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Probabilistic flood hazard mapping: effects of uncertain boundary conditions

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Abstract. Comprehensive flood risk assessment studies should quantify the global uncertainty in flood hazard estimation, for instance by mapping inundation extents together with their confidence intervals. This appears of particular importance in the case of flood hazard assessments along dike-protected reaches, where the possibility of occurrence of dike failures may considerably enhance the uncertainty. We present a methodology to derive probabilistic flood maps in dike-protected flood prone areas, where several sources of uncertainty are taken into account. In particular, this paper focuses on a 50 km reach of River Po (Italy) and three major sources of uncertainty in hydraulic modelling and flood mapping: uncertainties in the (i) upstream and (ii) downstream boundary conditions, and (iii) uncertainties in dike failures. Uncertainties in the definition of upstream boundary conditions (i.e. design-hydrographs) are assessed through a copula-based bivariate analysis of flood peaks and volumes. Uncertainties in the definition of downstream boundary conditions are characterised by uncertainty in the rating curve with confidence intervals which reflect discharge measurement and interpolation errors. The effects of uncertainties in boundary conditions and randomness of dike failures are assessed by means of the Inundation Hazard Assessment Model (IHAM), a recently proposed hybrid probabilistic-deterministic model that considers three different dike failure mechanisms: overtopping, piping and micro-instability due to seepage. The results of the study show that the IHAM-based analysis enables probabilistic flood hazard mapping and provides decision-makers with a fundamental piece of information for devising and implementing flood risk mitigation strategies in the presence of various sources of uncertainty.

1 Introduction

Many studies in the literature highlight how inundation hazard and risk assessments are affected by several sources of uncertainties which limit their reliability (e.g. Merz and Thieken, 2005; Apel et al., 2004, 2008; Most and Wehrung, 2005; Hall and Solomatine, 2008). In this context, there is a consensus in the scientific community that a proper risk analysis should provide an indication of uncertainty, emphasising how the identification of the optimal flood risk management strategy can be pursued only if all major sources of uncertainty are adequately taken into consideration and a quantification of their impacts is provided (USACE, 1992).

Uncertainty has always been inherent in flood assessment and considered in flood defence engineering by means for example of adoption of an adequate freeboard (Hall and Solomatine, 2008). The unavoidable presence of uncertainty can be attributed to the fact that flood risk evaluations are usually carried out for extreme events that are seldom observed, which makes the calibration of flood risk assessment models difficult, if not impossible (Apel et al., 2004). Under such circumstances, the evaluation of uncertainty sources is a pragmatic extension to conventional validation. Furthermore, Hall and Solomatine (2008) and Apel et al. (2008) emphasise this need, highlighting how the quantification of the uncertainty could help to judge the consistency and the reliability of hydraulic risk assessment as well as to provide useful advices for future data collection or research activities in order to yield more reliable results. In a context where model calibration and validation is difficult due to consideration of extreme events or lack of data, Hall and Anderson (2002) and Hall (2003) suggest a transparent and

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comprehensive description of the cause-effect relationships adopted in the methodology and implemented in mathematical formulations. This is particularly relevant in the case of dike failure analysis, where the uniqueness of breaches reduces or even eliminates the possibility to calibrate and validate deterministic numerical models. Evaluation of possible scenarios could only be handled by means of causal models considering uncertainties in dike breach processes (Hall, 2003; Vorogushyn et al., 2010).

In practical applications, the assessment of inundation areas is usually carried out in a deterministic fashion by means of hydraulic models. Those are first calibrated relative to a specific historical flood event, and then used to estimate flood extents relative to different (and typically higher) event magnitudes. This procedure, even when physically based and numerically complex models are considered (e.g. fully 2-D model, etc.), relies on some fundamental assumptions that may be summarised as follows: (i) capability of the model to correctly reproduce the hydraulic behaviour of the river and inundated floodplains; (ii) time stationarity of model parameters, i.e. the roughness coefficients calibrated for a specific event are considered suitable for a range of flooding scenarios that could differ significantly from the calibration event; (iii) all hydraulic information (i.e. flow hydrographs, rating curves) are error-free.

In a context characterised by these sources of uncertainty, the definition of probabilistic flood hazard and flood risk maps appear the most reasonable way to proceed. Di Baldassarre (2012) argues that there are at least three main reasons why probabilistic flood hazard maps should be preferred to deterministic ones: (1) hydrological and hydraulic analysis are always affected by uncertainty, which often cannot be neglected; (2) a fair presentation of the results of any analysis should also quantify and illustrate the associated uncertainty, and this can be accomplished only in a probabilistic framework; (3) stakeholders and decision-makers should be provided by hydrologists with probabilistic inundation maps to guide and support the definition of flood mitigation strategies; when deterministic maps are produced it implies that a decision has already been made by hydrologists, who are hence no longer behaving like scientists, but rather as decision-makers themselves. As a result, the deterministic estimation of flood extension may involve inexact and dangerous consequences, especially if it is used for planning and development purpose in the flood-prone area. In flood risk research, a number of studies have already considered and classified various uncertainty sources based on the distinction between two types of uncertainty: (i) natural or aleatory uncertainty, associated with the natural variability of the phenomena of interest and (ii) epistemic uncertainty, resulting from imperfect knowledge of the system (e.g. Apel et al., 2004; Hall and Solomatine, 2008; Merz and Thieken, 2005; Most and Wehrung, 2005), or from simplifications associated with the selected modelling approach and parametrizations (e.g. 1-D model instead of 2-D, constant or distributed roughness coefficients etc.).

Many previous studies analysed the effect of uncertainty associated with roughness parametrizations of hydraulic models (Aronica et al., 2002; Bates et al., 2004; Pappenberger et al., 2005). Additionally, Pappenberger et al. (2006) analysed the uncertainty in upstream and downstream boundary conditions when applied to flood inundation predictions with a 1-D flow model. Other authors considered additional uncertainties in flood hazard and risk chain, including extreme value statistics (Apel et al., 2008; Merz and Thieken, 2009), dike breach processes, e.g. breach locations and dimension (Apel et al., 2004; Vorogushyn et al., 2010, 2011) as well as flood damage estimations (Apel et al., 2008; Merz and Thieken, 2009; de Moel et al., 2011; Vorogushyn et al., 2012). They concluded that currently uncertainties in damage estimations and in extreme value statistics dominate the uncertainties in risk estimates, although this conclusion remains site-specific.

The effects of uncertain (upstream and downstream) boundary conditions on flood hazard assessment is still poorly understood, and the literature on this topic is sparse. Our analysis focuses in particular on the uncertainty associated with rating curves used as downstream boundary conditions, while the aleatory uncertainty related to the selection of a design hydrograph is taken into account, referring to different flood hydrographs estimated with a bivariate flood frequency analysis.

The effect of the downstream boundary condition on the area of interest is reduced, if not completely removed, by extending the hydraulic model far downstream of the area of interest. However, this expedient may be costly and time consuming to implement, or difficult due to a lack of data. To address these issues the modeller needs to consider if and how the uncertainty in the downstream boundary condition impacts her/his computations. Since the effects of rating-curve uncertainty on flood hazard mapping is the main goal of our investigation, we deliberately referred to a case in which we set the boundary condition at the downstream end of the considered river reach.

Even though the literature reports several studies highlighting the global uncertainty affecting discharge measurements and rating-curve construction (e.g. Domeneghetti et al., 2012; Di Baldassarre and Claps, 2011; Di Baldassarre and Montanari, 2009), the literature on the effects of rating-curves uncertainty of flood hazard and flood risk assessments is still sparse. Moreover, institutions and agencies in charge of hydroclimatic monitoring usually do not provide practitioners and users with indications of uncertainty associated with rating curves. Conversely, rating curves are usually utilised in a deterministic way although their sampling variability may be significant and may play a dominant role in practical applications (Domeneghetti et al., 2012).

Our study makes use of the outcomes of a previous analysis on rating-curve uncertainty performed for the same river

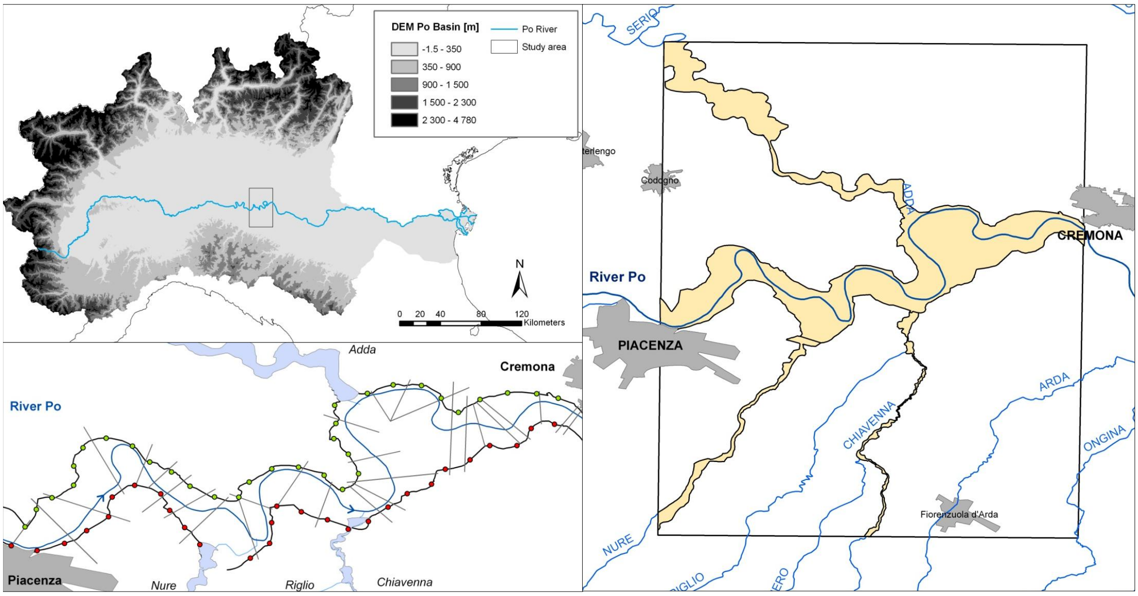

Fig. 1. Study area. Upper left panel: Po River basin and study area (box); lower left panel: river cross-sections (grey lines) and levee system discretization for the left (green dots) and right (red dots) side; right panel: 2-D raster-based model extension (grey box) and floodplain area (yellow).

reach (Domeneghetti et al., 2012), in order to explore the impact of this uncertainty on probabilistic flood hazard mapping. Our investigation was performed by setting up a hybrid probabilistic-deterministic flood hazard assessment model for the flood-prone areas located along a diked reach of the lower portion of the Po River. We discuss how the consideration of this uncertainty may impact flood management decisions compared to a deterministic specification of boundary conditions.

2 Methodology

Chains of models that describe fluvial inundation processes and flood damages are typically applied for flood hazard and risk assessment. In this approach, each modelling step or chain link exhibits a number of inherent uncertainties that are summarised in Table 1, starting from a triggering event to the final inundation pattern. Referring to some natural and epistemic sources of uncertainty (sources listed in italic in Table 1), the study aims at quantifying the contribution of different terms of uncertainty, evaluating the feasibility and the amount of uncertainty reduction that can be achieved by adopting additional information or different procedure. We analyse the role of uncertain boundary conditions on flood hazard statements by means of the Inundation Hazard Assessment Model (IHAM) (Vorogushyn et al., 2010).

IHAM model is a hybrid probabilistic-deterministic model developed for flood hazard assessment along protected river reaches considering dike failures. The model is comprised of three main modules: an unsteady one-dimensional hydraulic model (1-D model) for river channel and area between dikes, a probabilistic dike breach model, which evaluates dike system stability under hydraulic load conditions, and a 2-D raster-based diffusive wave model (2-D raster-based model; Merz, 1996) for the simulation of floodplain flow in the case of dike failures (see Fig. 2). All three modules are continuously coupled at runtime. The 1-D model routes a flood wave in the river channel and over floodplains between dikes. It computes the hydraulic load on flood protection dikes in terms of water level and impoundment duration. During the simulation, each discretised dike section is evaluated for failure due to overtopping, piping and slope instability due to seepage flow through the embankment (micro-instability; see Vorogushyn et al., 2009). In the case of dike failure, the outflow volume through the breach into the flood-prone area is computed and used as a boundary condition in the 2-D storage cell model. The simulation of water exchange between river channel and floodplain, including the reverse flow, is incorporated by means of a continuous data exchange between modules. A distinctive characteristic of the IHAM model is the coupled modelling chain of channel flow, dike failure and inundation processes without a priori assumption on the location, time and characteristics of the dike failure. Those are determined during the simulation based on the current hydraulic load and dike propensity to failure.

The schematic structure of the IHAM model is shown in Fig. 2, which highlights the model core system (three coupled modules), and the pre- (input) and post- (output) processor phases. The modelling system is run in a Monte Carlo framework (MC) to address the considered sources of

Table 1. Sources of uncertainty in flood hazard mapping grouped into natural and epistemic uncertainty (adapted from Apel et al., 2004); sources in italic are directly considered into the presented analysis.

Modules	Natural uncertainty	Epistemic uncertainty
(1) Hydrological analysis	– annual maximum discharge; – *flow hydrograph shape*;	– measurement error; – limited time series length; – statistical inference; – parameter estimation – peak discharge estimation; – *flow hydrograph wave form;*
(2) Rating-curve	-variation of river geometry in time;	– *discharge measurement errors;* – mathematical expression for rating-curve estimation; – number of pair used for rating-curve estimation; – *methodology for rating-curve estimation;* – *interpolation/extrapolation errors;*
(3) Flood routing	–variation of river geometry over time;	– error in model selection; – numerical simplification; – parameter calibration;
(4) Dike stability	– *geometrical variation over space;* – *variation of geotechnical parameters in space;* – *final width and development time of levee breaches;*	– measurements errors of levee geometry; – *variability estimations of levee parameters (permeability, turf quality, material cohesion, etc.);* – formalisation of dike breach processes;
(5) Flood dynamics	– variability of surface roughness in space and time due to variable land use;	– error in model selection; – numerical simplification; – DEM inaccuracy; – parameter estimation;

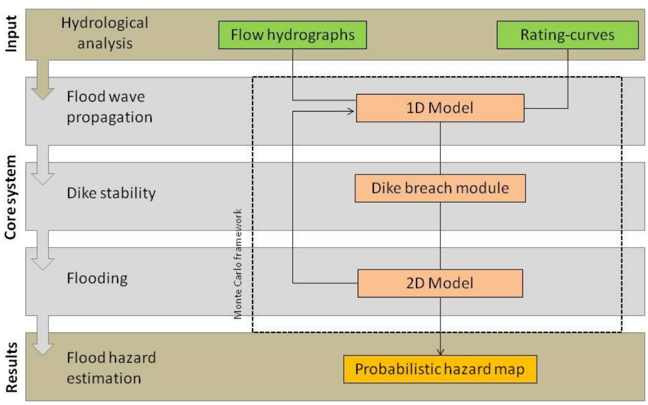

Fig. 2. Schematic structure of the IHAM model adopted for flood hazard estimation under uncertainty conditions.

uncertainty (e.g. upstream and downstream boundary conditions) and the stochasticity of dike breaching processes.

IHAM model considers the uncertainty related to dike system stability implementing the "Dike breach module" (see Fig. 2 and Sect. 3.2). It evaluates the probability of dike failures upon hydraulic loading computed by the 1-D model. Each section of the dike system with a length of approximately 1.2 km is tested for dike stability based on the current load during the whole simulation. The probability of failure for a given hydraulic load is estimated through fragility curves (see e.g. Sayers et al., 2002) defined for each dike section for three failure mechanisms: overtopping, piping and micro-instability (Apel et al., 2004; Vorogushyn et al., 2009).

In the case of single or multiple dike collapses, the development time and the final dimension of each breach are stochastically generated based on probability distribution functions fitted to historical observations (see Govi and Turitto, 2000, and Sect. 3.2).

Limited knowledge about flow dynamics, errors on flow-rates measurements and inaccuracy related to the applied methodology for rating-curve estimation (epistemic uncertainties) are considered in an MC simulation. As a result, the IHAM model computes dike failure probabilities for the whole embankment system and provides probabilistic flood hazard maps for a flood prone area indicating the uncertainty bounds of spatial inundation characteristics. A more detailed description of the IHAM modelling system is provided by Vorogushyn et al. (2010).

In this paper, the IHAM model has been extended to analyse the effect of the uncertainty related to flood waveform and to downstream boundary conditions (rating curves) on dike and flood hazard mapping. It was set up for the study area of a 50 km reach of the Po River between the gauges at Piacenza and Cremona (see Fig. 1).

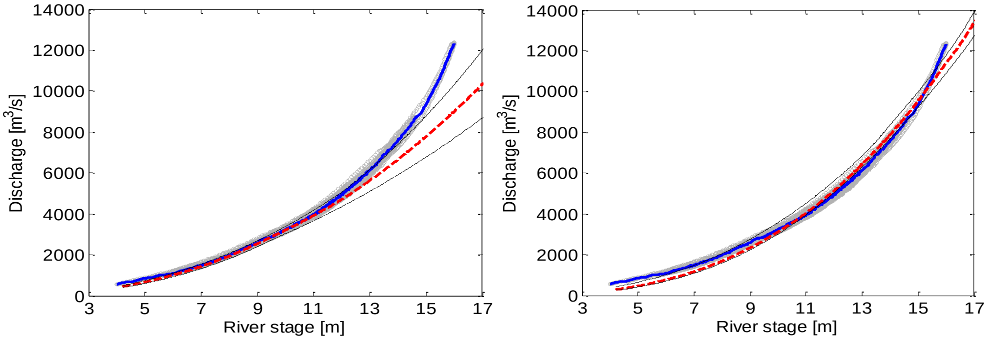

Fig. 3. Rating curves estimated at the Cremona cross-section: normal rating curve (blue line), median rating curve (red dashed line), and corresponding 90 % confidence intervals (black lines) for Traditional (left panel) and Constrained (right panel) approaches (Domeneghetti et al., 2012).

2.1 Uncertainty in upstream boundary conditions

Several studies in the literature highlight how flood frequency analysis plays a dominant role in the overall flood hazard uncertainty (see e.g. Apel et al., 2008; Merz and Thieken, 2009). In particular, an appropriate estimation of peak discharge and flood volume associated with a specific return period is important when flood hazard is related to dike stability (Vorogushyn et al., 2009). For piping and slope-instability, the peak water level and also the duration of dike impoundment, which is related to flood volume, are decisive. The shape of the flood event and the duration of high water levels in the river could strongly influence dike-breaching mechanisms, activating piping or micro-instability phenomena which may not be observed for a high peak and low volume event. Furthermore, even in the case of a dike breach due to overtopping, the shape of the flood event and its overall flood volume could influence the overflow volume, and consequently the inundated area. In light of these considerations, the uncertainty in flood event estimation considering both flood peak and volume is addressed adopting different flow hydrographs as upstream boundary conditions in a Monte Carlo framework (see Sect. 3.4).

2.2 Uncertainty in downstream boundary condition

Domeneghetti et al. (2012) proposed a general numerical procedure for quantifying global uncertainty of stage-discharge relationships by using numerical hydrodynamic models. Referring to the Cremona river cross-section (see Fig. 1) and considering errors affecting river flow measurements (UNI EN Rule 748:1997, 1997, ISO748:97), the authors applied two different procedures for rating-curve estimation, which they termed Traditional and Constrained approach, and they quantified the global uncertainty for both (Fig. 3). Grey dots in Fig. 3 represent stage-discharge points simulated by means of a quasi-2-D model of the River Po that has Cremona as an internal cross-section (the downstream boundary condition in this model is set 300 km downstream). In particular, the quasi-2-D model was calibrated for a specific flood event and then used for reproducing the hydraulic conditions at the Cremona cross-section for 10 historical flood events. The compound of discharge-level pairs simulated at the Cremona gauge (grey dots in Fig. 3) were then used to mimic several synthetic field-measurements campaigns (each one of which were made up of 15 discharge-stage pairs, for details see Domeneghetti et al., 2012). The Traditional approach constructs a rating curve by fitting a series of stage-discharge values observed within the range of measurable streamflows (i.e. 6000 $m^3 s^{-1}$ at Cremona, EU ISO EN Rule 1100-2:2010, 2010, ISO1100-2:10), while the Constrained approach refers to one additional stage-discharge pair computed by means of a simple 1-D steady-state model that also uses Cremona as an internal cross-section. The 1-D model is first calibrated referring to the maximum measured pair of each synthetic campaign and then used to estimate the maximum discharge capacity at the Cremona section. The Constrained rating curve is finally estimated by fitting measured discharge and water-level pairs and by concurrently forcing the curve to honour the estimated maximum discharge capacity of the Cremona cross-section (Domeneghetti et al., 2012). The reduction in extrapolation errors ensured by the Constrained approach, which is visible in Fig. 3, results in reduced bias and variability of the estimated rating curves.

Repeating the procedure for several synthetic field-measurement campaigns, (see Domeneghetti et al., 2012, for details) the median (red dashed line in Fig. 3) and the 90 % confidence interval (thin black lines in Fig. 3) for both methodologies were estimated. In particular, left and right panels of Fig. 3 report the "true" or reference normal rating curve (blue thick line) obtained at Cremona river cross-section from the compound of unsteady stage-discharge pairs (grey dots). Also, the left panel of Fig. 3 reports the global uncertainty relative to the Traditional approach. In this case, the extrapolation error associated with the utilisation of the curve beyond the range of observed data introduces a significant deviation with respect to the reference normal rating curve, as it is clearly illustrated by the width of 90 % confidence interval and bias of the Traditional rating curve in Fig. 3. The right panel of Fig. 3 reports the median rating curve (red dashed line) and 90 % confidence interval relative to the Constrained approach.

Our study analyses the impacts of rating-curve uncertainty on flood hazard mapping and highlight the differences between Traditional and Constrained approaches to rating-curve construction, comparing them with the results that one would obtain by using a single deterministic median rating curve.

3 Study area and model implementation

Our study considers a 50 km reach of the middle-lower portion of the Po River (Fig. 1), which spans from Piacenza (upstream gauge) to Cremona (downstream gauge). The reach can be characterised as a unicursal river, having a width varying between 200 and 500 m and a wide floodplain area. The floodplain inside the major river embankments is partly cultivated and plots are additionally protected by a system of minor dikes (Castellarin et al., 2011).

3.1 1-D Model

The hydrodynamic simulation of the flood wave propagation along the study reach is carried out using a 1-D model based on the full Saint-Venant equations numerically solved with the classical implicit four-point finite difference scheme (Wilson Engineering, 2003). The channel geometry is characterised by 29 cross-sections (Fig. 1) derived from a 2 m DTM recently provided by AdB-Po (2005), which combine information collected by means of LiDAR (data collected using two different laser scanners: 3033 Optech ALTM and Toposys Falcon II), multi-beam sonar survey for the navigable portion of the river and data retrieved by means of traditional ground survey of river cross-sections.

The cross-sections are extracted from the DTM following the rules for optimal cross-section spacing (Castellarin et al., 2009). The unsteady 1-D model is driven by a flow hydrograph and conditioned through a rating curve as a downstream boundary. The representation of tributaries is limited to the River Adda, which is the biggest along the considered reach of the Po River. The Adda contribution is modelled as a lateral inflow hydrograph as the tributary may appreciably alter the Po streamflow downstream of its mouth. Considering their negligible contributions during the major floods events experienced along the study reach in the 1994 and 2000 the Nure and Chiavenna streams are not considered as tributaries during flood simulations.

The 1-D model is calibrated for a flood event with an estimated return period of approximately 50 yr, which occurred in the Po River in October 2000. The October 2000 event reproduces the hydraulic behaviour of the study reach in case of extreme floods because all floodplains protected by the system of minor dikes were flooded during the event. The 1-D model is calibrated by manually adjusting the roughness coefficients to match the maximum water levels that were provided by the wrack marks along the reach. The model calibration is performed twice: (1) adopting the Traditional median rating curve (Fig. 3, red dashed line of the left panel) and (2) using the Constrained median relation (red dashed line on the right panel of Fig. 3).

The high water marks of October 2000 flood are accurately reproduced by the model, with a mean squared error (MSE) of 0.22 and 0.28 m for the Constrained and the Traditional case, respectively. MSE values are not negligible, but they may be regarded as satisfactory due to the magnitude of the simulated flood event and simplifications adopted in the geometrical description of the riverbed (pure-1-D model and single roughness coefficient for main channel and lateral floodplains).

Calibrated Manning's values mainly vary between 0.04 and 0.05, and therefore they are in good agreement with those estimated by previous studies on the same reach (see e.g. Castellarin et al., 2009, 2011; Domeneghetti et al., 2012; Di Baldassarre and Montanari, 2009).

3.2 Dike breach module

The main embankment system was discretised into several sections, each one with a length of about 1.2 km resulting in 28 and 32 sections, respectively, for the right and left side of the embankment system (Fig. 1, lower left panel). During the simulation, each section is tested for dike stability using fragility functions, which provide the probability of dike-section failure upon hydraulic loading simulated by the 1-D hydrodynamic model. Fragility functions for each breach mechanism (overtopping, piping and micro-instability) were developed for each dike section based on the geotechnical and geophysical characteristics of the embankment system, which were compiled by the River Po Basin Authority (AdB-Po-GEOVIT, 2004; AdB-Po-DISEG, 2001) or derived from the literature and summarised by Vorogushyn et al. (2010).

In the case of dike failure, breach width (B_w) is stochastically sampled through a Monte Carlo procedure from a truncated log-normal probability density function fitted to a series of historical observations in the Po river system (see Fig. 4, Table 2 and Coratza, 2005). The truncated distribution is constrained by the minimum and maximum values of (B_w) observed in the Po River system (see Table 2). This probabilistic approach was adopted as an alternative to physically based morphodynamic modelling in order to address the uncertainty associated with the estimation of ultimate breach widths. Breach width morphodynamic modelling remains highly uncertain (Wahl, 2001) and no simple and robust relationships between ultimate breach widths and hydrologic and morphologic parameters of floodplain areas

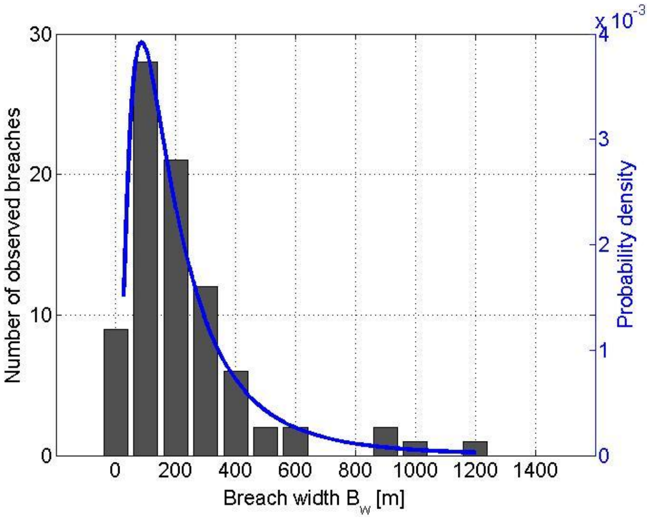

Fig. 4. Empirical frequency distribution of breach widths, B_w, observed along the Po River in the period 1800–1951 (bars) and fitted probability density distribution (blue line; log-normal).

that control the breach throughflow have been developed so far.

The breach development time (h_w) was adopted in the range 0.5–4 h and assumed to follow a normal distribution with mean of 2 and standard deviation of 1.5 h. The resulting values for breach times are comparable with those adopted in other studies conducted for the same or comparable rivers (e.g. Apel et al., 2004; Alkema and Middelkoop, 2005; Di Baldassarre et al., 2009; Vorogushyn et al., 2010; Han et al., 1998).

3.3 2-D model

In the case of a dike failure, the flood propagation over the dike-protected floodplains is simulated by a 2-D raster-based model run on a 50 m × 50 m resolution grid. The topographical information for the whole study area (Fig. 1; global extension 890 km^2) were retrieved from the ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer – Global Digital Elevation Model; www.gdem.aster.ersdac.or.jp) and rescaled to the coarser grid resolution in order to reduce the computational load.

Considering the absence of detailed information on inundation extents experienced in the area of interest and to the uniqueness of breach event, the calibration of the 2-D raster-based model appeared to be a difficult task. Consequently, spatially distributed Manning's roughness coefficients were assigned to each cell based on literature values (Chow, 1959) for land use classes retrieved from CORINE land use classifications (COoRdination of Information on the Environment – Land Cover, 2006).

Table 2. Width of dike breaches, B_w: statistics observed along the Po River in the period 1800–1951 (data from Coratza, 2005)

B_w statistics for the Po River	Obs. value
Number of historical breaches with observed B_w	84
Mean B_w [m]	240
Median B_w [m]	180
Min B_w [m]	27
Max B_w [m]	1200

3.4 Development of flood scenarios and model simulations

In order to account for the flood volume, which can be relevant for the stability of flood protection structures (Vorogushyn et al., 2009; Klein et al., 2010), we applied a copula-based bivariate flood frequency analysis.

The annual maximum peak discharge (q) and the corresponding flood volume (v) observed in a time window of 30 days around the flood peak (10 days before the peak, rising limb, and 20 days after the peak, recession limb) were extracted from the mean daily flow series in the period from 1951 to 2008 at gauge Piacenza. The adopted time span of 30 days entirely embraces the flood waves that occurred at the study reach; it is evidently site-specific and should be reconsidered in other case studies. The dependence structure of the couple of variables (Q, V) was described using a copula approach. Among several fitted copulas, the Gumbel copula provided the best fit to the empirical relationship between Q and V according to the selected criteria (i.e. RMSE, AIC, Kolmogorov–Smirnov test and tests based on the empirical copula and on Kendall's transform (Genest et al., 2009; Fermanian, 2005).

Indicated as $F_Q(q)$ and $F_V(v)$ the marginal distribution functions of Q and V (a GEV and a log-normal distribution, respectively), the relationship between the uniformly distributed variables $u = F_Q(q)$ and $v = F_V(v)$ can be expressed by means of the Gumbel copula (1)

$$C_\theta(u, v) = e^{-[(-\ln u)^\theta + (\ln v)^\theta]^{1/\theta}}, \tag{1}$$

where $\theta \geqslant 1$ is a dependence parameter estimated over the set of observations (Salvadori and De Michele, 2007).

Figure 5 illustrates the selected flood events associated with different return periods, Tr. A critical event is determined if either Q or V exceeds given thresholds defined through the copula function associated with an exceedance probability ("OR"-case). We focused on a return period of 200 yr (hereafter also referred to as Tr200), which is the reference recurrence period adopted by AdB-Po for designing and verifying the main embankment system of the Po River. Red dots of Fig. 5a indicate the (q, v) pairs used to discretise the Tr200 contour line in our study, by means of which we

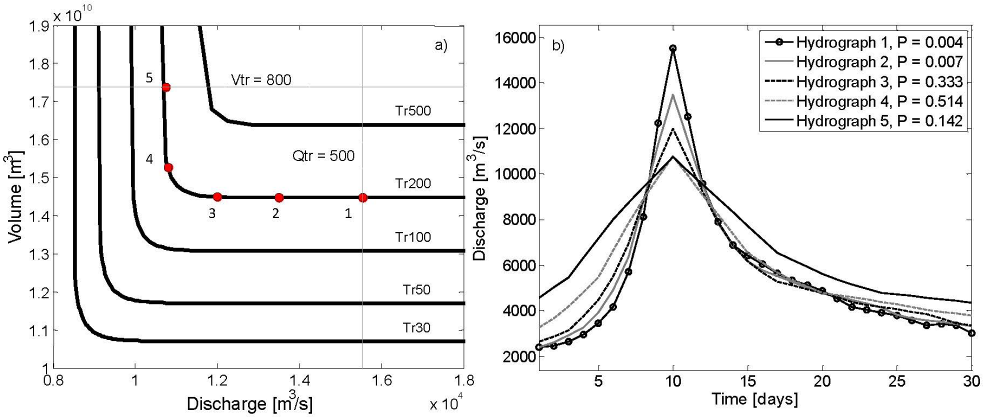

Fig. 5. Bivariate analysis: **(a)** level curves for the Gumbel copula for different return periods (black lines) and (q, v) pairs adopted for the 200 yr event (red dots); **(b)** flow hydrographs corresponding to copula-based (Q, V) pairs.

took into account the natural variability of flood hydrographs. These events are not equivalent in terms of flood volume and peak discharges and they also differ in terms of their probability of occurrence (Volpi and Fiori, 2012). We assigned to each one of the five selected (q, v) pairs (or scenarios) a probability of occurrence estimated as follows: we computed the joint probability density function (joint pdf) along the contour line based on marginal probabilities (see e.g. Volpi and Fiori, 2012); the contour line has been discretised into five stretches, which were identified by halving the curvilinear distance between two scenarios; finally, the relative frequency of occurrence of each scenario was estimated as the integral of the joint pdf over each stretch and standardised by the integral of the joint pdf over the entire level curve (see legend of Fig. 5b).

We retrieved the shape of the synthetic flow hydrographs analysing the series of historical flood events recorded at Piacenza. Estimated base flow was first subtracted from each observed hydrograph, which was then divided by the maximum discharge, obtaining a dimensionless hydrograph with unit peak flow. We then computed the mean of all dimensionless flood hydrographs and rescaled the resulting mean hydrograph to match peak discharges and flood volumes estimated through the bivariate analysis for the five Tr200 events (red dots in Fig. 5a). Figure 5b reports the five synthetic hydrographs obtained in the study and their corresponding empirical relative probability of occurrence. IHAM was driven by the developed flood hydrographs, taking into account the relative probability of each. To investigate the effect of rating-curve uncertainty on flood hazard estimation, flood scenarios were simulated, adopting different downstream boundary conditions defined for the Cremona gauge. Approximately 8000 Monte Carlo simulations were run in total to propagate the uncertainty in upstream and downstream boundary conditions to flood hazard estimations. In particular, subsets of ~ 2000 runs were used to explore the effects of uncertainty on flood hazard mapping:

- *MedianT* subset; flow hydrographs were randomly selected as upstream boundary conditions, whereas the median rating curve for Traditional approach (red dashed lines on left panel of Fig. 3) was used as downstream boundary conditions.
- *MedianC* subset; same as before but adopting the Constrained median rating curve as downstream boundary condition.
- *RandomT* subset; both upstream (i.e. flow hydrographs) and downstream (i.e. Traditional rating curves) boundary conditions are stochastically sampled. In particular, referring to the left panel of Fig. 3, the rating curve is sampled between the 90 % confidence interval (black lines in the Figure) during each Monte Carlo simulation.
- *RandomC* subset; same as before by considering Constrained rating curves.

4 Results

Figure 6 reports results provided by the 1-D model for the RandomT subset. The upper panel of the figure reports the minimum levee-crest elevation (red dashed line) for the study reach of the Po River and compares it with the median (black line) and the range of variability (grey dashed lines) of water surface simulated for the Tr200 event. In the lower panel of Fig. 6, the water depth variability simulated for RandomT (black line) is compared with the one obtained from the RandomC subset (dashed line). The lower panel of Fig. 6 clearly shows the impact of rating-curve uncertainty in terms of water levels along the downstream end of the studied Po River reach (RandomT and RandomC subsets). The variability introduced by the downstream boundary condition influences the water levels simulated upstream through a backwater effect for a remarkable distance (i.e. 25–35 km in this case).

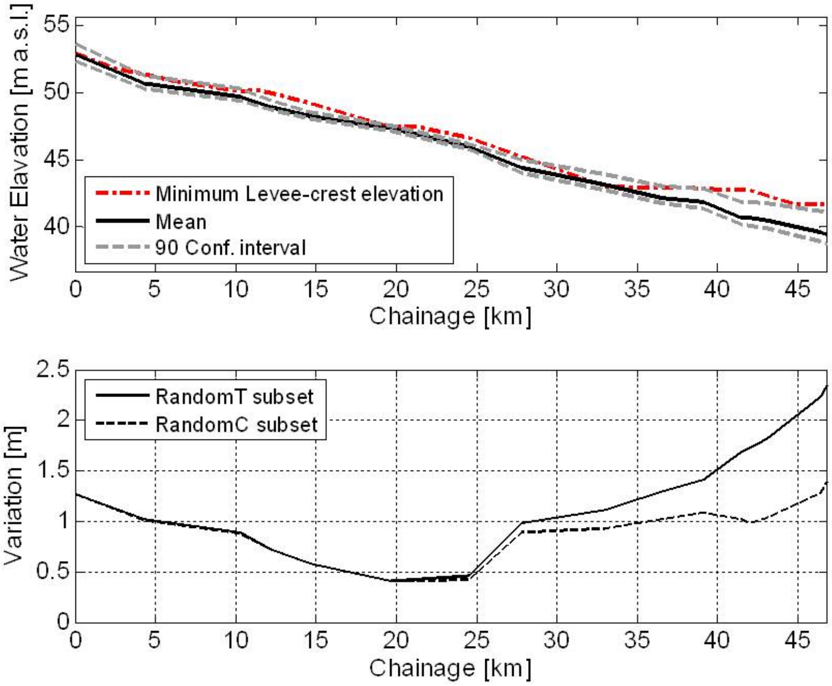

Fig. 6. Monte Carlo simulations; upper panel: range of variation (grey dashed line) and median (black line) water elevation profiles simulated for the RandomT subset along the Po River, compared with the minimum dike-crest elevation (red dashed line). Lower panel: water depth variability simulated along the Po River for RandomT (black line) and RandomC (dashed line) subsets.

Panel (a) of Fig. 7 reports the probabilistic flood hazard map related to a specific return period of 200 yr and obtained for the MedianT subset (∼ 2000 runs); the probability of inundation of each cell in the flood prone area is indicated through a blue colour scale. Such a measure is calculated as the ratio between the number of simulations in which the cell is wet (i.e. water depth > 0 cm) and the total number of Monte Carlo runs.

High probabilities of inundation in Fig. 7a are symptomatic of the presence of critical river stretches (e.g. higher probability of overtopping). Although the flooding probabilities for the majority of the areas are quite small ranging between 20–30 %, results highlight a critical condition in the embankment stretch located downstream of Torrente Chiavenna tributary. In this case, a local depression on the dike crest results in a high probability of overtopping, leading to a remarkable probability of inundation for the flood-prone area opposite to the tributary mouth (dark blue colour in Fig. 7a).

The probabilistic map in Fig. 7b reports the difference in probability of inundation arising from the consideration of the uncertainty bounds around the median Traditional rating curve, that is the difference between the inundation probability obtained for the MedianT and RandomT subsets. Figure 8a shows the probabilistic inundation map obtained for the MedianC subset (∼ 2000 Monte Carlo runs), while Fig. 8b provides the difference in inundation probability between probability inundation maps obtained for the MedianC and RandomC subsets (∼ 2000 Monte Carlo runs each).

The map reported in Fig. 8b does not highlight tangible variations in the probability of flooding for the area outside the main embankments due to the rating-curve uncertainty. Patchy variations (shown in Fig. 8b) seem to be caused by the stochastic definition of breach dimension and development time. Concerning the rating-curve uncertainty, relative to the unbiased rating curve constructed with the Constrained approach, Fig. 8 clearly shows the importance of the variability of the rating curve, i.e. confidence interval width (lower panel of Fig. 6). In this case, the reduced uncertainty, i.e. the narrow confidence interval and small extrapolation errors (right panel of Fig. 3), results in a limited effect on flood estimation and inundation assessment.

Figure 9 compares probabilistic flood hazard maps computed on the basis of the RandomT, panel (a), and RandomC, panel (b), subsets (∼ 2000 Monte Carlo runs each). Areas highlighted in the figure emphasise the difference between the two subsets. Even though the uncertainty in downstream boundary conditions is considered in both scenarios, the highlighted area appears to be inundated only when the Traditional approach is considered. This result could have been expected in light of the evident extrapolation error affecting rating curves constructed with the Traditional approach, which results in a worsening of the overtopping phenomenon.

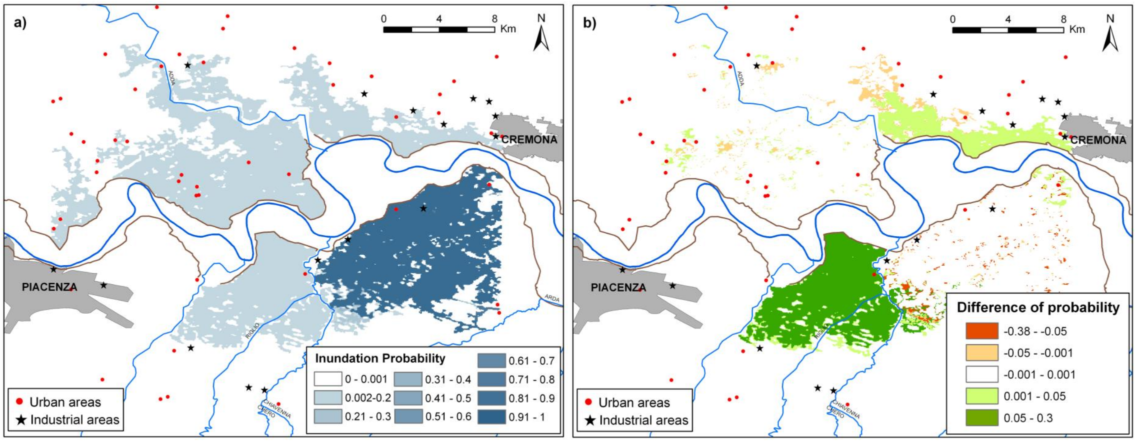

Fig. 7. (a): probabilistic inundation map for the Tr200 event adopting the MedianT subset; **(b)**: difference in probability of flooding adopting RandomT and MedianT subsets.

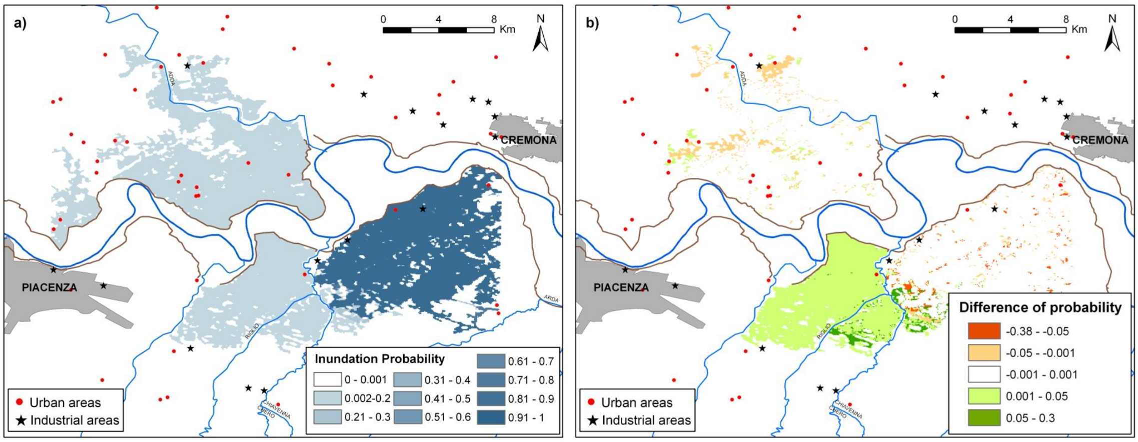

Fig. 8. (a): probabilistic flood hazard map for the Tr200 event adopting the MedianC subset; **(b)**: difference in probability of flooding adopting RandomC and MedianC subsets.

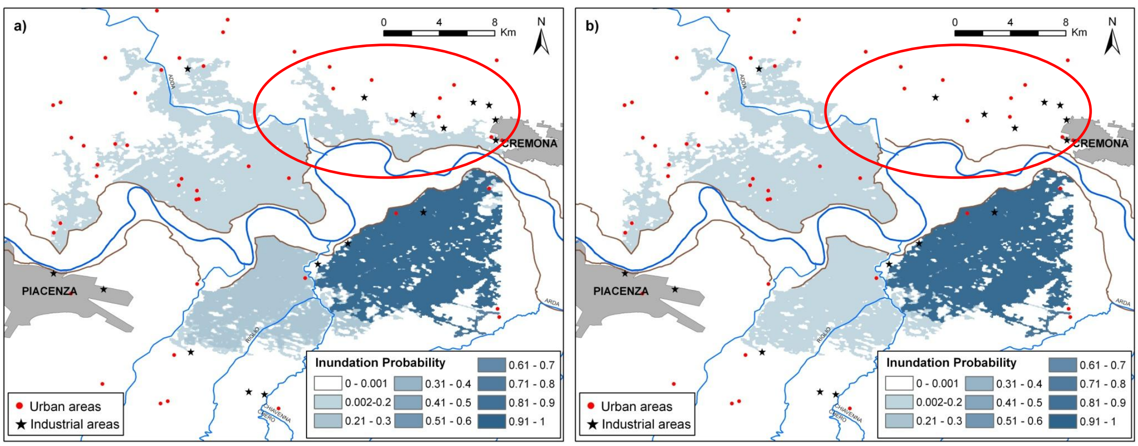

Fig. 9. Probabilistic flood hazard maps for the Tr200 event obtained with variable Traditional (**a**: RandomT subset) and Constrained (**b**: RandomC subset) rating curves.

In all considered scenarios, overtopping was the only breach mechanism responsible for dike failure. None of the dike sections failed due to piping and micro-instability, even though the bivariate approach ensured a significant variability of the flood volume for the 200 yr flood event (see Fig. 5).

5 Discussion

It is worth emphasising here that, when assessing the flood hazard conditions along a river reach dominated by subcritical flow conditions, extending the modelling domain far enough downstream the stretch of interest may limit (or completely remove) the possible negative effects of uncertain downstream boundary conditions. Nevertheless, we deem the assessment of the effects of uncertainty from downstream boundary conditions on flood hazard mapping to be very important for two main reasons. First, the extension of the modelling domain could be costly, or hampered by various practical limitations (lack of topographical data, computational burden, time constraints, etc.). Second, the backwater length that is needed for identifying the optimal location of the downstream boundary condition is generally estimated through simplified computational schemes and, hence, the backwater length is rather uncertain too.

For instance, for subcritical flow conditions with a Froude number significantly lower than one, Samuels (1989) suggests computing the distance where the backwater upstream of a control (as well as other disturbances) decays to less than 0.1 of the original value, $\triangle x$, as

$$\triangle x \approx 0.2D/s, \tag{2}$$

where D is the bankfull depth of flow and s is the surface (or main channel) slope. For the considered river reach, with a bankfull depth D of ~ 16 m and an average channel slope s of 0.25 ‰, Eq. (2) returns ~ 13 km. Using a 1-D hydraulic model of the study reach to calculate the steady-state water surface profile relative to a discharge of 12 500 $m^3\,s^{-1}$, and setting the water depth 1.5 m above the normal depth at the downstream end to mimic the uncertainty associated with Traditional rating curve (see left panel of Fig. 3), one may easily verify that $\triangle x$ (defined above) results equal to ~ 18 km. It should be noted that both estimates are significantly lower than 25–35 km, that is the distance at which the variability introduced by the downstream boundary condition influences the simulated inundation probabilities through a backwater effect. This result, obtained from a MC simulation experiment and the cascade of numerical hydrodynamic models, clearly highlights that simplified modelling approaches, as those briefly recalled above, may significantly underestimate the effects of the uncertainty in downstream boundary conditions.

Results presented in the previous section clearly highlight the remarkable impact of the methodology applied for rating-curve construction and associated uncertainty on flood hazard assessment, and in particular on dike breaching and inundation probability. The variability of rating curves produces a significant uncertainty in flood probability estimation. Figure 7b shows for our case study that the deterministic (i.e. neglecting uncertainty, MedianT subset) utilisation of a rating curve constructed using a traditional approach (i.e. fitting the available discharge-water level observations) results in a significant underestimation of flooding probability. As a general remark, it is worth noting here that the flooding probability could be underestimated or overestimated in other study areas depending on local conditions, yet we want to underline the significant bias that may affect the flood inundation estimates. The bias sign depends on the specific local conditions, which may produce systematic underestimation, or overestimation, of the water levels in the downstream end of the considered river reach, affecting the overtopping probabilities of the main embankments.

The limited variability of rating curves obtained by means of Constrained approach entails a reduced variability in terms of water elevation along the river and this results in a more reliable evaluation of dike stability and likelihood of flooding. Although we are aware that this result could also be partly associated with our case-study, the analysis reveals how the reduction of the extrapolation error could be a good strategy in order to reduce bias and uncertainty on flood hazard estimation when the uncertainty of the rating curve cannot be considered (i.e. deterministic interpretation of the curve) and has to be neglected during flood hazard assessments for various practical limitations (e.g. when performing real-time flood inundation modelling).

The two maps in Fig. 9 emphasise the effects on inundation probability estimates of bias on water levels that might be associated with a Traditional approach to rating-curve construction relative to the Constrained approach (see also Fig. 3). The comparison of these maps highlights a possible misinterpretation of hazard estimation due to extrapolation errors associated with the curve fitting exercise (i.e. rating-curve construction). The highlighted cells (red ellipse) appear flooded only in the case of the application of the Traditional approach (Fig. 9a), and this is a consequence of the better reproduction of the hydraulic behaviour of the Po River at Cremona cross-section ensured by the Constrained rating curve (see Fig. 3).

Concerning the scientific debate on probabilistic versus deterministic inundation maps, some considerations may be raised from Fig. 8b which illustrates the difference in terms of inundation probability between RandomC and MedianC subsets. Both subsets refer to the Constrained approach for constructing rating curves, therefore the most accurate of all considered cases both in terms of possible extrapolation errors (i.e. limited bias) and global rating-curve uncertainty (i.e. limited confidence interval). The comparison between the two maps enables one to understand the difference in terms of flood probability that originates from the uncertainty in the downstream boundary condition. Differences, although limited in terms of inundation probability, are present over wide regions (see for instance the green area in Fig. 8b) and, more importantly, they are located quite far from the gauged river cross-section where the boundary condition is set (∼ 25–35 km upstream of the downstream end). Furthermore, it should be emphasised that even though these differences in terms of flooding probability are modest they may result in a non-negligible variation in terms of overall flood risk, e.g. due to the interactions of hazard (probability) with exposure and vulnerability of the area, especially when a wider spectrum of return periods is considered (as opposed to Tr = 200 yr selected in this study).

Similar results in terms of overall extension of the floodable area may also be obtained from deterministic inundation maps, however, the added value of probabilistic inundation mapping relies on its capability to represent the uncertainty of the output in a very effective way. The representation of the uncertainty associated with the output facilitates the interaction between scientists and decision-makers, who may or may not have a strong background in numerical-hydraulic modelling.

To promote the utilisation of probabilistic maps, scientists should provide decision-makers with information on their meaning and stress the distinction between the overall inundation probabilities and those related to a specific return period. Inundation probabilities represented in this work (see e.g. Sect. 4 and Figs. 7 and 9) refer to a 200 yr return period and are therefore specific to a particular set of synthetic flood events. The overall probability of inundation for a given point within the flood-prone area of the River Po could be different if all possible flood return periods and respective scenarios were considered. However, since the Po River Basin Authority grounds the flood risk assessment, management and mitigation by considering a specific return period, i.e. 200 yr, the probability of inundation associated with 200 yr floods is a meaningful representation of the flood hazard for the decision-making process. Once adequately informed, the decision-maker will decide how best to deal with this uncertainty (e.g. by including highlighted areas of Fig. 9b among the restricted areas in the spatial planning acts) and weight her/his decision by the probability of flooding. On the other hand, if the decision on the appropriate protection level is required based on the overall flood risk assessment, the entire spectrum of the return periods should be taken into account with their respective uncertainty estimations. This is also feasible with the presented methodology.

Finally, concerning our particular case study, the analysis pointed out that dike stability is strongly controlled by peak discharges rather than by flood volumes. Although the variability of flood volume was explicitly considered in the flood hydrograph scenarios (Fig. 5), the embankment system was in fact found to be sensitive to overtopping failures only. Failures due to piping or micro-instability did not occur in the Monte Carlo runs due to the remarkable thickness of the main river embankments (average riverside slope 1 : 2 or 1 : 3; average landside slope 1 : 5–1 : 6). This result is in agreement with what has been observed along the study reach of the Po River during the October 2000 flood event (Coratza, 2005). However, evidences of sandboils along the study reach during recent flood events in 1994 (magnitude similar to the October 2000 event) and 2000 suggest a starting retrogressive erosion and the presence of a non-negligible danger of piping (Coratza, 2005). Therefore, breach mechanisms other than overtopping should not be excluded from the analysis a priori.

6 Conclusions

The debate relative to the deterministic and probabilistic approach for flood hazard estimation is still ongoing in the scientific community (Di Baldassarre, 2012; Di Baldassarre et al., 2010; Montanari, 2007). Providing flood probability maps for the flood prone areas appears to be an efficient way to visualise the likelihood of flooding and it also offers additional information concerning the reliability of its estimation.

The scientific community is well aware of all risks associated with deterministic statements (i.e. binary, yes or no kind of statements) when the system under study is uncertain. Nevertheless, the output of numerical simulations as well as hydraulic and hydrological input data are often used in practice and applied regardless of their uncertainty. Probabilistic inundation maps are still scarcely adopted as additional assets by decision-makers called to define flood protection strategies. This should mainly be attributed to a lack of specific guidelines as well as to a limited ability of the scientific community to communicate the meaningfulness and effectiveness of this kind of spatial representation of flood hazard. We investigated the effects of the uncertainty in the definition of the downstream boundary condition given by the rating curve on the flood probability estimation for a diked reach of the Po River. The evaluation was carried out with the IHAM model, which enables the evaluation of failure probabilities of the dike system under variable hydraulic conditions and for different breaching mechanisms. The intrinsic uncertainty in flood hydrographs was considered through a bivariate approach by modelling the correlation structure of peak streamflow and flood volume by means of a copula approach.

Results of the analysis highlight how rating curves' uncertainty significantly affects flood mapping assessment and, in particular, probabilistic flood mapping, when the curves themselves are used as downstream boundary conditions. This aspect appears particularly relevant when the range of uncertainty for high flow rates becomes wide due to the extrapolation error introduced during rating-curve construction. In this context, the methodology used for rating-curve construction plays a fundamental role in the model chain for flood hazard assessment. We investigated the effects in terms of dike breaching and inundation probability of two methodologies for rating-curve construction, referred to in the study as Traditional and Constrained approaches (see also Domeneghetti et al., 2012). In the case of rating curve constructed by means of a typical approach (e.g. Traditional approach) the analysis shows through a series of Monte Carlo simulation experiments that neglecting the uncertainty associated with empirical rating curve may lead to highly inaccurate, and therefore dangerous, inundation mapping. In this context, the study clearly points out how taking into account the rating-curve uncertainty through a probabilistic approach significantly enhances the reliability of the flood hazard mapping. Also, the results of our analysis pointed out that limiting the extrapolation error while constructing empirical rating curves (for instance by adopting an approach similar to the so-call Constrained approach illustrated in Domeneghetti et al., 2012) significantly reduces the effect of uncertain boundary conditions on the flood likelihood estimation. Additionally, the reduction of rating-curve bias leads to a more reliable flood hazard estimation, reducing the risk of unfounded estimation of floodable areas. This is an important aspect when practical constraints (i.e. lack of data, available time, money, etc.) prevent the modeller from extending the study domain downstream, i.e. locating the downstream boundary conditions sufficiently far enough away from the area of interest, which could evidently reduce, or completely remove, the effect of rating-curve uncertainty on model results. A probabilistic statement of flood hazard, which incorporates a quantification of the uncertainty affecting the output of numerical hydraulic modelling, represents a fundamental piece of information for decision-makers, when, for instance, they are called to define spatial development plans for a given area, or when they need to identify priorities in the organisation of civil protection actions during a flood event. Probabilistic flood inundation maps are the most natural and straightforward graphical representation of such a statement, and should always be preferred to deterministic inundation maps.

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