Reconstruction and Analysis of the Po River Inundation of 1951

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Abstract:

Flood inundation models have become essential tools in flood risk management, being used also in the analysis of historical flood events, which is often needed for a reliable assessment of the potential flood hazard. This study aims at reconstructing the 1951 inundation of the Polesine Region, Italy. The 1951 flooding was a mayor natural catastrophe that caused a large inundated area (1080 km^2) and produced devastating social consequences. The reconstruction of the 1951 hydraulic conditions is based on partial knowledge of discharges and water stages at the Pontelagoscuro gauging station (downstream of the 1951 levee breach) using extrapolation of the rating curves beyond the measurement range. This is, even today, something open to uncertainty. We applied a decoupled hybrid approach to the hydraulic modeling: a 1D model is used to simulate the flow into the river and to compute the flow through the levee breach; this result is then adopted as the inflow condition for a 2D model application on the inundated area. A good agreement between the patterns of the observed and reconstructed inundation areas was found, and the timing of the inundation was also found to be close to the information derived from the historical chronicles. The results of the flood inundation modelling exercise provide two practical insight: (i) obstacles in the floodplains increased the flooded area by 40% and prolonged the time to reach the sea from 5 to 15 days, (ii) the peak discharge of the event was overestimated by up to 20%

INTRODUCTION

The increased socio-economic relevance of flood risk assessment has led to the development of innovative methodologies for the hydraulic simulation of river and floodplain systems, and has promoted the development of new techniques for flood hazard and inundation mapping (e.g. Di Baldassarre *et al.*, 2010; Vorogushyn *et al.*, 2010). In particular, one-dimensional (1D) and two-dimensional (2D) hydraulic models have been used more and more as numerical tools (e.g. Aronica *et al.*, 2002; Hesselink *et al.*, 2003; Pappenberger *et al.*, 2005; Horritt *et al.*, 2007) as these models have proven to be able to effectively simulate river hydraulics and floodplain inundation at different levels of detail (e.g. Horritt and Bates, 2001, 2002). Flood inundation models appear also to be useful tools for the reconstruction and analysis of historical events (e.g. Di Baldassarre *et al.*, 2009b; Horritt *et al.*, 2010), which can be very important to provide a comprehensive assessment of exposure to floods and to develop flood risk management plans as required by the recent Floods Directive 2007/60/EC (European Commission, 2007).

In this context, this paper describes the analysis and reconstruction of the 1951 inundation of the Polesine Region, Italy. The 1951 event was a natural catastrophe and had major hydrological relevance, as during that event, the historical maxima of discharge and water stage were observed in the downstream part of the Po River, even though a breach occurred while levels were rising. The 1951 peak discharge is therefore a crucial value for flood assessment in the lower Po region, because many studies on flood risk management in the Po River have been based on the estimated peak discharge of the 1951 event. The height of the levee system of the Po River, for instance, is almost everywhere established on a design flood wave (SIMPO, 1982), based on discharges 10% higher than the ones estimated for the 1951 event.

The objective of this research is twofold: (i) to show the applicability of a new approach in reconstructing historical inundation events by means of hydraulic modelling and (ii) to reconstruct discharges and water stages at the Pontelagoscuro's gauging station (downstream of the 1951 levee breaches), reaching a correct estimate of the maximum values, after validation by means of the results of the outflow modelling.

The whole approach is compliant with the uncertainty in the rating curves, which are known to affect flood discharge data (e.g. Pappenberger *et al.*, 2005; Di Baldassarre and Montanari, 2009; Di Baldassarre and Claps, 2011). Flood discharges are usually not directly measured, but derived from observed water stages by means of a rating curve. This step entails a significant uncertainty in the results, which becomes more relevant when extrapolating the rating curve far beyond the range of the calibration measurements. One of the possibilities to validate rating curves in the range of large discharges is to reconstruct a single significant value, as a historical maximum, by means of accurate hydraulic modelling. In that case, model accuracy depends on the reliability of initial and boundary conditions. When historical inundation events are considered, it is quite difficult to reconstruct initial and boundary conditions. Therefore, a detailed analysis and reconstruction of the observed inundation areas, volumes and timing can help in reaching a reasonable validation of the conditions assumed for the model and a reasonable estimate of the peak discharges. These estimates can then be used to verify the hypotheses made on the rating curves, as will be shown later in this paper.

Therefore, the main contribution of this paper is to validate the estimate of the flood peak discharge using the outflow model to check the consistency in all aspects of the inundation. The 2D modelling of the outflow dynamics can provide detailed information about flood wave velocity, inundated areas and volumes that can be used for subsequent analysis or for validating the 1D model results in terms of the outflow discharges. In this study, which reconstructs an historic event of 60 years ago, we decided to verify and validate the results using the recorded timing of the inundation, which is one of the clearest sources of information available. This estimate is less uncertain than that obtainable by only extrapolating the rating curve beyond the measurement range. The reconstruction of the historical inundation event is tackled by means of the HEC-RAS and SOBEK numerical models. Model results were validated using data on water levels, the recorded timing of the peak, the extension of the inundated area and the timing of the inundation as obtained from chronicles and reports. Boundary conditions for the 1D model were built using recorded levels at two gauging stations, one located upstream and another downstream the main levee breach. Hydraulic conditions in these sections will be extensively discussed in the following.

STUDY AREA AND AVAILABLE DATA

The Po River is the longest river in Northern Italy, with about 650 km length, starting in the Western Alps and draining into the Adriatic Sea, where it creates a large delta formed by hundreds of minor channels. With an area of 71 000 km^2, the drainage basin is also the largest in Italy. It is characterized by a peculiar hydrographic and topographic configuration, due to the presence of both Alpine and Apenninic rivers, that leads to a complex response to precipitation events, especially in terms of timing of flood peaks coming from the Apenninic and Alpine tributaries.

The hydraulic modelling analysis was performed on a 90-km reach of the lower part of the River Po (Figure 1), between the gauging stations of Ostiglia and Papozze. The investigated reach excludes the branches that are part of the Po Delta, as they are located downstream of the Papozze gauging station. Levee breaches that caused the catastrophic flood on the night of November 14th 1951, near the village of Pontelagoscuro, were in the considered reach. Within the studied reach, the riverbed is basically canalized between two lateral banks, with an overall width of about 1 km that is reduced to 400 m at a few locations, such as near the sections of Revere and Pontelagoscuro.

The area affected by the inundation, i.e. the Polesine region, consists of the plain between the lower portion of the rivers Adige and Po, up to the Adriatic Sea that defines the East border of this region. The Polesine region is marked by the darker grey color in Figure 1. Morphologically, the Polesine region is a wide lowland area, with large areas below sea level. A network of embanked rivers and channels crosses the region, defining a number of sub-areas that are isolated from each other.

Figure 1. Test site: the lower portion of Po River and The Polesine Region; location of Ostiglia (Δ) and Papozze (▲) gauging stations, upstream and downstream limits of the 1D model

Application of the 2D model will demonstrate how separation of sub-areas, due to man-made obstacles such as roads and embankments, significantly affected the flooding dynamics.

Available data

The relevant data were collected with the help of the Interregional Agency for the Po River (Agenzia Interregionale per il Fiume Po, AIPO, Italy). The data consisted of time series of river discharges and water levels, river bed geometry, the morphology of the flooded areas and the timing of inundation. Being related to an event of 60 years ago, data collection required patience and care.

Recorded water stages at Ostiglia and Pontelagoscuro's gauging stations are reported in the 1951 Hydrological Yearbook (Servizio Idrografico e Mareografico Nazionale, 1956). These values are considered reliable, except for the peak value at the section of Pontelagoscuro as it is located downstream the main levee breach. Different references give different values of the peak water level at Pontelagoscuro (see Table I).

Table I. 1951 peak water level at Pontelagoscuro

Reference	**Water level at Pontelagoscuro** *m ASL*
1951 Hydrological Yearbook – Section F	12.79
Civil Engineering Office of Rovigo	13.70
Ufficio Idrografico Magistrato del Po	12.49
Caratteristiche idrometriche del tratto inferiore del Po, M. Rossetti (1960)	13.58

The primary levee, where the upstream breaches occurred, had a crest elevation of 13.35 m asl in 1951. As the failure was due to overtopping, the water level had to be higher than the levee crest. For this reason, we consider valid the peak water level of 13.58 m asl given by Rossetti (1960) and used by Mainardi (1991).

The opening of the three breaches on the primary levee is well documented in the chronicles (6.30 PM of 14th November at Paviole and around 8.30 PM at Bosco-Malcantone). As until the 30th November, it was impossible, due to the impressive outflow, to carry out the bathymetric survey, no information about breach development was found. The only available data (Figure 2) is the final breach geometry, as reported by Sbrana (1952). We assumed the breach to open instantaneously. This assumption does not have a significant effect on the results of the inundation model, because of the long duration of the flood that lasted more than 16 days (e.g. Di Baldassarre *et al.*, 2009a). We defined the bottom of the breaches at the same elevation as the ground level behind the levee (around 7 m asl). Therefore, the scour hole was not taken into consideration.

The propagation of the flood is well described in the studies by Mainardi (1991) and Govi and Turitto (2000). The inundation started on the 14th of November 1951 at 6.30 PM, when the first breach occurred. The maximum flood extent occurred two weeks later, the 27th of November, when the flood water reached the sea. The total inundated area was around 1080 km^2, and depths up to 6 m were observed in the area near the city of Adria. Of relevant importance is the timing and the sequence of inundation in the sub-areas defined by the minor-channel

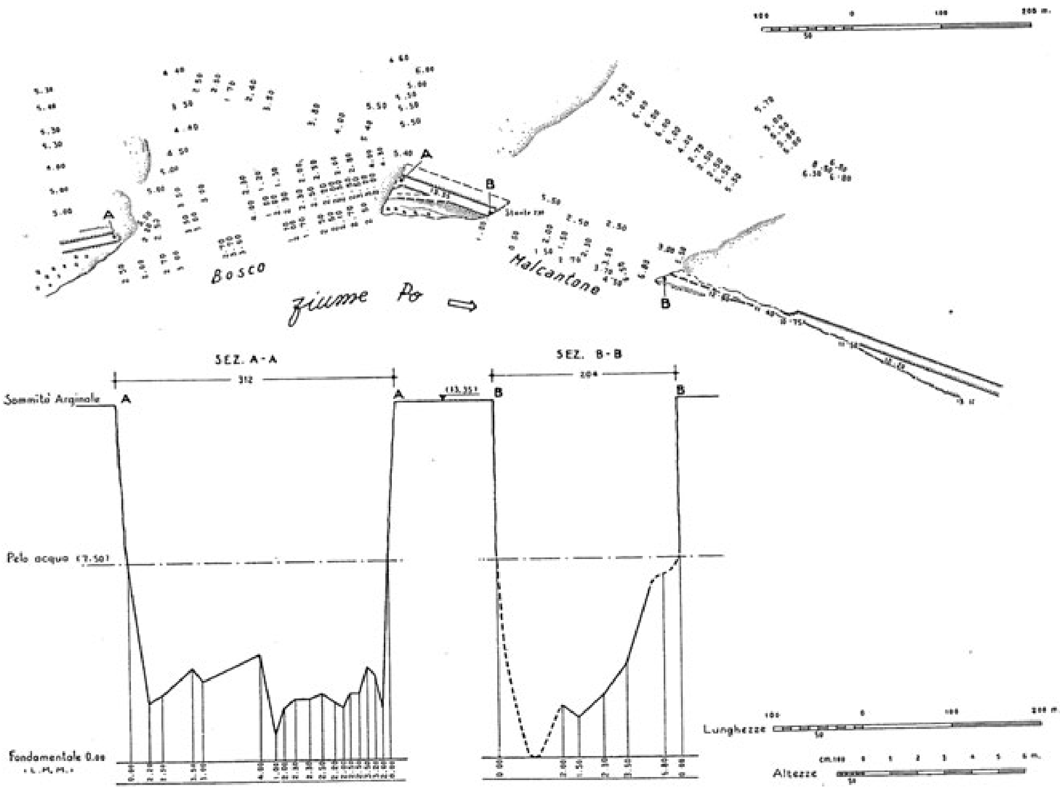

Figure 2. Final geometry for Bosco and Malcantone breaches, as reported by Sbrana (1952)

dikes: Rovigo was flooded after 50 h (distance of 24 km) and Adria (40 km) was flooded after 60 h.

INUNDATION MODELLING

A hybrid decoupled methodology, based on the combination of 1D and 2D approaches, was used to perform the numerical simulations. In this application, as the Po levees are about 10 m higher than the flooded area, the assumption of no hydraulic interaction between the two currents can be considered reasonable. This combined type of modelling was already demonstrated as valid by Aureli *et al.* (2006) for a similar reach of the River Po. Compared to a fully 2D model the 1D–2D approach has the advantage of a consistent reduction in the computation time.

In the present study, a freeware 1D model (HEC-RAS; Hydrologic Engineering Center, 2001) was used to simulate the flow in the river and to compute the flow through the levee breach. The simulated flow through the breach was then adopted as the inflow condition for the 2D model of the inundated area (SOBEK; Delft Hydraulics, 2000). The advantages of using a fully fledged code like SOBEK for the 2D part is that this software can suitably simulate the flood propagation on a plain characterized by minor channels, embankments and dikes, elements that made the inundation sequence particularly complex.

1D modelling. The geometry of the 93-km reach of the River Po, from Ostiglia (Mantova province) to Papozze (Rovigo province), was described by using 21 cross sections surveyed in 1954 by the Magistrato del Po. The automatic routine of the HEC-RAS geometric data editor was used to interpolate between these cross sections. The stage-discharge relations used as boundary conditions for the 1D HEC-RAS model were the historical (1954) rating curves at Revere and Pontelagoscuro (measurement range up to 4000 m^3/s). The roughness coefficient was used as a calibration parameter. The model calibration was performed in a steady-state mode, comparing results for different Manning coefficients with the historical records of discharges and water levels. Considering also the uncertainty associated to direct measurements, we were able to define a confidence interval for the results in a range of Manning coefficients, n, from 0.029 to 0.031 $s/m^{1/3}$. Results for the best fitting parameter ($n = 0.030$ $s/m^{1/3}$) are shown in Figure 3.

After the calibration of the 1D model, the November 1951 flood hydrograph was simulated. As flow boundary condition, the hydrograph at the upstream end of the reach (Ostiglia) was used. The hydrograph was derived from the water stages available at the Ostiglia gauging station, reported in the 1951 Hydrological Yearbook. Given that the backwater length for this reach is between 14 and 20 km (Castellarin *et al.*, 2009), the water levels at Ostiglia were not significantly affected by the breaches that occurred 40 km downstream. A constant slope along the river was assumed to estimate the water level at the downstream boundary at Papozze. The three known levee breaches (located at Bosco, Malcantone and Paviole) were defined within HEC-RAS by modelling the left bank as a lateral structure and then imposing the failure, by lowering of the structure at a fixed time. As there were some uncertainties about the historical observation of the growth rate and the ultimate depth of the breaches, their geometry and dynamics were imposed using the following assumptions: (i) the formation of scour holes, caused by the impressive outflow, was not taken into consider-

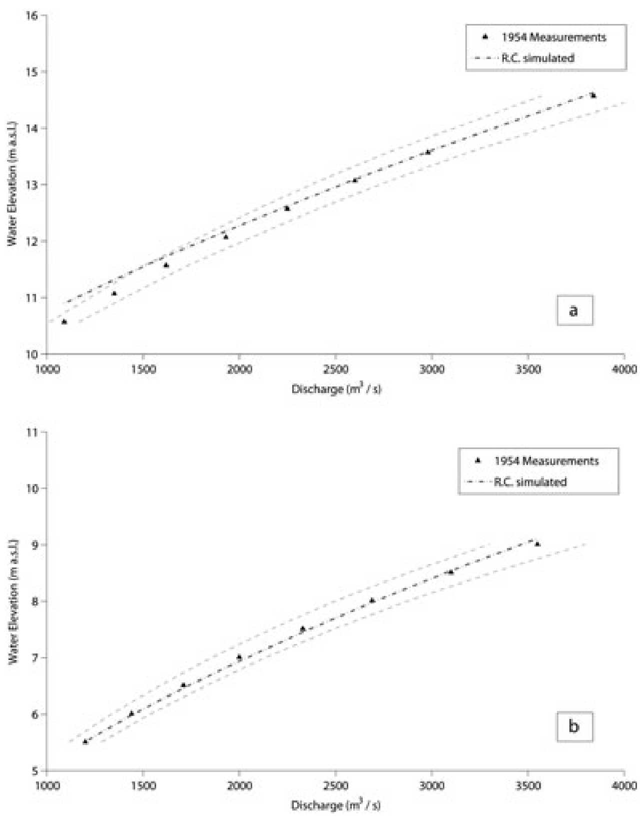

Figure 3. Rating Curves at Revere-Ostiglia (a) and Pontelagoscuro (b). The stage-discharge values measured in 1954 (grey triangles) are compared with the reconstructed rating curve obtained using Manning's coefficient n = 0.03 s/m1/3 (black dotted line). The figure also takes into account a 7% uncertainty range (grey dashed line) as given by Di Baldassarre and Montanari (2009)

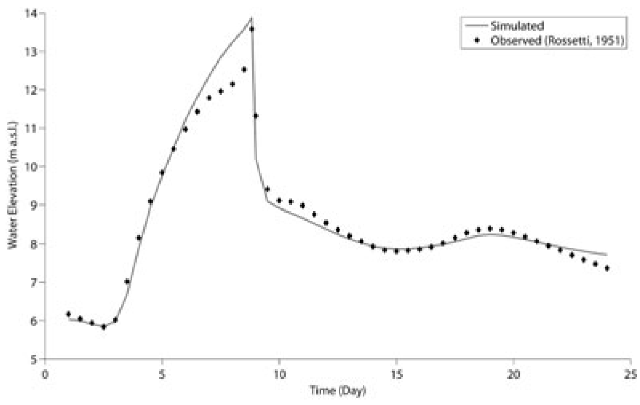

Figure 4. Model evaluation: observed and simulated stage hydrograph in the middle of the reach (Pontelagoscuro) during the 1951 event. The visible difference between simulated and observed levels, just before the flow peak, is due to the non-uniform storage characteristic of the Po-system as described in Jansen *et al.* (1979)

ation for modelling the depth of the breach; (ii) the breach was assumed to occur instantaneously, an assumption that does not affect the results of the model because the duration of the Po flood is long in comparison to the duration of breach growth (Di Baldassarre *et al.*, 2009a).

The model results have been validated by comparing the simulated water levels with the observed hydrograph (Figure 4) at Pontelagoscuro, as reported in the 1951 Hydrological Yearbook. This station is located between the two breaches and in a central position along the considered reach. From Figure 4, one can recognize that in the first part of the hydrograph, just before the peak flow, there is a clear difference between the simulated and observed levels. This is a peculiarity of the non-uniform storage characteristics of the Po system (Jansen *et al.*, 1979). Along the Po River, floodplains are protected from minor events by a secondary levee system located near the channel banks. When the flood discharge overtops these levees, the peak of the flood wave is cut due to the storage effect of closed (inactive) floodplains beyond the secondary levees. In the case of a major event, such as that of 1951, the Po system may fail: once the floodplain is filled up, the water level in the river rises rapidly, as additional storage of water is impossible. The 1D model can account for the temporary storage in inactive floodplains. However, in the present study, this detailed simulation has not been attempted, both for the insufficient data and because the levee failure occurred much later, when no storage effects occurred. Figure 4 shows that the peak value was reached after the end of the non-uniform storage and is well reconstructed by the model.

2D Modelling. To simulate the flow in the flooded area, a 2D model (SOBEK) was used. The simulated flow through the breaches was used as boundary condition. The topographic data of the inundated area consisted of a 90-m resolution digital elevation model derived by the NASA SRTM project (Farr *et al.*, 2007). The SRTM data have an original spatial resolution of 90 m, that we averaged to a coarser resolution of 190 m to reduce the random vertical noise and to remove small imperfections in the DEM. For flat regions, like the Polesine plain, the magnitude of the random vertical error can be lower than 2 m (Rodriguez *et al.*, 2006). It is important to remark that this geometry represents the terrain configuration in February 2000, the time of the Shuttle Endeavour Mission, and not the original 1951 topography. At the time of the event under study, there were differences due to the morphological characteristics of the Polesine Region (a lowland plain, part of an extending delta). To deal with this level of uncertainty, objects such as road embankments, channels and levees that were present in 1951 and that significantly affected the flood dynamics were included in the model. Given the role played in the inundation dynamics, a particular attention was dedicated to recovering and reconstructing the historical configuration of these man-made obstacles. Since no backwater effects were involved, 1D and 2D models are decoupled. Therefore, the topographical model needs to be consistent only with the relative ground elevations, and so accuracy in absolute elevations is not an issue in this case. Given the extension and the topography of the study area, a flat plain with extremely low differences in elevation, and that we averaged our grid to a coarser resolution, we can assume that vertical random errors do not affect significantly our results.

The 2D model results were verified by comparing the observed flood extent map of the November 1951 event (reported in the specific annex, Section F, of the 1951 Hydrological Yearbook) with the simulated maximum inundation extent (Figure 5). To evaluate the match between the observed and simulated areas, a measure of fit, defined by Horritt *et al.* (2007), was used:

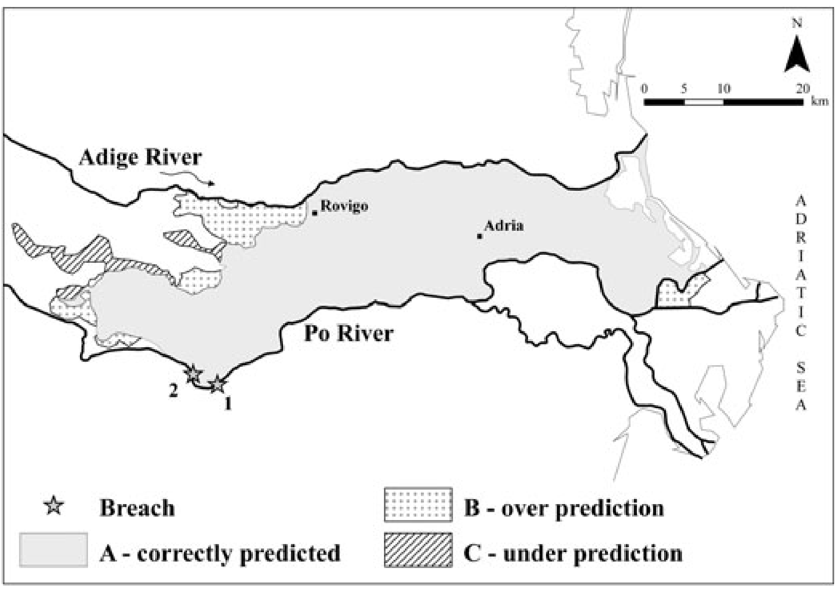

Figure 5. Simulated and observed inundation areas; A, B and C zones are represented to have a measure of fit as given by Horritt *et al*. (2007). The figure also shows the location of the 1951 levee breaches that occurred in Paviole (1) and Bosco-Malcantone (2)

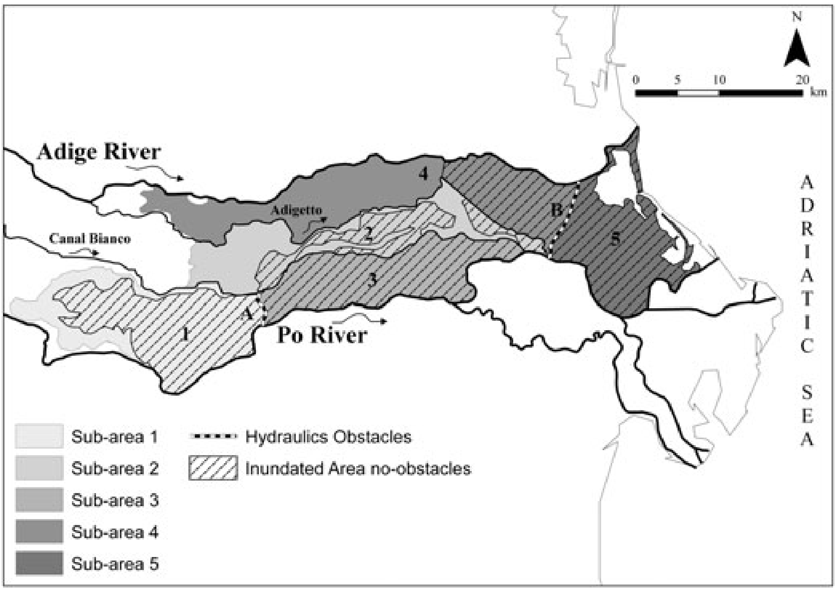

Figure 6. Sub-areas (from 1 to 5) that defined the steps of the inundation. The main hydraulic obstacles, Fossa di Polesella (A) and Canale di Valle (B) are reported. The results of a simulation in an obstacle-free scenario is also shown in this figure (black dashed area)

$$F = \frac{A}{A+B+C} \cdot 100 \quad (1)$$

where A is the area correctly predicted as wet by the model, B is the area predicted as wet but observed as dry (over-prediction) and C is the wet area not predicted by the model (under-prediction).The measure of fit F was found to be about 87%. Considering that several data were retrieved just from the chronicles (Lugaresi, 2001), this appears to be an encouraging outcome.

The timing of inundation has also been investigated and used to validate the model results, by reconstructing the inundation sequence in the sub-areas defined by the river and by minor-channel embankments (Figure 6). The numbering of sub-areas defines the steps of the inundation sequence. Only for sub-areas 2 and 3 there are some differences between observed data and model results: in the chronicles, the inundation is reported to occur at the same time in these sub-areas, but the model simulates a delay in the inundation of the eastern part of sub-area 2. It is interesting to notice that the presence of obstacles in the flood plain forced the flow into defined routes, hampering the flow towards the sea and causing the inundation of areas located upstream of the breaches (the western part of sub-area 1 in Figure 6) and outside the natural drainage path (the western part of sub-area 4 in Figure 6). In detail, two main obstacles transverse to the natural flow direction (Fossa di Polesella and Canale di Valle) had deeply affected the inundation dynamics and timing, while the minor channel levees (Adigetto and Canal Bianco) played an important role in constraining the flow in defined routes and dividing the plain in separated polders.

Results from the 2D model application give an indication of the correct estimate of the total volume through the levee breaches, which amounts to around 37 million m^3.

To better understand how and how much hydraulic obstacles affected the dynamics of the flood wave propagation over the plain, a simulation in an obstacle-free scenario was run. The results given by this scenario (dashed area in Figure 6) show that the inundated area would have been 30% smaller than the observed one and the time to reach the sea would have reduced to 5 days, instead of 15. These results, which underline the impact of artificial obstacles on flood propagation, are of interest as they concern also the present-day flood management plans for the region under study.

Table II. Results of the reconstruction of the 1951 inundation

Cross section	Progressive distance from Tanaro *km*	1951 event: Past study (SIMPO '82) Discharge *m^3/s*	1951 event: Past study (SIMPO '82) Water level *m ASL*	1951 event: This study Discharge *m^3/s*	1951 event: This study Water level *m ASL*
Revere-Ostiglia	510	11 260	19.76	9500–10 100	19.48–19.49
Pontelagoscuro	565	11 580	14.20	9100–9650	14.19–14.22

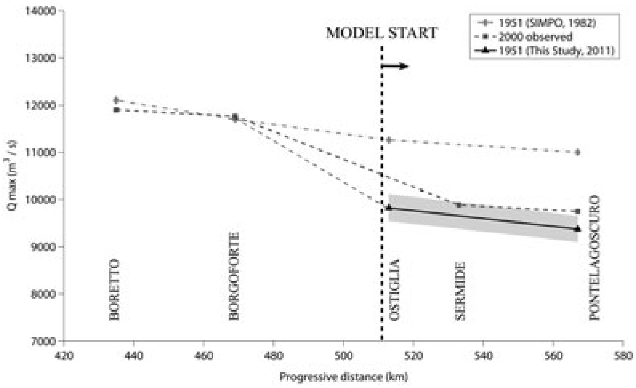

Figure 7. Trend of maximum discharge along the Po River. Reconstruction of 1951 discharge made by PAST studies (light-grey dotted line) and THIS study (black solid line) are compared with the 2000 event discharges (dark-grey dotted line). The light-grey area around the estimated values represents the uncertainty

DISCUSSION: CRITICAL ISSUE CONCERNING THE 1951 PEAK DISCHARGE ESTIMATE

Based on the results of the flood inundation modelling, some considerations about the relation between water stages and discharges can be drawn. Table II shows the discharge values reconstructed previously in a no-breach scenario using another model of the Po River (AdBPO, Po River Basin Authority) and the ones obtained in the present study. To highlight the uncertainty in the results, we decided to provide a range of discharge values, on the basis of the confidence interval. This interval is defined, as stated before in the paper, by the uncertainty in the 1D model roughness coefficient.

Even considering the uncertainty, one can recognize that the maximum discharge in the lower portion of the Po River obtained in this study is significantly lower (about 20% less) than the one estimated in the past, i.e. the value that was used to create the SIMPO design flood hydrograph (SIMPO, 1982). It is worth remarking again that the 1951 peak discharge value has been crucial in defining flood risk management actions and measures on the Po River, such as the levee height, that is almost everywhere based on the SIMPO design flood profile.

To further validate the present study results, the peak estimates were compared with those obtained in an event of comparable magnitude on the Po River in October 2000 when, of course, no levee breaches occurred. By considering the 1951 peak discharges (Figure 7) and those of the 2000 flood event, reconstructed from the surveyed water stages, a significant anomaly appears in the lower portion of the Po River. In the upstream sections of Boretto and Borgoforte, the maximum recorded discharge of the 2000 event was very close to the maximum discharge observed during the 1951 flood. In contrast, at the downstream cross section of Pontelagoscuro, the recorded peak discharge of the 2000 flood event was much less than the previously estimated 1951 peak as reported in SIMPO (1982). However, the peak discharge value reconstructed in this study for the 1951 flood seems more consistent with the observed discharge of the 2000 flood. Therefore, this study seems to accurately reproduce the attenuation of the peak discharge between Borgoforte and Pontelagoscuro, which was actually observed during the 2000 flood when no levee breach occurred. The 1951 peak discharge value calculated at Ostiglia by the present study confirms the observation during the 2000 event of a significant attenuation between Borgoforte and Sermide, located 18 km downstream Ostiglia (see Figure 7), where gauging station were active in 2000.

The above-mentioned discrepancy on the estimated 1951 peak can be explained assuming that previous analyses may have overestimated the peak discharge of the 1951 event by underestimating the volume of water that flowed from the river into the closed floodplains beyond the secondary levees between Borgoforte and Pontelagoscuro. Therefore, accurate computation of the outflow volumes, requiring careful definition of the spatial domain and validation both in the extension and in the timing of the inundation, is crucial for the 1951 peak estimate and fully motivates the efforts of applying 2D rather than 1D modelling.

CONCLUSIONS

Historical events can be important for defining flood risk management plans in a region; nevertheless, their dynamics are affected by considerable uncertainty as it is often difficult to define the past hydraulic conditions. This work describes the hydraulic conditions that occurred in a historical inundation event, with the aim of reconstructing peak discharge values by accurate estimation of the volume of water that overflowed the adjacent polders. To this end, we simulated the discharge hydrograph that flowed through the Po River levee breaches, in 1951, which caused the catastrophic inundation of Polesine Region in Italy. To obtain a reliable reconstruction of the event, this study used flood extent maps for the comparison of observed and simulated inundation areas. Also, the inundation timing was used to validate the results, as it is one of the clearest sources of information available for the 1951 event. To comply with various hydraulic boundary conditions, we used a combined 1D-2D numerical modelling approach, with the objective of reconstructing and verifying discharges estimated downstream the main breaches, at Pontelagoscuro, during the 1951 inundation. This estimate is particularly valuable as during this event, the maximum values of discharges and water stages were recorded in the lower portion of the Po River.

The estimation of flood peak discharges is crucially related to the reliability of stage-discharge relationships in the highest part of the curve. In this study, the independent reconstruction of discharges that occurred in a given event led to the validation of the highest point in the rating curves. The present work treated as hard data the direct measurements of water level and river discharge that were used to calibrate the hydraulic model in view of their associated uncertainty (negligible for water level measurements, and 7% accuracy for direct discharge measurements; e.g. Pappenberger *et al.*, 2005;

Di Baldassarre and Montanari, 2009). In contrast, the river discharge values used were not derived from the rating curve (as it is typically done in standard approaches) but, instead, were derived by the hydraulic model. This original approach provides an estimate of the flood discharge which is less uncertain than the one obtained by only extrapolating the rating curve beyond the measurement range.

The results of the present study also lead to two practical conclusions: (i) the 1951 peak discharge has been so far overestimated by up to 20%, and this is confirmed by hydraulic evidence that emerged in a subsequent major event in October 2000, (ii) man-made obstacles in the Polesine floodplain increased the flooded area by 40% and tripled the time to reach the sea. The last observation gives a useful advice for developing better flood management plans in wide lowlands, where artificial embankments can significantly affect flow directions.

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