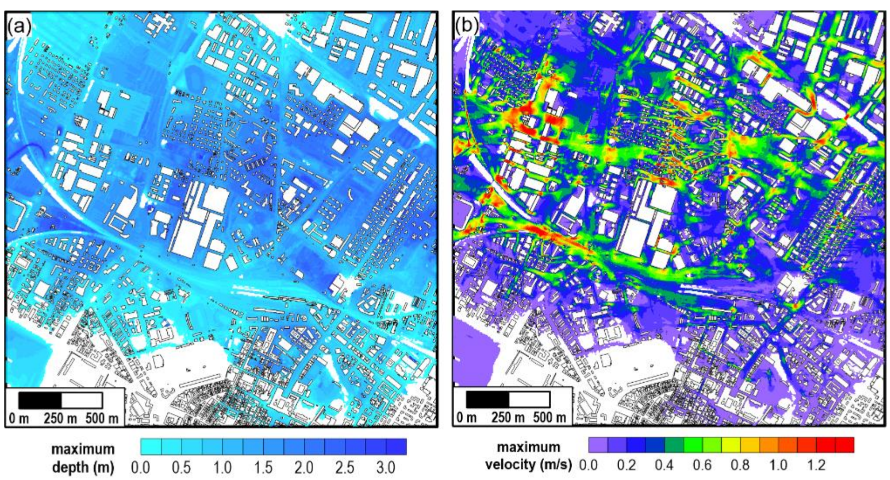


Figure 5. Detail of the complex hydrodynamic field in the city of Modena: maximum water (a) depth and (b) velocity for one breach scenario on the Secchia River.

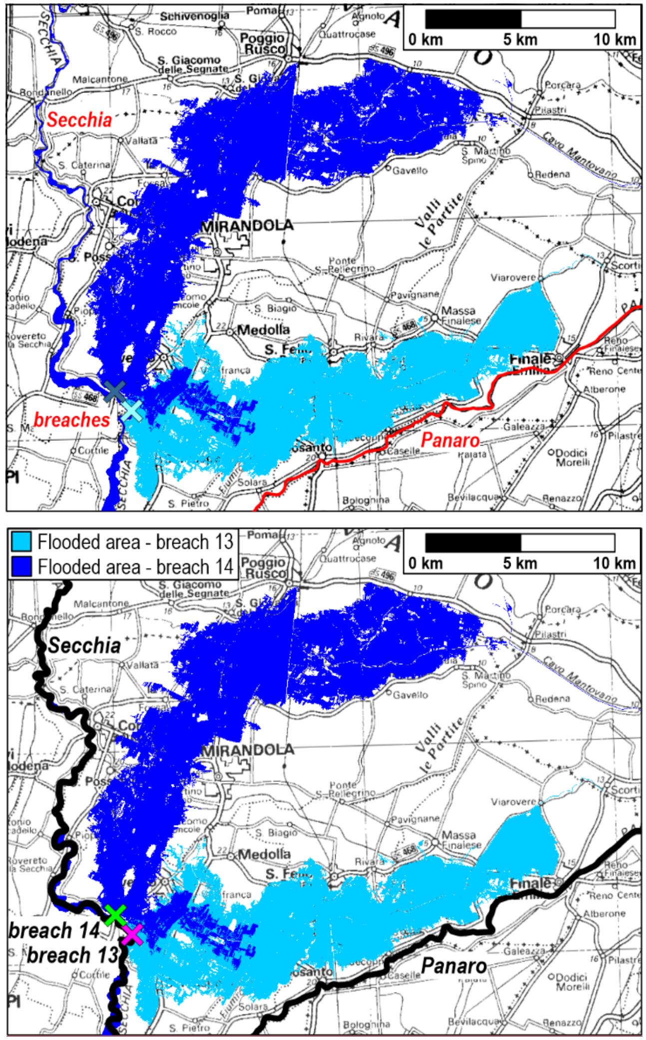


Figure 6. Example of the simulated flooded areas generated by two consecutive breaches (#13 and #14) on the Secchia River (the breach positions are indicated by crosses) for inflow B: the first breach scenario (cyan) mainly involves the eastern part of the domain, whereas the inundation for the second one (blue) moves northwards.

Inflow	***L*** **(m)**	***T*** **(h)**	***vol*** **(10^6 m^3)**	**Δ*vol*** **(%)**	***area***$_{24}$ **(km^2)**	**Δ *area***$_{24}$ **(%)**	***area***$_{48}$ **(km^2)**	**Δ *area***$_{48}$ **(%)**	***area***$_{72}$ **(km^2)**	**Δ *area***$_{72}$ **(%)**
A	100	3	52.75		68.04		99.08		117.20	
A	70	3	48.35	-8%	63.52	-7%	93.89	-5%	111.99	-4%
A	130	3	55.09	4%	70.11	3%	101.55	2%	120.29	3%
A	100	1.5	54.31	3%	69.53	2%	100.55	1%	119.05	2%
A	100	4.5	51.19	-3%	65.97	-3%	97.59	-2%	115.39	-2%
B	100	6	38.24		56.78		84.07		101.67	
B	70	6	35.20	-8%	51.71	-9%	80.00	-5%	96.47	-5%

B	130	6	39.89	4%	58.99	4%	86.54	3%	104.71	3%
B	100	3	41.00	7%	61.02	7%	87.94	5%	105.83	4%
B	100	9	35.51	-7%	50.92	-10%	80.52	-4%	97.40	-4%

Table 1. Sensitivity analysis on the final breach width L and opening time T for one scenario on the Secchia River (see Fig. 3), with both inflows A and B. Results are compared based on the total outflow volume vol, and the flooded area 24, 48 and 72 h after the breach opening ($area_{24}$, $area_{48}$ and $area_{72}$, respectively). Their relative differences (Δvol, $\Delta area_{24}$, $\Delta area_{48}$, $\Delta area_{72}$) with reference to the baseline simulation are also reported for each tested configuration.