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This is a pre print version of the following article:

Original

Simulation of the January 2014 flood on the Secchia River using a fast and high-resolution 2D parallel shallow-water numerical scheme / Vacondio, Renato; Aureli, Francesca; Ferrari, Alessia; Mignosa, Paolo; DAL PALU', Alessandro. - In: NATURAL HAZARDS. - ISSN 0921-030X. - 80:1(2016), pp. 103-125. [10.1007/s11069-015-1959-4]

Availability:

This version is available at: 11381/2797911 since: 2021-10-13T15:25:12Z

Publisher:

Springer Netherlands

Published

DOI:10.1007/s11069-015-1959-4

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note finali coverpage

(Article begins on next page)

02 May 2026

Simulation of the January 2014 flood on the Secchia River using a fast and high-resolution 2D parallel shallow-water numerical scheme

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Abstract

The capability of a GPU-parallelized numerical scheme to produce accurate and fast simulations of floodings induced by levee-breach in large domains, adopting high resolution Digital Terrain Maps (DTMs), is investigated. The good predictive skills of the presented 2D shallow water model were proven with regard to the inundation caused by a levee breach occurred on the Secchia River, Italy in January 2014. The numerical computations were carried out on a domain of about 180 square

kilometers adopting a Cartesian grid of approximately 7.2 Mcells with size 5 m. The results of the simulation were validated against several field data and observations, including a high resolution Synthetic Aperture Radar image. A ratio between simulation and physical times of about 1/15 was achieved; this kind of simulation tools opens up new perspectives in the devising and implementing of flood event management strategies for civil protection purposes and with the aim of minimizing the economic loss.

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2

3

Introduction

4 In the recent years trends in flood frequencies and flooding damage appear to be increasing with a
5 consequent worsening of the social and economic repercussions. According to Jongman et al.
6 (2014), from 2000 to 2012 flooding events in Europe caused losses for about 4.9 billion euros every
7 year, and the latest inundations of 2013 (central Europe and UK) brought damages of 12 billion
8 euros. Moreover, owing to climate change, flooding events are expected to double by 2050 and
9 global losses to increase till more than 500%. Similarly Hallegatte et al. (2013) underline how
10 global flood losses will achieve in 2050 the value of 52 billion dollars per year and considering the
11 climate change they estimate annual losses to reach 1 trillion dollars per year. Hence, the
12 development and application of tools capable to provide accurate and fast predictions for flood
13 management is crucial to obtain a reduction of the damages caused by floods. Several analyses have
14 been carried out to demonstrate that 2D shallow water numerical models can be proficiently applied
15 to the simulation of flood events also with the aim of designing measures to prevent flood damage.
16 After having involved specialists and decision-makers, Leskens et al. (2014) concluded that flood
17 simulation models are not yet used by decision makers as widely as it could be expected. This is
18 mainly ascribed to the fact that the computational time of traditional 2D shallow-water numerical
19 models is still excessive and also to the fact that the numerical models are not yet flexible enough to

20 adapt to real situations. This well-known problem has led the researchers to investigate different
21 modelling approaches in the attempt to speed up their computations without loss of accuracy. For
22 example Horritt and Bates (2002) investigated different predictive performances of 1D and 2D
23 models in estimating the inundation extents by studying a 60 km reach of Severn River (UK).
24 Focusing the attention to flooding events due to levee breaches, Masoero et al. (2013) and Di
25 Baldassarre et al. (2009) studied respectively the 1951 and 1879 historical inundations on the Po
26 River in Northern Italy. Mazzoleni et al. (2014) analyzed synthetic scenarios to define the flood
27 hazard due to levee breaches. Domeneghetti et al. (2013) analyzed the effect of several unavoidable
28 sources of uncertainty that characterize the models of inundations triggered by levee breaches. In all
29 these analyses the river is described by means of a 1D model, used also to compute the discharge
30 hydrograph flowing through the levee breach, this hydrograph is then adopted as inflow boundary
31 condition for the 2D numerical scheme of the flood-prone area. This means that 2D simulations are
32 then performed only in the plains outside the river region. The main motivation for the adoption of
33 this approach lies in the necessity to reduce the computational time: creating a fully 2D models of
34 both the river region and the flood-prone area entails in fact a high computational effort. However,
35 often the flow in the river region cannot be accurately described through 1D numerical
36 schematization due to the presence of a main channel which meanders within the valley limits and
37 since close to the breach the velocity in the direction normal to the thalweg is not negligible.
38 Moreover the adoption of two different non-linked numerical schemes for the river and the flood-
39 prone area does not allow to model properly backwater effects which can have a significant
40 influence on the discharge flowing through the breach.

41 Some authors have proposed to develop 1D-2D coupled numerical schemes (Gejadze & Monnier
42 2007, Bladé et al. 2012, Morales-Hernández et al. 2013, Morales-Hernández et al. 2014) to
43 overcome the limitation described before. In those models the river region is discretized by means
44 of cross-sections whereas the 2D model is used to describe the large areas outside the river region,
45 where the 1D assumptions does not hold. When coupled models are adopted special care has to be

46 made to define the boundary conditions for the 1D and the 2D models in such a way that both
47 global mass and momentum are conserved at the coupling zones (Morales-Hernández et al. 2013).
48 Moreover in such models the region where the 1D approximation holds has to be defined a priori.
49 As pointed out by Leskens et al. (2014), the adoption of two different numerical schematizations
50 makes the use of numerical models much more complex and less flexible for flood disaster
51 management. To overcome these limitations, already manifest in the recent past, Aureli and
52 Mignosa (2004) and Aureli et al. (2006) developed fully 2D numerical models of both the river
53 region and the flood prone areas for the modelling of flooding scenarios due to levee breaches in the
54 Po River, although with low spatial resolution.

55 Until recently the traditional surveying techniques allowed the description of river reaches mainly
56 through series of cross sections and terrain data outside the river banks were usually provided at a
57 low resolution, adequate to that exploitable at the time by the modelling tools. An accurate high
58 resolution modelling of flows was, as consequence, barely achievable. More recently Light
59 Detection and Ranging (LiDAR) and Digital Terrain Models (DTM) with spatial resolution of 1–3
60 m and elevation accuracy of 10 cm have become more and more widespread and are now available
61 for many flood prone areas. As an example more than 62% of England and Wales (81% of urban
62 areas) is covered by LiDAR surveys (Di Baldassarre and Uhlenbrook 2012). This represents a
63 revolution for flood risk modeling.

64 Schumann et al. (2014) pointed out how the availability of high resolution DTMs can dramatically
65 enhance the capability of flood modeling at local scale, offering the chance of obtaining accurate
66 maps of the risk related to flood disasters. Marks and Bates (2000), Gallegos et al. (2009) and
67 Dottori et al. (2013) analyzed the effect of spatial resolution on 1D and 2D flood modeling,
68 highlighting the capability of shallow–water models to simulate inundations in urban and sub-urban
69 areas when high resolution is used. However high resolution simulations entail considerable
70 computational costs.

71 Sanders et al. (2010) presented a parallel shallow-water numerical model based on Message Passing
72 Interface (MPI) technique which allows remarkable speedups (ratios between the sequential
73 computational time over the GPU parallel time for the same code). Alternative to this approach is
74 the adoption of GPU-parallelized codes using CUDA programming language. The advantages of
75 the GPU parallelization, with respect to a traditional MPI framework, are the significantly
76 decreased cost per processor and the efficient on-card communication. Whereas MPI
77 communication requires large supercomputers, which are very expensive to buy and to maintain,
78 GPU cards can be installed on standard desktop computers. The parallelization of 2D Shallow
79 Water Equations models has been presented in the past by different authors (Crossley et al 2010,
80 Brodtkorb et al. 2012, De la Asunción et al. 2013, Lacasta et al. 2014, Vacondio et al. 2014 and
81 Lacasta et al. 2015) for structured and non-structured grids.

82 High resolution modelling of floods induced by levee breach is here analyzed adopting an original
83 GPU-parallelized model implemented by Vacondio et al. 2014 and based on an explicit Shock–
84 Capturing Finite Volume method for the solution of the 2D Shallow Water equations. Speedups of
85 two orders of magnitude are thus achieved. Thanks to this efficient parallelization the issues related
86 to long computational times are addressed; moreover the river and the flood prone areas are
87 integrated in a single computational domain and the flow phenomenon is modelled as a whole
88 avoiding the special treatments proper of linked 1D and 2D numerical schemes. To illustrate the
89 capabilities of this approach and its potential impact in flood risk management activities the real
90 flood event occurred on the River Secchia (Italy) on January 2014 as a consequence of a breach in
91 the river right embankment, was simulated. The levee breach was in all probability triggered by the
92 presence of a burrowing animal den. The region of Northern Italy under investigation, bounded by
93 the Po River and by its two consecutive tributaries Secchia and Panaro, was in the past subject to
94 several floods due to breach collapse. At least three of these events were catastrophic and caused
95 the inundation of wide plains (more than 500 km²), with considerable water depths (6-7 m) (Aureli
96 and Mignosa, 2004). If the breaching mechanisms of the past events are only partially known, in the

97 recent years the awareness of the causes of levee collapses is progressively increasing. Among the
98 most important causes of levee breaching are nowadays included the dens of burrowing animals
99 whose presence in the levee body can represent a real threat capable to trigger the erosion
100 processes.

101 A lot of research is currently being undertaken to achieve a realistic representation of the failure
102 mechanisms of earthen dams and levees. Many studies (Zhu et al., 2004, Macchione, 2008,
103 Macchione and Rino, 2008) describe the characteristics of dam breaches by estimating various
104 parameters: geometrical (height, width, failure time), hydraulic (reservoir volume, initial water
105 height), geotechnical (material erodibility). Recently Viero et al. (2013) proposed the reconstruction
106 of different flooding events due to levee breaches in Northern Italy considering both overtopping
107 and piping processes, on the basis of a simplified physically based 1D-link capable to simulate the
108 breach initiation and growth In the present study, the breach evolution in time has been modelled
109 according to the field data collected during the event.

110 Model calibration was achieved against the high amount of field data collected during the event,
111 not least the radar data available from the COSMO-SkyMed archive and captured about 60 hours
112 after the beginning of the levee collapse.

113 The paper is organized as follows: in Section 1, the study case and a collection of the available field
114 data are presented. Section 2 is dedicated to the description of the numerical simulations; the model
115 is briefly illustrated and detailed analyses regarding the topographic data, the roughness estimation
116 and the imposed boundary conditions are reported. The simulation results are shown and verified in
117 Section 3 and finally, in Section 4 the conclusions of the work are reported.

118

119

120 **1. Study area and available field data**

121 At 6:00 A.M., during the flood event of January 19th 2014, a levee breach occurred in the Secchia
122 right bank near Modena (North-Central Italy, Figure 1). Here the river is bounded by artificial
123 earthen levees of remarkable height above the surrounding lands. Even if water levels in the river
124 were far from overtopping the crest, a small portion of the levee body collapsed, triggering the
125 flooding. The breach was in all likelihood originated by the presence of burrowing animals dens, as
126 inferred *a posteriori* by an accurate inspection of high-resolution aerial photographs taken before
127 the failure and by an incipient similar breach observed in the same day along the left levee of the
128 neighbor Panaro River. Progressively the breach widened and deepened, reaching a maximum
129 width of about 80 m at about 3:00 P.M. of January 19th 2014. The flooding caused the displacement
130 of thousands of people and one death, 75 km² of flooded lands, and estimated overall losses for
131 about 400 million euros. The information about timing, geometry and evolution of the levee breach
132 were provided through direct observation and aerial photos (Figure 2).
133 Field information about flood propagation time and flooding extent, useful for calibration purposes,
134 were achieved through press services, media and people directly involved or interested in the event.
135 Satellite synthetic Aperture Radar (SAR) observations, acquired at 3 m spatial resolution during the
136 flooding event, were also obtained from the COSMO-SkyMed Mission archive and allowed a
137 synoptic view of the flooding extent about 60 hours after the beginning of the breaching process.

138

139 **2. Numerical simulations**

140 **2.1. Topographic data**

141 The area involved by the flooding is characterized by the presence of two main villages and it is
142 bounded at east by the left levee of the Panaro River, the right tributary of the Po River following
143 the Secchia River.

144 A digital terrain model (1 m resolution), based on a LIDAR survey, was available to describe the
145 geometry of the riverbeds and of the flooded area. Since the acquisition was performed during

146 summer, when the Secchia river is almost totally dried up, no other information was necessary to
147 correctly describe the bathymetry.

148 Many embankments of roads, railways and artificial channels cross the region and exerted an
149 important influence on the flooding dynamics. To achieve a correct description of all these
150 important geometrical features, a high resolution mesh is required in the mathematical modelling.

151 To reach a good compromise between an accurate description of all the main characteristics of the
152 bathymetry and the computational time, in the present study a Cartesian mesh with size equal to 5 m
153 was adopted. In order to preserve the crest elevation of the artificial embankments after the
154 downsampling of the DTM, each 5x5 m cell crossed by an embankment was identified and its
155 elevation was set equal to the maximum value of the original 25 points belonging to that cell.

156 In Figure 3 a detail of the terrain elevation of a complex highway junction is shown, considering
157 both the original DTM with 1 m resolution and the corrected 5 m resolution mesh adopted for the
158 numerical modelling. The 5 m mesh is still capable to describe the details of all the embankments
159 and highway ramps that may exert an influence on the flooding evolution.

160

161 2.2. Numerical model

162 The numerical model here adopted solves in a finite volume framework the integral form of 2D
163 SWE (e.g. Toro 1999a):

$$164 \frac{d}{dt} \int_A \mathbf{U} dA + \int_C \mathbf{H} \cdot \mathbf{n} dC = \int_A (\mathbf{S}_0 + \mathbf{S}_f) dA. \quad (1)$$

165 where A is the area of the integration element, C the element boundary, \mathbf{n} the outward unit vector
166 normal to C , \mathbf{U} the vector of the conserved variables and $\mathbf{H} = (\mathbf{F}, \mathbf{G})$ the tensor of fluxes in the x and
167 y directions respectively:

168

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

169 where h is the flow depth, u and v are the velocity components in the x and y directions and g is the
 170 acceleration due to gravity. The bed and friction slope source terms \mathbf{S}_0 and \mathbf{S}_f are expressed
 171 according to the following relations:

172

$$\mathbf{S}_0 = \begin{bmatrix} 0; -gh \frac{\partial z}{\partial x}; -gh \frac{\partial z}{\partial y} \end{bmatrix}^T$$

$$\mathbf{S}_f = \begin{bmatrix} 0; -gh \frac{n_f^2 u \sqrt{u^2 + v^2}}{h^{4/3}}; -gh \frac{n_f^2 v \sqrt{u^2 + v^2}}{h^{4/3}} \end{bmatrix}^T \quad (3)$$

173 in which z is the bed elevation with respect to a horizontal reference plane and n_f is the roughness
 174 coefficient according to the Manning equation. For the friction source term the implicit
 175 discretization of Caleffi et al. (2003) is adopted: this prevents the formation of spurious oscillations
 176 in the presence of very small depths, which might occur when a naive explicit formulation is used,
 177 whereas an explicit discretization of the bed slope is performed in order to satisfy the C-property
 178 also in presence of wet-dry interfaces (Vacondio et al. 2014). The problem of obtaining a balance
 179 between fluxes and source terms in Equation (1) has received considerable attention in the recent
 180 literature. Some authors addressed the problem rectifying the SWEs formulation by numerical
 181 treatment (Vázquez-Cendón, 1999, Zhou et al., 2001; Valiani & Begnudelli, 2006a,b and Aureli et
 182 al., 2008;). Mourillo & García-Navarro (2010, 2012) introduced a new approach defining a weak
 183 solution that inherently incorporates the source terms. Rogers et al. (2003) derived an algebraic
 184 modification of Equation (1) capable to balance the hyperbolic system of equations, regardless of
 185 the discretization of the slope source term and of the approximate Riemann solver. Liang &
 186 Borthwick (2009) further modified the idea presented by Rogers et al. (2003), by proposing a
 187 different way to manipulate the SWEs, which is suitable also for problems with wet-dry interfaces.

188 In this work the Liang & Borthwick (2009) formulation is adopted and the terms of Equations (2)
 189 are modified as follows:

$$\begin{aligned}
 & \mathbf{U} = [\eta; uh; vh]^T \\
 & \mathbf{F} = \begin{bmatrix} uh \\ u^2h + \frac{1}{2}g(\eta^2 - 2\eta z) \\ uvh \end{bmatrix}, \quad \mathbf{G} = \begin{bmatrix} vh \\ uvh \\ v^2h + \frac{1}{2}g(\eta^2 - 2\eta z) \end{bmatrix}, \quad (4)
 \end{aligned}$$

191 where $\eta = h + z$ is the free surface elevation above datum and the bottom source term \mathbf{S}_0 is:

$$\mathbf{S}_0 = \left[0; -g\eta \frac{\partial z}{\partial x}; -g\eta \frac{\partial z}{\partial y} \right]^T \quad (5)$$

193 The bottom source term is discretized using a centered formulation. As indicated before the C-
 194 property is inherently guaranteed by the modified form of the SWEs reported in Equation (4).

195 The partial differential equations (1) are solved on a Cartesian grid adopting a second order accurate
 196 (in space and time) Finite Volume (FV) numerical approximation of the SWEs. Regardless of the
 197 order of accuracy, the fluxes are calculated using a HLLC approximate Riemann solver (Toro,
 198 1999b).

199 The fluxes \mathbf{F} and \mathbf{G} in x and y directions are evaluated at the intercells $(i \pm \frac{1}{2})$ and $(j \pm \frac{1}{2})$,
 200 respectively. To avoid the formation of high velocities and instabilities, if the water depth $h_{i,j}$ is
 201 lower than a very small threshold h_ϵ the cell is dried ($h = 0$). To prevent any significant mass
 202 conservation error h_ϵ has been defined equal to 1×10^{-5} , which is close to the machine precision.
 203 Moreover in the cells with water depth smaller than 20 cm the fluxes are corrected as suggested by
 204 Kurganov & Petrova (2007). In this way the development of non-physical velocities close to the wet
 205 dry front is avoided.

206 The second order of accuracy in time is obtained by a second order Runge-Kutta method:

$$\mathbf{U}_{i,j}^{n+1} = \mathbf{U}_{i,j}^n + 0.5\Delta t^n \left[\mathbf{D}_i(\mathbf{U}_{i,j}^n) + \mathbf{D}_i(\mathbf{U}_{i,j}^{n+\frac{1}{2}}) \right] \quad (6)$$

208 where the superscript n represents the time level, the subscripts i, j and $\Delta x, \Delta y$ are the cell positions
 209 and the grid sizes in x and y directions, respectively, and Δt^n is the timestep calculated accordingly
 210 to the Courant–Friedrichs-Lewy condition. The operator $\mathbf{D}_i(\mathbf{U}_{i,j})$ is defined as:

$$211 \quad \mathbf{D}_i(\mathbf{U}_{i,j}) = -\frac{\left(\mathbf{F}_{i+\frac{1}{2},j} - \mathbf{F}_{i-\frac{1}{2},j}\right)}{\Delta x} - \frac{\left(\mathbf{G}_{i,j+\frac{1}{2}} - \mathbf{G}_{i,j-\frac{1}{2}}\right)}{\Delta y} + \mathbf{S}_0 + \mathbf{S}_f \quad (7)$$

212 and $\mathbf{U}_{i,j}^{n+1/2}$ is obtained as:

$$213 \quad \mathbf{U}_{i,j}^{n+\frac{1}{2}} = \mathbf{U}_{i,j}^n + \Delta t^n \mathbf{D}_i(\mathbf{U}_{i,j}) \quad (8)$$

214 The modeling of a parallel system based on a GPU architecture requires some adaptation of
 215 traditional sequential algorithms.

216 The update of the conservative variables (vector \mathbf{U}) in a single time step from time t^n to time $t^{n+1} =$
 217 $t^n + \Delta t$, is described by a sequence of eight sub tasks (Vacondio et al. 2014). The CPU controls the
 218 iteration evolution and invokes the various tasks in order. Each task can be processed in parallel and
 219 is described by a distinct CUDA kernel.

220 Several optimization procedures have been developed, including a novel and efficient Block
 221 Deactivation Optimization (BDO), the implicit local ghost approach for the assignment of boundary
 222 conditions and a careful implementation to reduce the information exchanges between CPU and
 223 GPU. The code was validated against many severe benchmark test cases (Vacondio et al., 2014).
 224 The parallel implementation allows excellent speedup with respect to the number of processors in
 225 the GPU.

226

227 2.3. Riverbed roughness estimation

228 In the considered reach, only few discontinuous floodplains of relatively small extent are present
 229 between the river levees. This suggested to characterize the river region by means of a unique

230 roughness coefficient. For the Secchia River a 1D hydraulic model calibrated on the basis of four
 231 historical level gauges located along the river reach (the two most upstream being Ponte Alto and
 232 Ponte Bacchello) was developed in the past and thus available. Moreover, for the mentioned
 233 gauging stations, stage-discharge relationships are still published and updated by ARPA (Regional
 234 Agency for Environmental Protection in the Emilia-Romagna region), on the basis of regular
 235 discharge measures. However the roughness coefficient is sensitive both to model schematization
 236 (1D / 2D) and discretization (mesh size). Since in the present study a fully 2D model was adopted
 237 also for the riverbed, a new ad-hoc calibration was performed. With this aim the most significant
 238 and well documented event occurred in the last ten years (23rd - 30th December 2009) was adopted.
 239 In Figure 4 the discharge hydrograph at Ponte Alto (converted from the recorded levels through the
 240 station stage-discharge relationship) and the stage hydrograph at Ponte Bacchello, imposed as
 241 upstream and downstream boundary conditions respectively, are shown.

242 To estimate the most suitable roughness coefficient the Nash-Sutcliffe efficiency criterion (Nash
 243 and Sutcliffe, 1970), E_h , was adopted with reference to the water levels at Ponte Alto gauging
 244 station:

$$245 \quad E_h = \left[1 - \frac{\sum_{i=1}^N (h_i^{act} - h_i^{est})^2}{\sum_{i=1}^N (h_i^{act} - \bar{h}^{act})^2} \right] \cdot 100$$

$$246 \quad (9)$$

247 where N is the total number of stage hydrograph data, h_i^{act} and h_i^{est} are the i -th observed and
 248 estimated water level values respectively, and \bar{h}^{act} is the mean value of the actual hydrograph.

249 Table 1 shows the values of E_h for $n_f = 0.067$, 0.05 and 0.03 m^{-1/3}·s and Figure 5 shows the
 250 comparison between computed and observed water levels at Ponte Alto. Water levels computed
 251 with $n_f = 0.05$ m^{-1/3}·s showed the best agreement with the registered data and this value of Manning
 252 roughness coefficient was therefore adopted to characterize the riverbed.

253

254 2.4. Evaluation of the inflow boundary condition

255 The inflow discharge for the event of January 2014 (upstream boundary condition) was firstly
256 obtained by simply converting the stage hydrograph recorded at Ponte Alto gauging station with the
257 available stage-discharge relationship. However this rating curve was expected to underestimate the
258 inflow discharges after the occurrence of the breach, which is located only 6 km downstream of the
259 gauging station itself. The comparison between registered and simulated water elevation obtained in
260 this way is shown in Figure 6. The agreement is very satisfactory before the breach formation,
261 whereas afterwards the computed water elevations systematically underestimate the registered ones.
262 This confirms that the breach gives origin to a drawdown profile capable to exert a significant
263 influence on the rating curve at Ponte Alto.

264 In order to assess this problem, the 2D numerical model was run assuming a synthetic triangular
265 flood wave as upstream boundary condition and match wellin presence of the fully developed
266 breach. The stage-discharge values, obtained from this numerical simulation at Ponte Alto, were
267 fitted by a power law function to obtain a new rating curve for the station. This rating curve was
268 then adopted to convert water elevations into discharges for the January 2014 event only after the
269 complete development of the breach, whereas the original stage-discharge relationship was used
270 before the beginning of the breach formation. During the breach evolution (between 6.00 AM and
271 3.00 PM of the 19th January 2014) a linear interpolation between the two hydrographs was adopted
272 in order to take into account the progressive opening of the breach. The new hydrograph is plotted,
273 together with the uncorrected one, in Figure 7: after the opening of the breach the modified
274 discharges are significantly greater, with an increase in the peak value of about 80 m³/s.

275 The water levels at Ponte Alto, obtained imposing the new discharge hydrograph, are also plotted in
276 Figure 6. The numerical results with the corrected inflow boundary condition are in excellent
277 agreement with the registered data, and the issue of underestimation of water levels after the breach
278 formation is addressed.

279

280 2.5. Flooded area roughness estimation

281 Calibration of the roughness values in the flooded area outside the river region was accomplished in
282 two steps with the aim of evaluating two different Manning's n values suitable to represent the
283 roughness of rural and urban areas, respectively. With regard to the rural areas, the adoption of a
284 unique roughness coefficient was fairly justified by the almost homogeneous land use
285 characterizing the cropland in the low plain near Modena. Urban areas were then considered as
286 regions of higher resistance, characterized by their specific Manning coefficient to be estimated
287 afterwards the calibration of the roughness coefficient of the rural areas. Different methodologies,
288 alternative to the adopted approach, are available in literature to account for the influence of the
289 buildings on the flooding dynamics (Soares-Frazaõ et al., 2008; Schubert et al., 2008; Schubert and
290 Sanders, 2012); anyway a detailed modeling of the flood propagation through the buildings was
291 beyond the scope of the present study.

292 The first calibration step, devoted to the evaluation of the resistance parameter for the rural areas,
293 outside the riverbed, was accomplished holding the in-channel roughness at $0.05 \text{ m}^{-1/3}\cdot\text{s}$ and
294 executing three different runs each characterized by a different uniform value of n_f , respectively
295 equal to 0.07 , 0.05 and $0.03 \text{ m}^{-1/3}\cdot\text{s}$. For each simulation the time of arrival of the flooding at the
296 south-western boundary of the Bastiglia urban area, occurred actually 6.75 hours after the beginning
297 of the breaching process, was evaluated. Figure 8 shows the maps of the flooding extent at $0:45 \text{ PM}$
298 on 19^{th} January 2014 for the three mentioned simulations. The time of the comparison was chosen
299 properly to guarantee that the flood propagation did not interest yet any urban area.

300 Incidentally, the roughness value $n_f = 0.05 \text{ m}^{-1/3}\cdot\text{s}$ allows again to correctly reproduce the arrival
301 time of the wetting front at the entrance of the urban area of Bastiglia, while the arrival is
302 anticipated and delayed of about half an hour adopting in the model the lower (0.03) and the higher

303 (0.07) roughness coefficients, respectively. The obtained results show that the flooding dynamics is
304 not dramatically sensitive to the variation of the resistance parameter assigned to the rural areas.
305 Additional numerical simulations were then performed holding the rural areas roughness at $0.05 \text{ m}^{-1/3}\cdot\text{s}$
306 and varying the urban areas resistance parameter to reproduce the overall effect of buildings.
307 The calibration was accomplished on the basis of a correct reproduction of the arrival time of the
308 flooding at Bomporto. Five different values of n_f , equal to 0.083, 0.111, 0.143, 0.2 and $0.5 \text{ m}^{-1/3}\cdot\text{s}$,
309 were assumed. The Manning roughness value $n_f = 0.143 \text{ m}^{-1/3}\cdot\text{s}$ allows to correctly reproduce the
310 arrival of the flood front at Bomporto, while the flood arrival is anticipated of 2.75 and 1 hours
311 considering n_f equal to 0.5 and $0.2 \text{ m}^{-1/3}\cdot\text{s}$ respectively, and it is delayed of 1.5 and 4.5 hours
312 considering n_f equal to 0.083 and $0.111 \text{ m}^{-1/3}\cdot\text{s}$, respectively. Unlike the roughness of the rural area,
313 the flooding arrival time at Bomporto is significantly influenced by the roughness coefficient
314 assumed to describe the urban area at Bastiglia. On the contrary, numerical results are not as
315 sensitive to the roughness coefficient assumed to describe the Bomporto urban area, since there the
316 velocities almost vanish, due to the presence of the river embankments of Panaro River and
317 Naviglio channel which surround the village (see the following Figure 9).

318 A further validation of the quality of the calibration was provided by the information about the
319 volume of water lifted by the pumping station of Santa Bianca (about 18 Mm^3) that is in good
320 agreement with the computed value of the volume flowed in the northern portion of the flooded
321 domain (about 17.5 Mm^3).

322 **3. Simulations and results**

323 The flooding event was simulated from 12:00 PM of January 17th 2014, when the registered water
324 levels at the gauging stations started to increase significantly, till 6.00 AM of January 21th 2014
325 when the flood event might be considered as concluded (see Figure 10). According to field

326 observations the breach was assumed to progressively evolve during a period of 9 hours reaching a
327 maximum width of about 80 m.

328 The 2D simulations entailed a storage of about 2671 MB on the graphic card using 7.2 million
329 computing cells and required about 6 computing hours to simulate the period from 12:00 PM of
330 January 17th 2014 till 6.00 AM of January 21th 2014 (90 hours).

331

332 3.1. River reach

333 Figure 10 shows the flow hydrographs computed at the breach section and in other two sections
334 along the river reach, respectively 200 m upstream and downstream of it. At the end of the breach
335 evolution process about 525 m³/s, which correspond to more than 87% of the upstream discharge,
336 are flowing through the breach, whereas only the remaining 13% proceed downstream.

337 Figure 11 shows the stage hydrograph close to the breach. Here the spatial variability of the water
338 stage is high, due to the drawdown effect exerted by the outflowing discharge, so the figure is just
339 indicative. After the beginning of the breaching process (about 6:00 A.M. of January 19th) water
340 levels still increase, reaching the highest value of 36.05 m a.s.l. around 8:00 A.M. Then the levels
341 start to decrease quite abruptly reaching the value of about 33 m a.s.l. in the following 7 hours.
342 After the stabilization of the breach opening the water stages continue to decrease, with a further
343 lowering of 2 meters in about 33 hours.

344

345 3.2. Flooded area

346 In Figure 12 some significant frames of the flooding evolution are reported. According to the
347 available observations collected during the event, the timing of the simulated inundation is in good
348 agreement with the real flood event evolution. About 1 hour after the levee breach (7.00 A.M. of
349 19th January 2014), water quickly flooded near lowlands in North-East direction (Figure 12-a). At

350 2.00 P.M. the flood wave reached the center of the urban area of Bastiglia (Figure 12-b), where
351 most people were already evacuated. Few hours later (9.00 P.M.), the countryside of Sorbara was
352 flooded (Figure 12-c). At 10:30 A.M. of 20th January 2014, water reached the central Matteotti
353 square in Bomporto (Figure 12-d). At 2:00 P.M. of 20th January 2014 the flood wave reached the
354 SP5 road near Camposanto (Figure 12-e) which was overtopped only about 4 hours later (6:00 P.M.
355 of 20th January 2014) (Figure 12-f).

356 In the numerical simulation the overall volume flowed out from the breach was estimated to be
357 around 39 Mm³. About 21.5 Mm³ of this overtopped the levees of the Naviglio channel at Bastiglia
358 and moved to the eastern areas up to Bomporto, whereas about 17.5 Mm³ went ahead and flooded
359 the northern portion of the domain.

360 Figure 13 shows the comparison between real flooded areas, spotted through aerial images, and
361 computed ones. The first pair shows that the flooding is correctly reproduced by the computations at
362 Bomporto, where the East portion is flooded while the West one is not. The second pair of images
363 shows that the influence of the disused railway embankment, located north-east of Bastiglia, and the
364 flooding of the surrounding cultivated lands are also correctly represented by the numerical model.

365 Comparison between numerical results and SAR data was also performed. The COSMO-SkyMed 4
366 satellite crossed the areas of Modena on the 21th January 2014, acquiring an image at 5:20 P.M., at a
367 high spatial resolution of 3 m.

368 Figure 14 compares the extent of the flooded region deduced from the SAR image with that
369 obtained through the numerical computations. Due to the satellite flight path, the extreme North-
370 East portion of the domain under investigation was not covered by the image frame. The inundation
371 extent is well enough captured by the numerical model, especially in the south and north west ends.
372 Despite the high-resolution information of the flood extent available in the SAR image, in a not
373 negligible number of land parcels, located at the edge of the flooded area, the image is biased due to
374 multiple reflections between the water and the emerging vegetation which causes an increased

375 backscatter compared to that from a smooth open water surface (Mason et al. 2012a, Mason et al.
376 2012b). This is confirmed by the available aerial views captured during the event, one of which is
377 shown in Figure 15. Flooded land parcels, characterized by low backscatter, are apparently
378 contiguous to increased backscatter areas, which would be considered as dry on the basis of direct
379 analysis of the SAR image only. This issue makes impossible the evaluation of quantitative metrics,
380 like the one proposed by Bates and De Roo (2000), to measure the capability of the numerical
381 model to reproduce the observed inundation extent. However, the availability of aerial photos of the
382 parcels of land of doubtful characterization confirms unequivocally that the extent of the inundation
383 is correctly reproduced by the numerical simulations.

384 Figure 16 shows the map of maximum water depths (envelope) obtained by the numerical model.
385 Apart from the river and channel beds, the maximum values occur in the southern portion of the
386 flooded region, where water depths raise up to 2.6-2.8 m, due to the blocking effect of the several
387 embankments crossing this area. These values, especially in the urban areas where the signs of the
388 flood are more reliable due to the presence of mud, are in very good agreement with the
389 observations. Smaller depths (0-1 m) were computed (and observed) in the northern portion of the
390 flooded region, with the exception of the area just upstream the SP5 road near Camposanto, where
391 maximum depths of 1.4-1.6 m were computed, due to the retaining effect of the road embankment.

392 Finally, Figure 17 shows the map of the computed arrival times of the flooding. Very different
393 arrival times at a short distance highlight the blocking/delaying effects exerted on the flooding
394 dynamics by the embankments of artificial channels, roads and railways. As an example, points A
395 and B, located 1 km apart but on two opposite sides of a channel embankment, are reached by the
396 flooding 10.5 and 24.5 hours after the levee failure, respectively. Some areas in the most southern
397 part of the domain, where the ground elevation is higher, were flooded by backwater effects only
398 40-45 hours after the levee collapse (blue colors). From the map it is also evident the long delay
399 (more than 24 hours, green colors) occurred between the breach triggering and the flooding of
400 Bomporto. This suggests that some countermeasures (sandbags, inflatable rubber dams, etc.) could

401 have been implemented during the event in order to avoid the flooding or reduce the water depths in
402 this urban area.

403

404 **4. Discussion and conclusions**

405 Flood management in wide lowlands crossed by rivers bounded by artificial earthen levees of
406 remarkable height, as occurs in the Po River valley, is a crucial issue for multiple reasons. On one
407 side the trend in flood frequency appears to be increasing with a continue worsening of the stress
408 exerted upon the embankments, moreover the huge length makes very difficult the maintenance of
409 the defense systems in perfect working order; take for example the problem represented by the
410 presence of burrowing animals, whose deep dens may be the root cause of the significant piping
411 problems threatening the structural integrity of the levees. This was confirmed by the real event
412 investigated here, during which the Secchia and Panaro embankments were both subject to break
413 processes triggered by the presence of dens, despite of an hydrologic input of low return period. On
414 the other side it has to be considered that the domain is a portion of the main wide plain area of the
415 southern Europe which is rich in history and highly productive. Due to the value of the elements
416 exposed to risk, inundations of small extent lead often to economic losses of hundreds of million
417 euros . For the event here considered the flooding caused the displacement of thousands of people,
418 one death, 75 km² of flooded lands, and estimated overall economic losses for about 400 million
419 euros (more than 5 M€/km²). The development and application of tools capable to provide accurate
420 and fast predictions for flood management in these territories is therefore crucial **capital** and the
421 open challenge is the development of real time flood modelling tools capable to provide help in the
422 definition of protection strategies during the flood events.

423 In order to setup real-time flooding-forecast systems, useful for flood risk management, the time of
424 simulation is certainly a main issue. With the aim of real-time flood protection, as a matter of fact,
425 the computational time proper of traditional serial 2D shallow-water numerical models is still

426 excessive and makes their adoption impossible. The new parallel code here presented implemented
427 on CUDA-enabled GPU cards seem to fit for the purpose, allowing a high spatial resolution and
428 achieving a ratio between physical time and runtime greater than 15 (about 6 computing hours are
429 necessary to simulate 90 hours of physical time).

430 The continuously increasing storage capabilities of commercially available graphic cards permits
431 the adoption of grids composed of several millions computing cells, with the possibility to describe
432 the domain geometry at high resolution. In this way the LiDAR 1 m DTMs, which are now
433 becoming increasingly widespread, can be adopted with a minimum degrading, without appreciable
434 loss of accuracy in the representation of all the geometrical elements that can exert a significant
435 influence on the flood propagation. The exponential growth of all the related technologies, at the
436 affordable cost of standard desktop computers, makes the GPU parallelization an attractive
437 modelling approach. In confirmation of this fast growing process a new CUDA-GPU card, that
438 halves the computational time of the one here adopted, has been in the news recently. The original
439 GPU-parallelized model adopted here allowed an integrated description of the river and the flood
440 prone areas in a unique computational domain; the flow phenomenon was then modelled in its
441 entirety, avoiding the special treatments required at the linking of 1D / 2D numerical schemes. This
442 feature, along with the small time scale ratio characterizing the computations, suggests that a
443 database of a high number of possible flooding scenarios due to levee collapse, also under different
444 hydrologic inputs, could be set up for a region of interest within a very reasonable computational
445 time and cost, inconceivable just a few years ago.

446 The riverbed roughness has been calibrated using the available data at Ponte Alto gauging station
447 for the most significant previous flooding event in which the low lying area outside the river region
448 was not flooded. Conversely for the flooded areas two different roughness coefficients have been
449 defined for the rural and urban areas, respectively. Those coefficients have been adjusted in such a
450 way that the numerical simulation can reproduce the arrival times of the floodings at different
451 locations.

452 For an occurrence of a levee collapse the ‘offline’ adoption of the model, thanks to the availability
453 of the result database, would provide decision-makers with a valuable tool for the implementation
454 of mitigation strategies, allowing to infer with a reasonable confidence the flooding event evolution
455 with respect to the more similar scenario already simulated. Again with the aim of implementing
456 flood event management strategies, civil protection activities could take a great advantage also of
457 the coupling of the GPU-parallelized tool here presented with weather forecast and rainfall-runoff
458 models, thus allowing an ‘online’ model application during an event. In this case the uncertainty in
459 the computed flood extents, due to the absence of prior calibration, could be reduced through data
460 assimilation combining the flow variables with observations. Spatially distributed information about
461 inundation extents can be achieved through satellite high-resolution SAR images that are
462 characterized by a unique all-weather day-night capability. However, as presented here due to the
463 high amount of different kinds of field observations, proper image segmentation algorithms have to
464 be implemented to estimate correct waterline levels and positions due to the increased backscatter
465 induced by the emergent vegetation that gives origin to an underestimation of the flood extents in
466 some inundated parcels.

467 In the particular case here considered and discussed, both ‘offline’ and ‘online’ applications of the
468 presented modelling tool would have been of help to the devising of emergency protection
469 measures. This is especially true with respect to those territories that, for the relative distance from
470 the breach site, would have been involved by the flooding many hours after the levee collapse. The
471 knowledge of the inundation propagation characteristics, even in the presence of the many sources
472 of uncertainty usually affecting the hydrological scenarios, would have more effectively allowed the
473 adoption of emergency mitigation measures with the aim of avoiding the inundation or at least
474 reducing the water depths in the built up areas and the consequent human and economic losses.

475

476 **Acknowledgments**

477 Interregional Agency for the Po River (AIPo) and personnel directly involved in the management of
478 the emergency are gratefully acknowledged for providing a large amount of field data and
479 observations. We acknowledge the CINECA Award P-FLOOD2-HP10CHAL0S, 2014 under the
480 IS CRA initiative for the availability of high performance computing resources and support. Luigi
481 Romenghi is gratefully acknowledged for shooting and providing the aerial views of the flooding.

482

483 **References**

- 484 Aureli, F., Mignosa, P., 2004. Flooding scenarios due to levee breaking in the Po river. Proceedings
485 of the ICE - Water Management, Volume 157, Issue 1, 01 March 2004.
- 486 Aureli, F., Mignosa, P., Ziveri, C., Maranzoni, A., 2006. Fully-2D and quasi-2D modeling of
487 flooding scenarios due to embankment failure. International Conference on Fluvial Hydraulics -
488 River Flow 2006; Lisbon; Portugal; 6 September 2006 through 8 September 2006.
- 489 Aureli, F., Maranzoni, A., Mignosa, P., Ziveri, C., 2008. A weighted surface-depth gradient method
490 for the numerical integration of the 2d shallow water equations with topography. Adv. Water
491 Resour. 31, 962-974.
- 492 Bates, P., De Roo, A.P.J., 2000. A simple raster-based model for flood inundation simulation.
493 Journal of Hydrology, 236, 54-77.
- 494 Bladé, E., Gómez-Valentin, M., Dolz, J., Aragón-Hernández, J.L., Corestein, G., Sánchez-Juny, M.
495 2012. Integration of 1D and 2D finite volume schemes for computations of water flow in natural
496 channels, Adv Water Resourc, 42, 17–29
- 497 Brodtkorb, A.R., Saetra, M.L. Altinakar, M., 2012. Efficient shallow water simulations on GPUs:
498 implementation, visualization, verification, and validation. Comput. Fluids, 55 1–12.
- 499 Caleffi, V., Valiani, A., Zanni, A., 2003. Finite volume method for simulating extreme flood events
500 in natural channels. J. Hydraul. Res. 41, 167-177.
- 501 Crossley A, Lamb R, Waller S. 2010. Fast solution of the Shallow Water Equations using GPU
502 technology, Proceedings of the British Hydrological Society 3rd International Symposium,
503 Newcastle, UK, 13–19 July 2010

504 De la Asunción, M., Castro, M.J., Fernández-Nieto, E., Mantas, J.M., Acosta, S.O. , González-Vida
505 J.M., 2013. Efficient GPU implementation of a two waves TVD-WAF method for the two-
506 dimensional one layer shallow water system on structured meshes *Comput. Fluids*, 80 (2013), pp.
507 441–452

508 Di Baldassarre, G., Castellarin, A., Brath, A., 2009. Analysis of the effects of levee heightening on
509 flood propagation: example of the River Po, Italy. *Hydrological Sciences Journal* 54:6, 1007-1017.

510 Di Baldassarre, G., Uhlenbrook, S., 2012. Is the current flood of data enough? A treatise on
511 research needs for the improvement of flood modelling. *Hydrol. Process.*, 26: 153–158. doi:
512 10.1002/hyp.8226.

513 Domeneghetti, A., Vorogushyn, S., Castellarin, A., Merz, B., Brath, A., 2013. Probabilistic flood
514 hazard mapping: Effects of uncertain boundary conditions. *Hydrology and Earth System Sciences*,
515 Volume 17, Issue 8, Pages 3127-3140.

516 Dottori, F., Di Baldassarre, G., Todini, E., 2013. Detailed data is welcome, but with a pinch of salt:
517 Accuracy, precision, and uncertainty in flood inundation modeling. *Water Resour. Res.*, 49, 6079–
518 6085, doi:10.1002/wrcr.20406.

519 Gallegos, H.A., Schubert, J.E., Sanders, B.F., 2009. Two-dimensional, high-resolution modeling of
520 urban dam-break flooding: A case study of Baldwin Hills, California. *Advances in Water*
521 *Resources*, Volume 32, Issue 8, August 2009, Pages 1323-1335, ISSN 0309-1708,
522 <http://dx.doi.org/10.1016/j.advwatres.2009.05.008>.

523 Hallegatte, S., Green, C., Nicholls, R.J., Corfee-Morlot, J., 2013. Future flood losses in major
524 coastal cities, *Nature Climate Change* 3,802–806.

525 Horritt, M.S., Bates, P.D., 2002. Evaluation of 1D and 2D numerical models for predicting river
526 flood inundation, *Journal of Hydrology* 268, 87-99, Issues 1–4.

527 Kurganov, K., Petrova, G., 2007. A second-order well-balanced positivity preserving central-
528 upwind scheme for the Saint-Venant system, *Communications in Mathematical Sciences* 5(1), 133–
529 160.

530 I.Yu. Gejadze, J. Monnier, 2007. On a 2D 'zoom' for the 1D shallow water model: coupling and
531 data assimilation, *Comput Methods Appl Mech Eng*, 196, 4628–4643.

532 Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J.C.J.H., Mechler, R., Botzen, W.J.W.,
533 Bouwer, L.M., Pflug, G., Rojas, R., Ward, P.J., 2014. Increasing stress on disaster-risk finance due
534 to large floods, *Nature Climate Change* 4,264-268.

535 Lacasta, A., Morales-Hernández, M., Murillo, J., García-Navarro, P., 2014. An optimized GPU
536 implementation of a 2D free surface simulation model on unstructured meshes, *Advances in*
537 *Engineering Software*, 78, 1-15, <http://dx.doi.org/10.1016/j.advengsoft.2014.08.007>

538 Lacasta, A., Juez, C., Murillo, J., García-Navarro, P., 2015. An efficient solution for hazardous
539 geophysical flows simulation using GPUs, *Computers & Geosciences*, 78, 63-72,
540 <http://dx.doi.org/10.1016/j.cageo.2015.02.010>.

541 Leskens, G., Brugnach, M., Hoekstra, A.Y., Schuurmans, W., 2014. Why are decisions in flood
542 disaster management so poorly supported by information from flood models?, *Environmental*
543 *Modelling and Software* 53, 53-61.

544 Liang, Q., Borthwick, A.G.L., 2009. Adaptive quadtree simulation of shallow flows with wet-dry
545 fronts over complex topography. *Comput. Fluids* 38, 221-234.

546 Macchione, F., 2008. Model for Predicting Floods due to Earthen Dam Breaching. I: Formulation
547 and Evaluation. *J. Hydraul. Eng.* 134: 1688-1696.

548 Macchione, F. and Rino, A., 2008. Model for Predicting Floods due to Earthen Dam Breaching. II:
549 Comparison with Other Methods and Predictive Use. *J. Hydraul. Eng.* 134: 1697-1707.

550 Marks, K., Bates, P., 2000. Integration of high-resolution topographic data with floodplain flow
551 models. *Hydrol. Process.*, 14: 2109–2122. doi: 10.1002/1099-1085.

552 Masoero, A., Claps, P., Asselman, N. E. M., Mosselman, E., Di Baldassarre, G., 2013.
553 Reconstruction and analysis of the Po River inundation of 1951. *Hydrol. Process.* 27, 1341-1348.

554 Mason, D.C., Schumann, G.J.P., Neal, J.C., Garcia-Pintado, J., Bates, P.D., 2012a. Automatic near
555 real-time selection of flood water levels from high resolution Synthetic Aperture Radar images for
556 assimilation into hydraulic models: A case study. *Remote Sensing of Environment*. Volume 124.
557 Pages: 705-716.

558 Mason, D.C., Davenport, I. J., Neal, J.C., Schumann, G.J.P., Bates, P.D., 2012b. Near Real-Time
559 Flood Detection in Urban and Rural Areas Using High-Resolution Synthetic Aperture Radar Images.
560 *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 50, N°8, August 2012. Pages 3041-
561 3052.

562 Mazzoleni, M., Bacchi, B., Barontini, S., Di Baldassarre, G., Pilotti, M., Ranzi, R., 2014. Flooding
563 Hazard Mapping in Floodplain Areas Affected by Piping Breaches in the Po River, Italy. *J. Hydrol.*
564 *Eng.*, 19(4), 717–731.

565 Morales-Hernández, M., García-Navarro, P., Burguete, J., Brufau, P., 2013. A conservative strategy
566 to couple 1D and 2D models for shallow water flow simulation. *Computers & Fluids*, 81, 26-44.

567 Morales-Hernández, M., Lacasta, A., Murillo, J., Brufau, P., García-Navarro, P., 2014. A
568 Comparative study of accuracy and performance between a fully 2D GPU based and a 1D-2D
569 coupled numerical model in a real river. *Proceedings of International Conference on*
570 *Hydroinformatics, HIC* , 2014, New York City, USA.

571 Murillo, J., García-Navarro, P., 2010. Weak solutions for partial differential equations with source
572 terms: Application to the shallow water equations. *Journal of Computational Physics*, 229(11),
573 4327-4368, doi: 10.1016/j.jcp.2010.02.016.

574 Murillo, J., García-Navarro, P., 2012. Augmented versions of the HLL and HLLC Riemann solvers
575 including source terms in one and two dimensions for shallow flow applications, *Journal of*
576 *Computational Physics*, 231(20), 6861-6906, 10.1016/j.jcp.2012.06.031.

577 Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I - A
578 discussion of principles. *J Hydrol* 1970;10(3):282–90. [http://dx.doi.org/10.1016/0022-](http://dx.doi.org/10.1016/0022-1694(70)90255-6)
579 [1694\(70\)90255-6](http://dx.doi.org/10.1016/0022-1694(70)90255-6).

580 Rogers, B.D., Borthwick, A.G.L., Taylor, P.H., 2003. Mathematical balancing of flux gradient and
581 source terms prior to using roes approximate Riemann solver. *J. Comput. Phys.* 192, 422-451.

582 Sanders, B.F., Schubert, J.E., Detwiler, R.L., 2010. Parbrezo: a parallel, unstructured grid,
583 godunov-type, shallow-water code for high-resolution flood inundation modeling at the regional
584 scale. *Advances in Water Resources*, Volume 33, Issue 12, December 2010, Pages 1456-1467,
585 ISSN 0309-1708.

586 Schubert, J.E., Sanders, B.F., Smith, M.J., Wright, N.G., 2008. Unstructured mesh generation and
587 landcover-based resistance for hydrodynamic modeling of urban flooding. *Advances in Water*
588 *Resources*, 31 (12),1603-1621.Schubert, J.E., Sanders, B.F., 2012. Building treatments for urban
589 flood inundation models and implications for predictive skill and modeling efficiency. *Advances in*
590 *Water Resources*, 41, 49-64, doi: [10.1016/j.advwatres.2012.02.012](http://dx.doi.org/10.1016/j.advwatres.2012.02.012).

591

592 Schumann, G.J.P., Bates, P.D., Neal, J.C., Andreadis, K.M., 2014. Fight floods on a global scale.
593 Nature 507. 169.

594 Smith, L.S., Liang, Q., 2013. Towards a generalised GPU/CPU shallow-flow modelling tool.
595 Computers & Fluids, 88, 334-343, doi: 10.1016/j.compfluid.2013.09.018.

596 Soares-Fraza, S., Lhomme, J., Guinot, V., Zech, Y., 2008. Two-dimensional shallow-water model
597 with porosity for urban flood modelling. Journal of hydraulic research, Volume 46, Issue 1, Pages
598 45-64.

599 Toro, E., 1999a. Shock Capturing Methods for Free Surface Shallow Water Flows. Wiley, New
600 York.

601 Toro, E., 1999b. Riemann Solvers and Numerical Methods for Fluid Dynamics. Springer.

602 Vacondio, R., Dal Palù, A., Mignosa, P., 2014. GPU-enhanced Finite Volume Shallow Water solver
603 for fast flood simulations. Environ. Model. Softw. 57, 60-75.

604 Valiani, A., Begnudelli, L., 2006a. Divergence form for the bed slope source term in shallow water
605 equations. ASCE J. Hydraul. Eng. 146, 652-665.

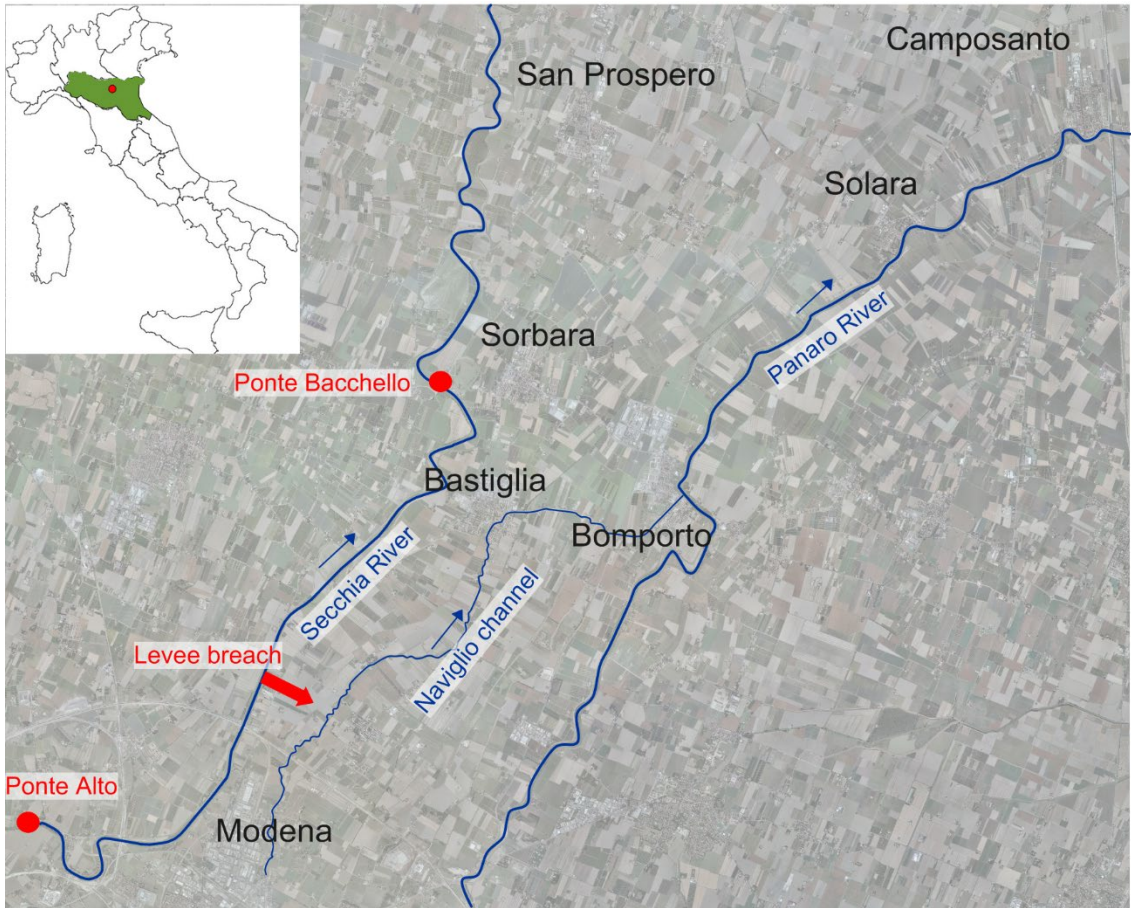
606 Valiani, A., Begnudelli, L., 2006b. Divergence form for bed slope source term in shallow water
607 equations. J. Hydraul. Eng. 132, 652-665.

608 Vázquez-Cendón, M.E., 1999. Improved Treatment of Source Terms in Upwind Schemes for the
609 Shallow Water Equations in Channels with Irregular Geometry, J. Comput. Phys., 148(2), 497-526,

610 Viero, D. P., D'Alpaos, A., Carniello, L., Defina, A., 2013. Mathematical modeling of flooding due
611 to river bank failure. Adv. Water Resour. 59, 82-94.

612 Zhou, J., Causon, D., Mingham, C., Ingram, D., 2001. The surface gradient method for the
613 treatment of source terms in the shallow-water equations. J. Comput. Phys. 168, 1-25.

614 Zhu, Y.H., Visser, P.J., Vrijling, J.K., 2004. Review on embankment dam breach modeling. Taylor
615 and Francis Group, 1189-1196.





(a)



(b)

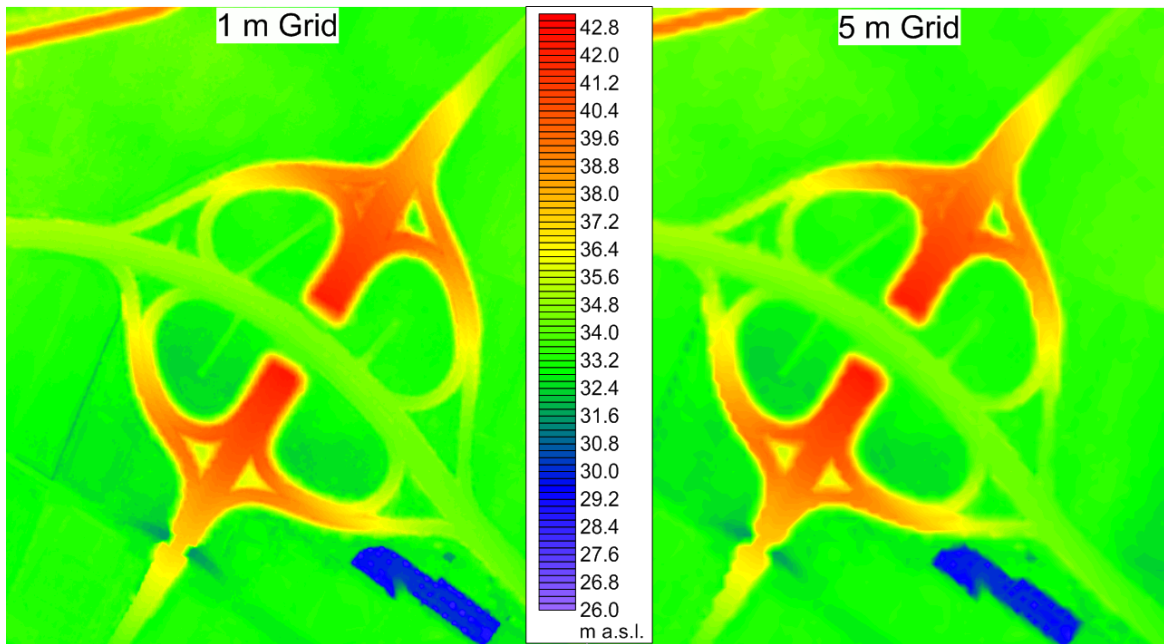


Figure 3. Bathymetry detail of highway intersection with original 1m resolution (left) and with corrected 5m resolution (right).

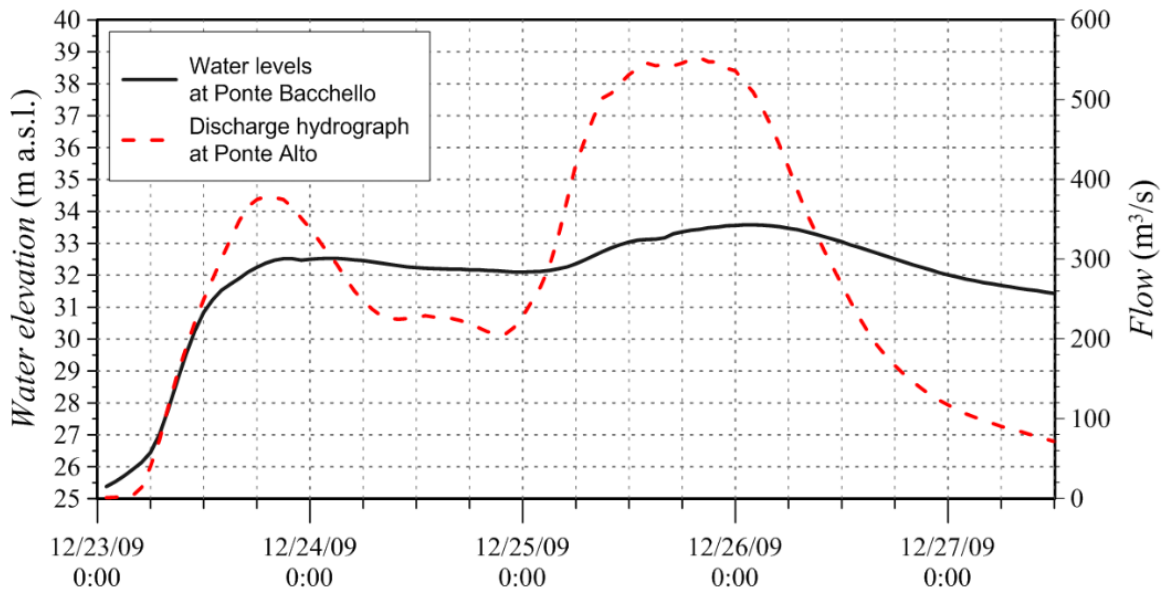


Figure 4. Flow and stage hydrographs of the December 2009 flood event at the gauging stations of Ponte Alto and Ponte Bacchello.

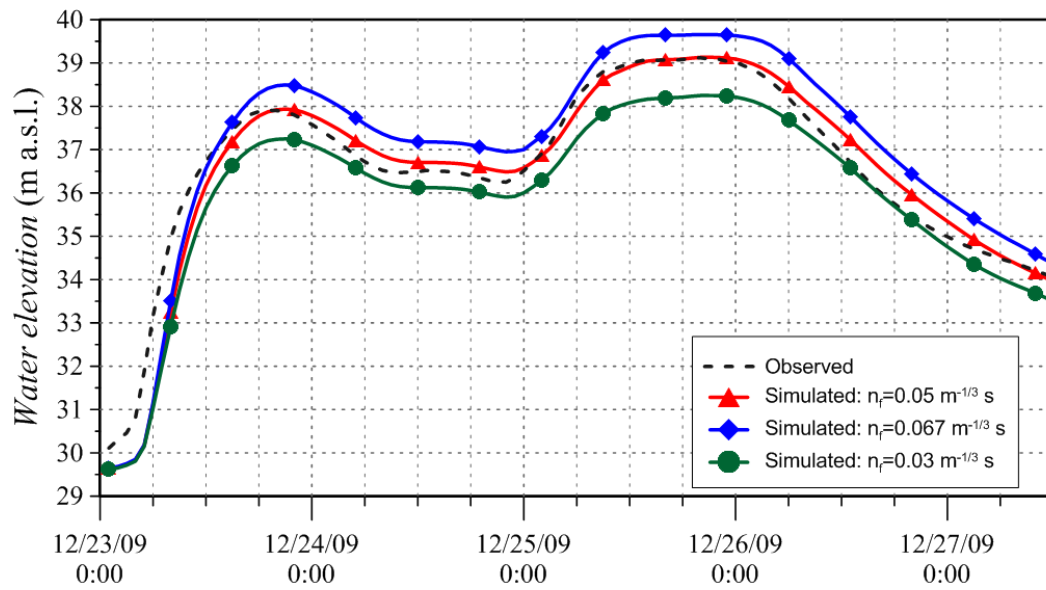


Figure 5. Stage hydrographs at Ponte Alto gauging station for the event of December 2009: comparison between observed and simulated data with different values of roughness.

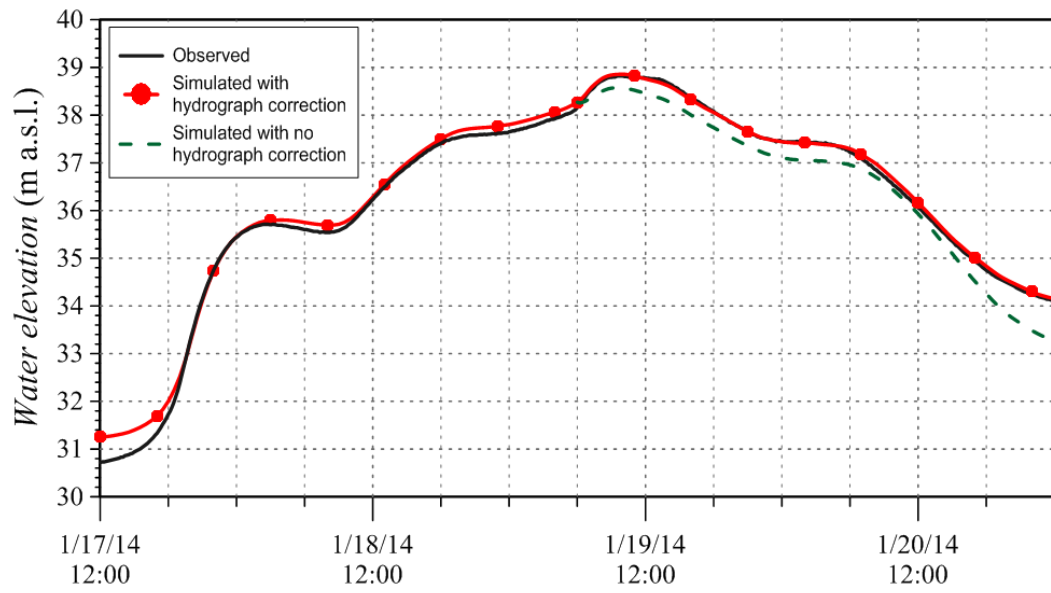


Figure 6. Observed and simulated stage hydrographs at Ponte Alto gauging station for the event of January 2014.

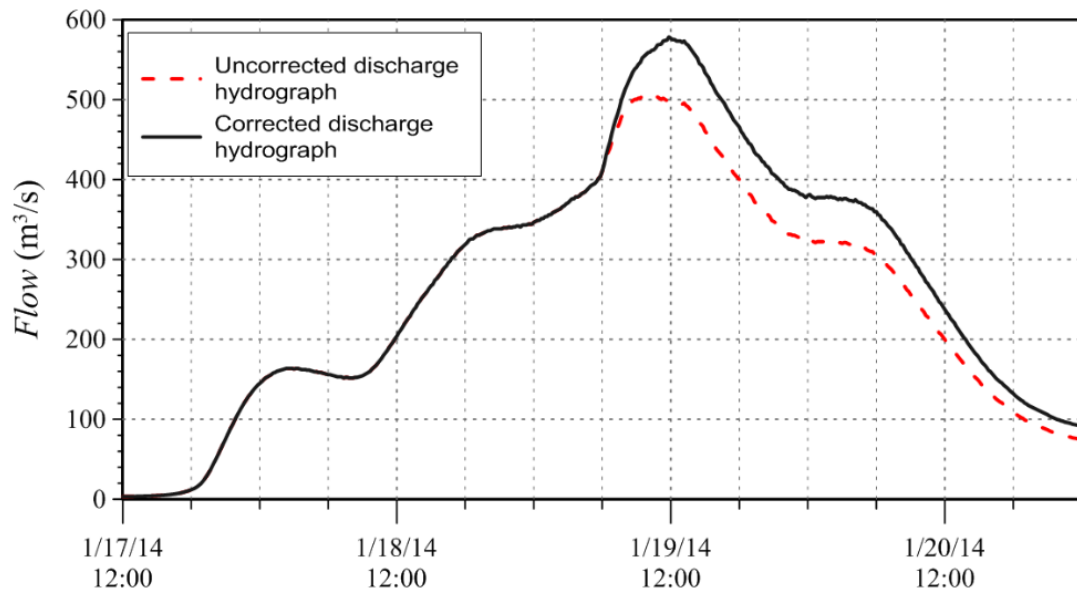


Figure 7. Uncorrected and corrected discharge hydrographs imposed as upstream boundary condition (Ponte Alto) for the flood event of January 2014.

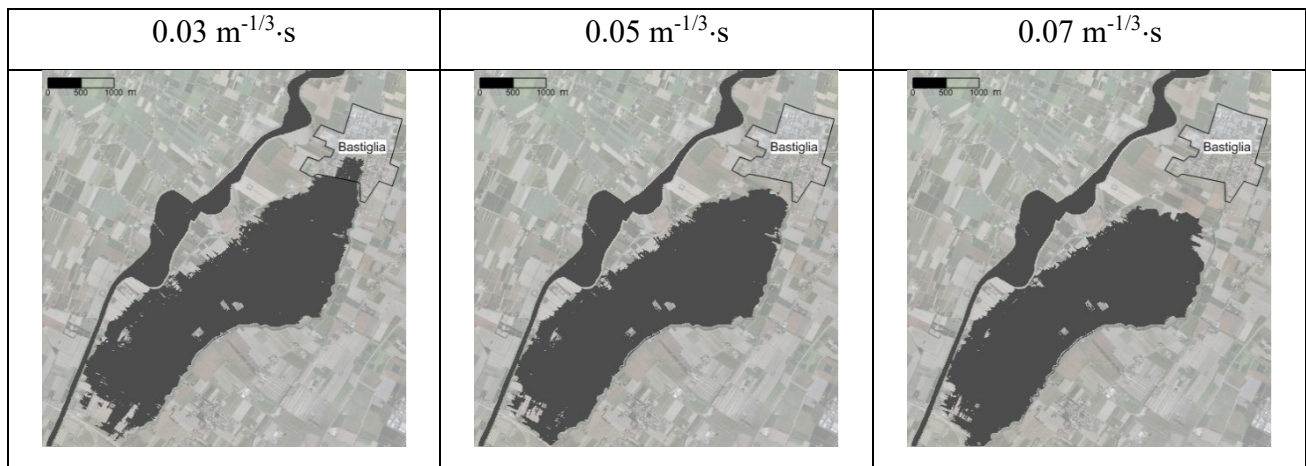


Figure 8. Map of the flooding extent at 0:45 PM on 19th January 2014 for the three simulation in presence of different roughness for the rural areas.

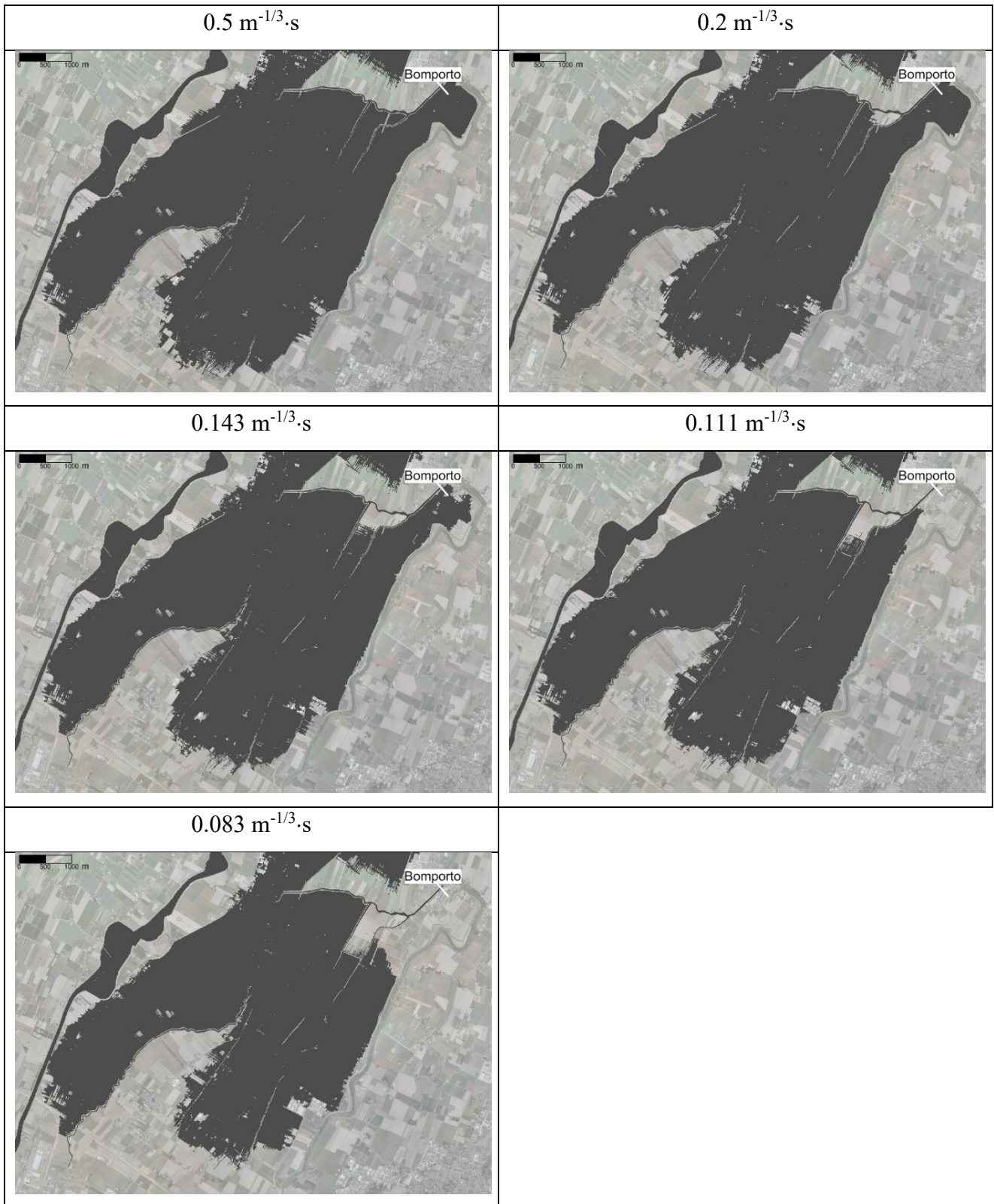


Figure 9. Map of the water depths at 10:30 AM on 20th January 2014 for the five simulations in presence of different roughness for the built-up area areas.

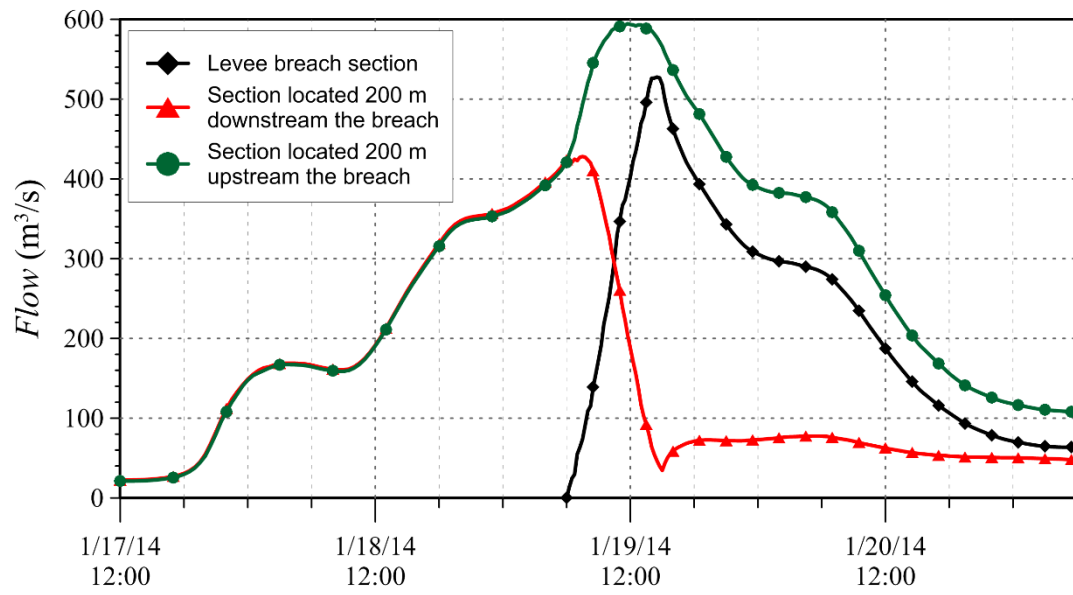


Figure 10. Discharge hydrographs at the sections of the breach, 200 m upstream and 200 m downstream along the river.

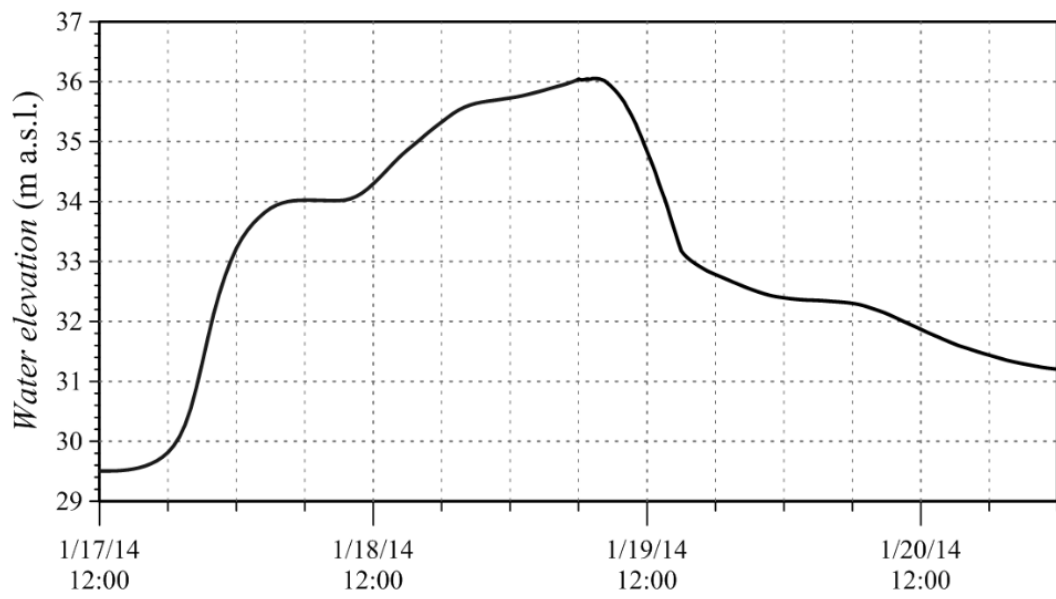


Figure 11. Stage hydrograph referred to a point in the river close to the breach section.

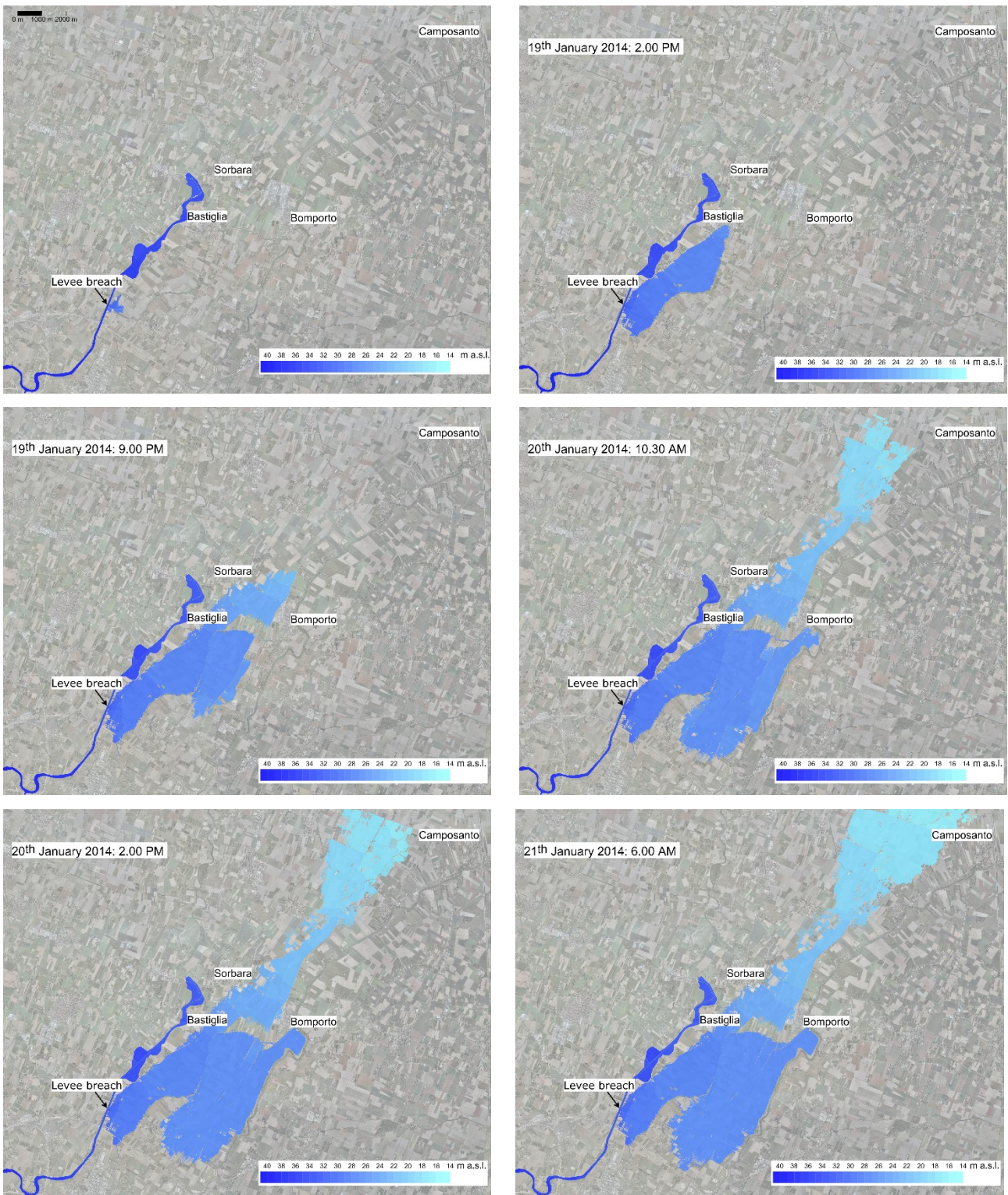
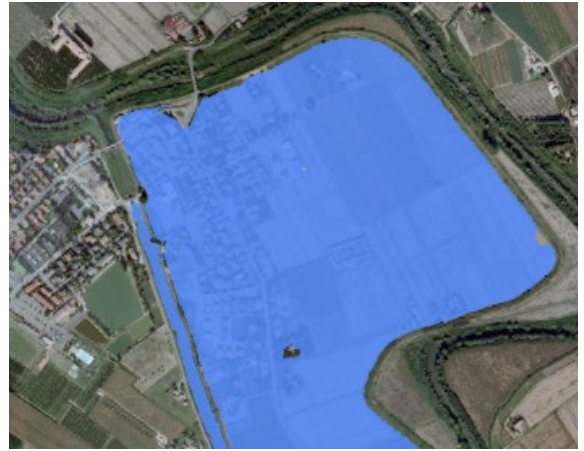


Figure 12. Numerical reconstruction of the flooding event. (a) 1 hour after the bank failure, (b) flooding of Bastiglia, (c) 15 hours after the bank failure, (d) flood wave arrival at Bomporto, (e) 32 hours after the bank failure, (f) 48 hours after the bank failure.



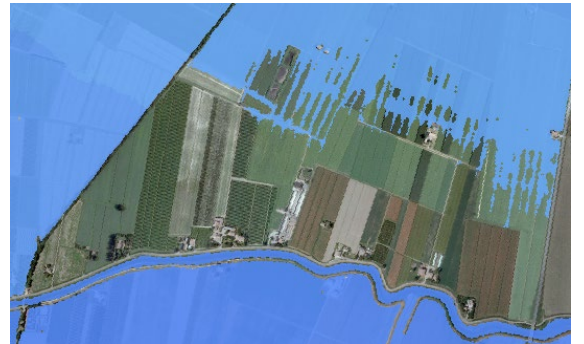
(a)



(b)



(c)



(d)

Figure 13. Bomporto town, 22nd January 2014 at 1.30 PM: comparison among simulated flooded area (b, d) and aerial views (a, c).



Figure 14. Comparison between the SAR image (foreground) and the simulated flooding (red area).

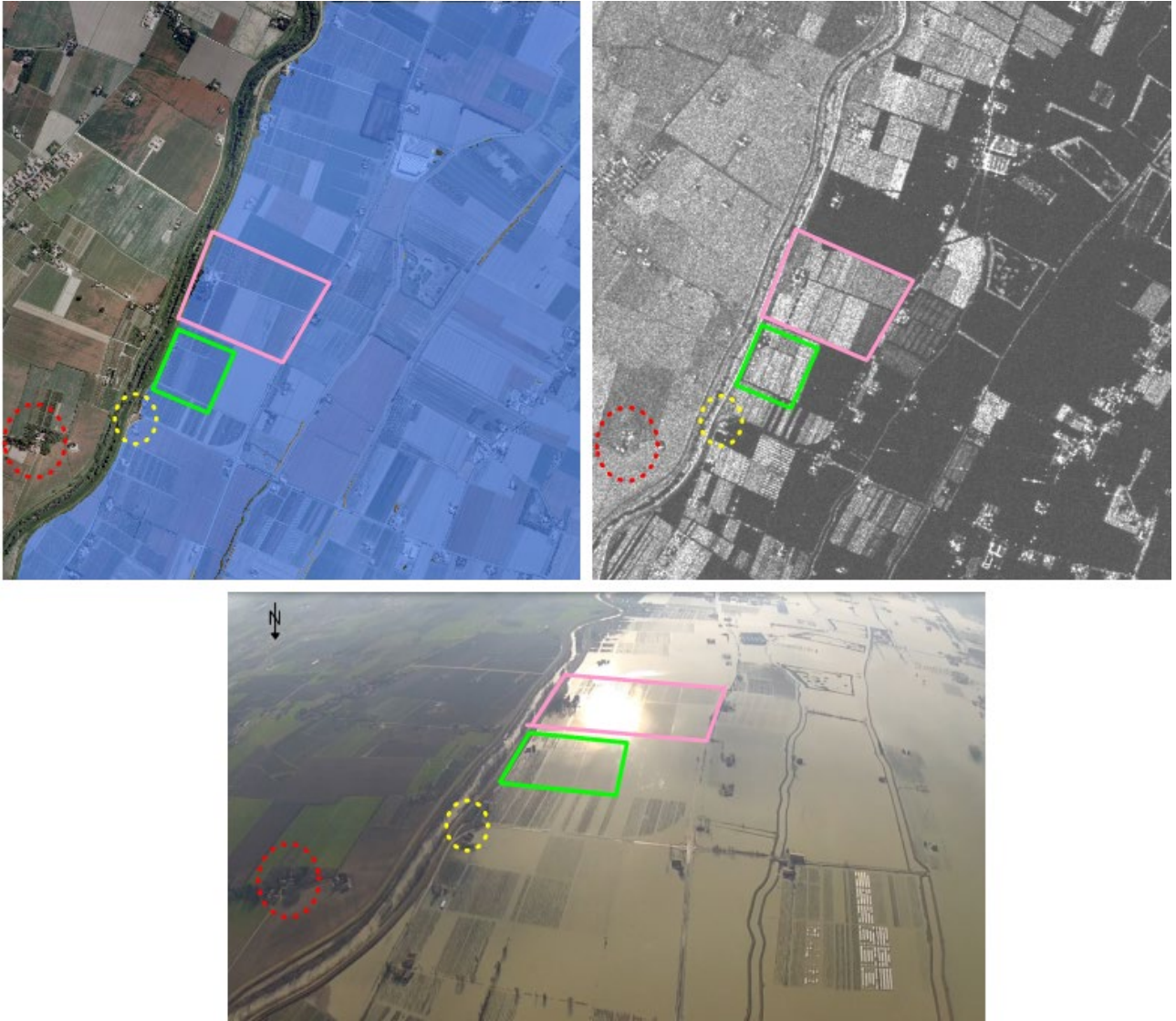


Figure 15. Comparison among computed results, SAR image and aerial image focusing on some parcels of land detected as not flooded in the binary SAR observation for the event under investigation.

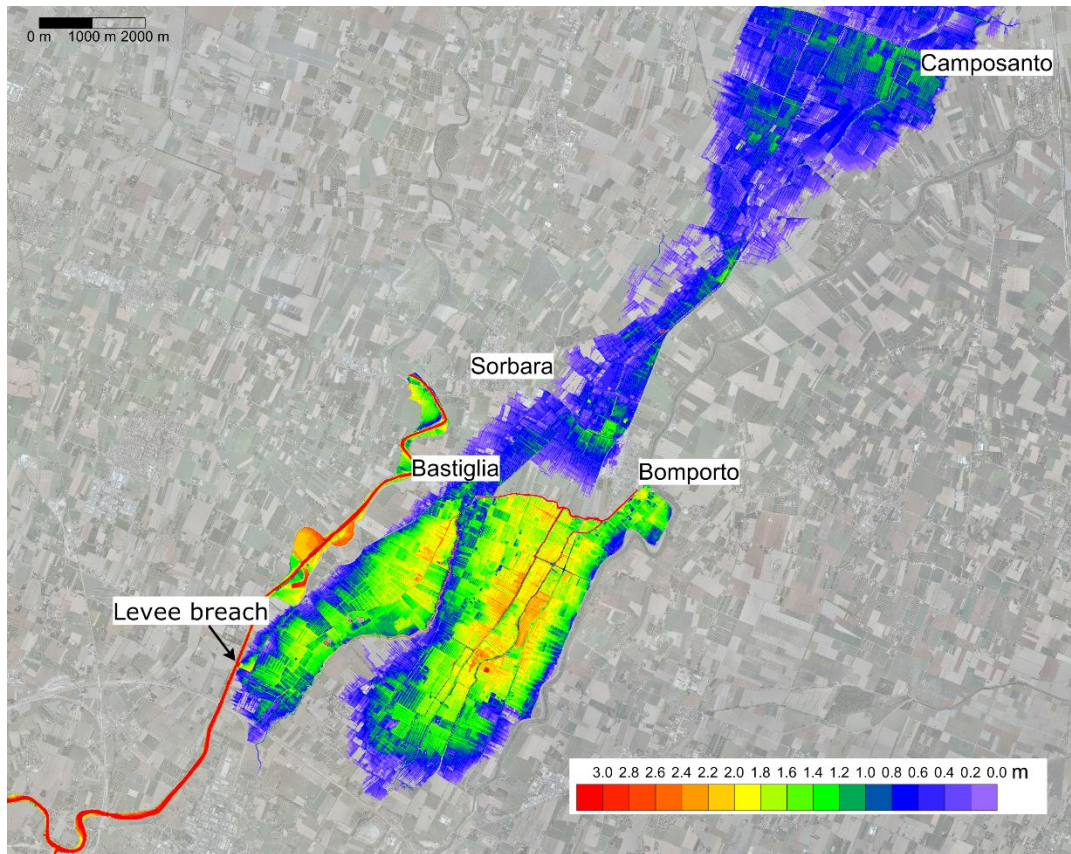


Figure 16. Map of simulated maximum water depths for the January 2014 event

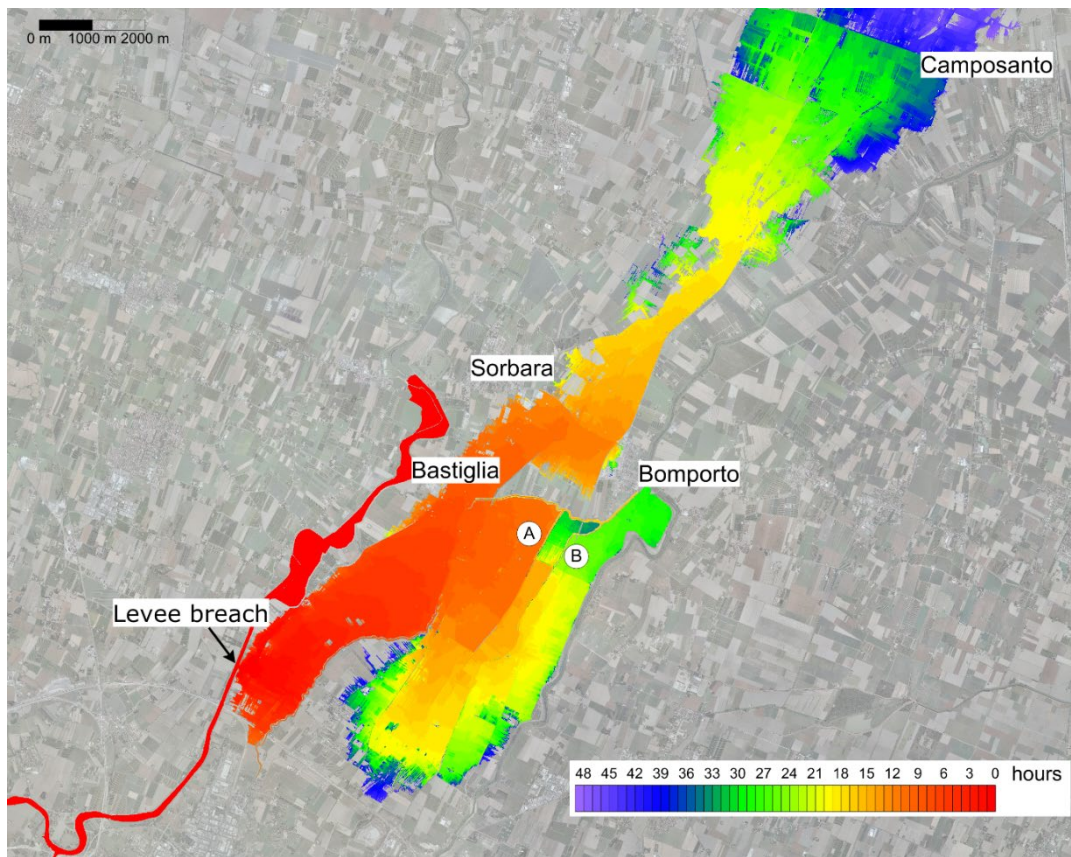


Figure 17. Map of flooding arrival times. Time zero is referred to the opening of the breach.

n_f ($\text{m}^{-1/3}\cdot\text{s}$)	0.067	0.05	0.03
E_h (-)	86.4	94.2	87.1

Table 1. Nash-Sutcliffe efficiency for the three different roughness coefficients considered