Uncertainty in design flood profiles derived by hydraulic modelling

Luigia Brandimarte and Giuliano Di Baldassarre

ABSTRACT

The scientific literature has widely shown that hydraulic modelling is affected by many sources of uncertainty (e.g. model structure, input data, model parameters). However, when hydraulic models are used for engineering purposes (e.g. flood defense design), there is still a tendency to make a deterministic use of them. More specifically, the prediction of flood design profiles is often based on the outcomes of a calibrated hydraulic model. Despite the good results in model calibration, this prediction is affected by significant uncertainty, which is commonly considered by adding a freeboard to the simulated flood profile. A more accurate approach would require an explicit analysis of the sources of uncertainty affecting hydraulic modelling and design flood estimation. This paper proposes an alternative approach, which is based on the use of uncertain flood profiles, where the most significant sources of uncertainty are explicitly analyzed. An application to the Po river reach between Cremona and Borgoforte (Italy) is used to illustrate the proposed framework and compare it to the traditional approach. This paper shows that the deterministic approach underestimates the design flood profile and questions whether the freeboard, often arbitrarily defined, might lead to a false perception of additional safety levels.

Key words | design flood, hydraulic modelling, levee design, uncertainty analysis

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INTRODUCTION

In floodplain management, the design of flood defense structures is a critical step, which requires the definition of a certain level of safety. This definition should be the result of a risk-based analysis and is therefore related to the potential flood damages. Different safety levels (usually expressed in terms of return periods) are used in different countries. In the Netherlands, for instance, the design of flood protection structures is based on discharge values corresponding to return periods between 250 and 10,000 years (e.g. Jonkman *et al.* 2008). In the United States, the current policy (Commission on Geosciences Environment and Resources 2000) for flood defense design refers to the 1-in-100 year flood (i.e. the discharge value corresponding to a return period of 100 years).

The traditional procedure to predict water levels corresponding to a specific design flood for a given return period (i.e. design flood profile) is based on the use of hydraulic models (e.g. Bates *et al.* 2004). Many different tools have proven to be very useful to approximate and simulate real-world behavior of a flood wave and flow path distribution along the river and across the floodplain (e.g. Moussa & Bocquillon 1996; Aronica *et al.* 1998; Todini 1999; Hall *et al.* 2005; Horritt *et al.* 2007; Prestininzi 2008; Di Baldassarre *et al.* 2009a).

However, the scientific literature has extensively shown that the results of hydraulic modelling and, more specifically, the simulated flood profiles are affected by many sources of uncertainty: model structure, model parameters, topography and boundary conditions (Aronica *et al.* 1998; Romanowicz & Beven 1998, 2003; Bates *et al.* 2004; Hall *et al.* 2005; Pappenberger *et al.* 2005). Yet, the design flood estimated via flood frequency analysis is also significantly uncertain mainly because of observation errors (e.g. rating curve; Di Baldassarre & Claps 2011), sample size and

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selection of the distribution model (Di Baldassarre *et al.* 2009b). A more detailed classification of these sources is reported in Apel *et al.* (2004) that differentiate between epistemic (incomplete knowledge) and aleatory (statistical) uncertainty (Beven 2008).

In flood defense design, the conventional approach to cope with the uncertainty is to simply add a certain freeboard to the simulated design flood profile (Commission on Geosciences Environment and Resources 2000). The definition of these standard freeboards is often arbitrary and seldom justified.

In this context, we proposed a pragmatic methodology to estimate design flood profiles and the associated uncertainty. To this end, an informal approach is used to estimate the uncertainty in hydraulic modelling and flood frequency analysis. The outcomes of this novel approach are compared to the traditional ones, obtained by using a standard freeboard. The discussion of the methodology is facilitated by an application of the proposed framework to a specific test site.

Test site

The test site is a 98 km reach of the Po river, between Cremona and Borgoforte (Figure 1). With its drainage area of about 71,000 km^2 and its 650 km extension, the Po river is the largest and longest river in Italy. The river reach under study is characterized by a stable main channel, around 300 m wide, and a floodplain confined by two continuous levee systems, whose overall width varies from 400 m to 4 km.

A high quality 2 m digital terrain model (DTM) of the middle-lower portion of the Po river (covering an extension of about 350 km) was made available by the Po River Basin Authority. The DTM was built from data collected during the year 2005 by two different laser scanners (3033 Optech ALTM and Toposys Falcon II), from altitudes of approximately 1,500 m. Below water, channel bathymetry of the navigable portion was characterized by a boat survey using a multi-beam sonar (Kongsberg EM 3000D), conducted in the same year, integrated elsewhere with the information collected during a previous ground survey conducted by the Interregional Authority of the Po River in 2005 (Castellarin *et al.* 2011). The DTM was processed to remove vegetation and validated against the data achieved through a differential global positioning system (DGPS). Mean quadratic residuals between the DGPS survey and DTM were around 0.13 m. Moreover, the validation procedure confirmed the absence of local systematic differences (Castellarin *et al.* 2009).

Hydraulic modelling

This study used the 1D code HEC-RAS (US Army Corps of Engineers, Hydrologic Engineering Center 2001) for

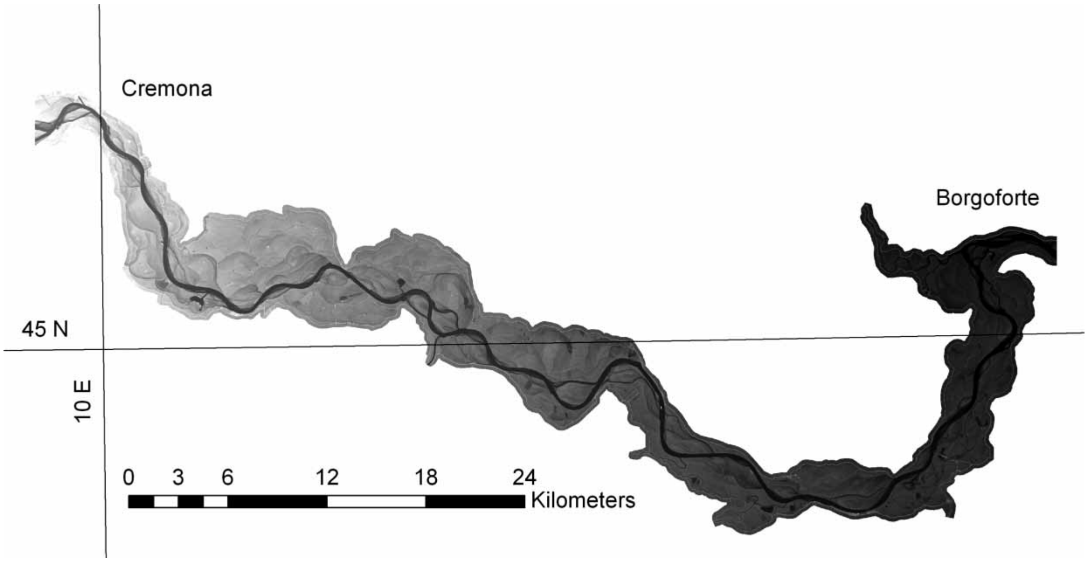

Figure 1 | Po river between Cremona and Borgoforte and LiDAR topography (gray scale).

simulating the hydraulic behavior of the 98 km reach of the Po river between Cremona and Borgoforte (Figure 1), in steady flow conditions. The geometric characteristics of the Po river reach were described by 88 cross sections extracted from DTM previously described.

HEC-RAS solves the governing equations for gradually varied flow, and water profiles are computed using the standard step procedure. More details can be found in the *Hydraulic Reference Manual* (US Army Corps of Engineers, Hydrologic Engineering Center 2001). The model neglects the interactions between main channel and floodplain during floods, the effects of unsteadiness and sediment transport processes. However, HEC-RAS has been widely used for hydraulic modelling (e.g. Pappenberger *et al.* 2005, 2006; Schumann *et al.* 2007; Brandimarte *et al.* 2009; Di Baldassarre *et al.* 2009a) and a number of studies have proven its reliability in simulating floods in natural rivers (e.g. Horritt & Bates 2002; Castellarin *et al.* 2009).

Here, the use of steady flow conditions is consistent with the proposed methodology, which is intended to be simple and pragmatic. This assumption was also supported by initial experiments showing that, in order to derive the maximum flood levels, a dynamic model was not needed (see also below). This is due to the fact that flood events affecting this test site are characterized by broad and slowly varying hydrographs. Moreover, steady flow routines are commonly adopted by regulatory agencies for floodplain mapping studies (Di Baldassarre *et al.* 2010).

Model calibration

In October 2000, a major flood event occurred along the Po river. The October 2000 estimated peak flow (about 11,850 $m^3 s^{-1}$) at Cremona was used as inflow data; while friction slope at Borgoforte was used as downstream boundary condition.

The model was then calibrated, by varying Manning's n roughness coefficients, against the high water marks (i.e. post-event measured maximum water levels) surveyed after the October 2000 flood event (Coratza 2005). The use of high water marks for model calibration is consistent with the purpose of the model itself, which is the prediction of flood profiles. Figure 2 shows the elevation of the river bed and the surveyed left and right bank high water marks. To represent the roughness characteristic of the 98 km river reach, it was assumed a single n value for the entire channel and one for the entire floodplain.

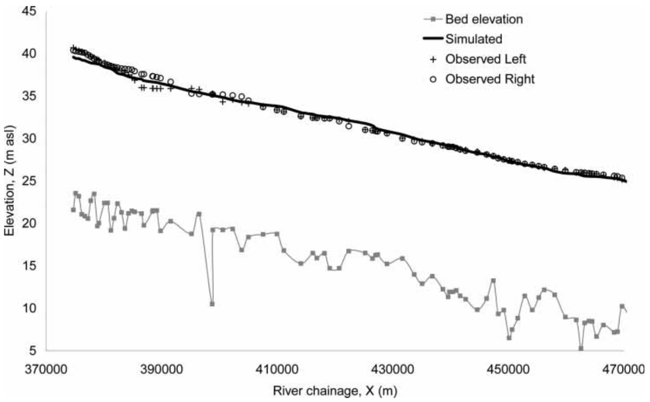

Figure 2 | Model calibration: observed left and right bank high water marks and results of the best fit model.

A sensitivity analysis was carried out by varying the Manning's channel coefficient in the range 0.02–0.06 $m^{-1/3}$ s and the Manning's floodplain coefficient in the range 0.06–0.14 $m^{-1/3}$ s. The performance of the hydraulic model in reproducing the October 2000 flood profile was assessed by means of the mean absolute error, ε. The sensitivity analysis also pointed out that other parameters of the hydraulic model (e.g. contraction and expansion coefficients) have a minor effect on the results of the model. Thus, standard values from literature were adopted (US Army Corps of Engineers, Hydrologic Engineering Center 2001).

The results obtained with the best fit model, in terms of water levels, are shown in Figure 2. The best performing combination of channel and floodplain coefficient (0.035 and 0.07 $m^{-1/3}$ s) is within the standard ranges reported in the commonly used tables for Manning's coefficient (Chow 1959). It is worth noting the good performance of the model (Figure 2): the maximum relative error between the observed and simulated water depths along the river reach is less than 3%.

Moreover, Figure 3 shows the model response. There are different sets of parameters that provide a mean absolute error lower than 0.5 m (Figure 3), which is a relatively good performance. In fact, 0.5 m is the expected magnitude of the accuracy of high water marks (Neal *et al.* 2009: Horritt *et al.* 2010). These optimal parameters lie inside a

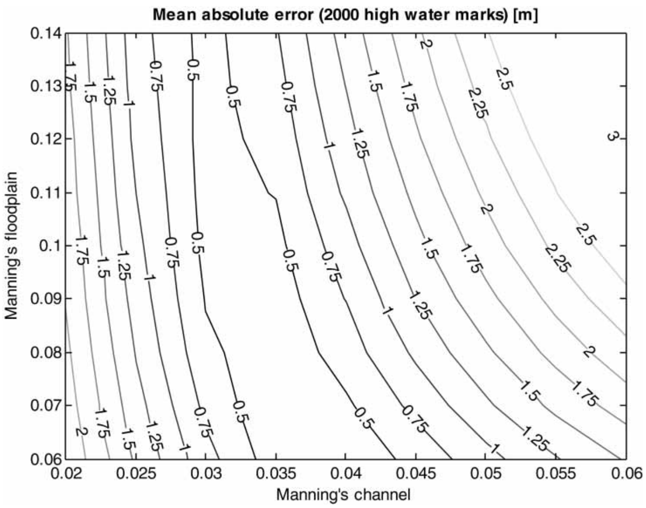

Figure 3 | Model responses to changes in Manning's coefficients.

certain (hyperbolic shape) area (Figure 2). This is a typical example of parameter compensation where decreasing Manning's *n* floodplain coefficients are compensated by increasing Manning's *n* for the channel (see Hunter *et al.* 2006 for a discussion of this behavior).

Lastly, it is interesting to note that the performance of the steady flow model (Figures 2 and 3) is comparable to the performance of an unsteady model, which was tested in the same river reach using the same calibration data (Di Baldassarre *et al.* 2009d).

Design flood estimation

As mentioned above, the design of flood protection structures is based on safety levels (i.e. return periods) which depend on the specific case. The main levee system of the Po river reach under study is designed by using the 1-in-200 year flood.

Thus, the 1-in-200 year flood was estimated by using the time series of 45 annual maximum flows, recorded at the Cremona gauge station (Figure 1). More specifically, to estimate the 1-in-200 year flood, the Gumbel extreme value probability distribution (Gumbel 1958), which is also known as extreme value type I (EVI) distribution, was utilized as it has the advantage to be parsimonious (only two parameters) and widely applied in hydrology (Maione *et al.* 2003). However, it should be noted that the use of Gumbel distribution has been criticized (Koutsoyiannis 2003). Nevertheless, the Kolmogorov–Smirnov goodness of fit test was applied to determine whether the set of observation data might have been drawn from the selected distribution. The fitted distribution was then used to estimate the 1-in-200 year flood ($Q_{200} \sim 13{,}700\ \mathrm{m}^3\ \mathrm{s}^{-1}$). It is interesting to note that the choice of a steady flow approach allowed us to avoid estimating the shape of the 1-in-200 year flood hydrograph and therefore introducing additional sources of uncertainty.

Design flood profiles (with uncertainty)

The traditional approach for the prediction of design flood profiles is to use a calibrated (and, rarely, validated) hydraulic model to simulate the design flood. The current policy in the Po river basin requires that levees should have at least 1 m of freeboard above the 200-year flood profile elevations. Thus, for the specific application example, the best fit model (Figure 2) was run in steady-state conditions using the estimated Q_{200} as upstream boundary condition (Cremona). Obviously, in simulating the 1-in-200 year flood, the inundation of the flood-prone areas protected by the levees was not allowed. Figure 4(a) shows the results of the simulation in terms of water level (1-in-200 year flood profile) and the profile (simulation results plus 1 m), which would be traditionally used to design or verify flood defense structures (e.g. levee system).

As mentioned above, many sources of uncertainty affect the simulated flood profile used to design flood defenses. A rigorous analysis of all the sources of uncertainty in the estimation of the design flood is not an easy task and might be computationally infeasible. Hence, we propose a simple and pragmatic approach to cope with uncertainty, which is based on the Generalized Likelihood Uncertainty Estimation (GLUE; Beven & Binley 1992), widely used in hydrological modelling (e.g. Montanari 2005; Winsemius *et al.* 2009; Krueger *et al.* 2010). It should be noted that the application of GLUE is criticized by part of the scientific community (e.g. Mantovan & Todini 2006; Montanari 2008) as it requires a number of subjective decisions that should be transparent and unambiguous (Hunter *et al.* 2005). Yet Vrugt *et al.* (2009) showed that formal Bayesian approaches that make very strong assumptions about the

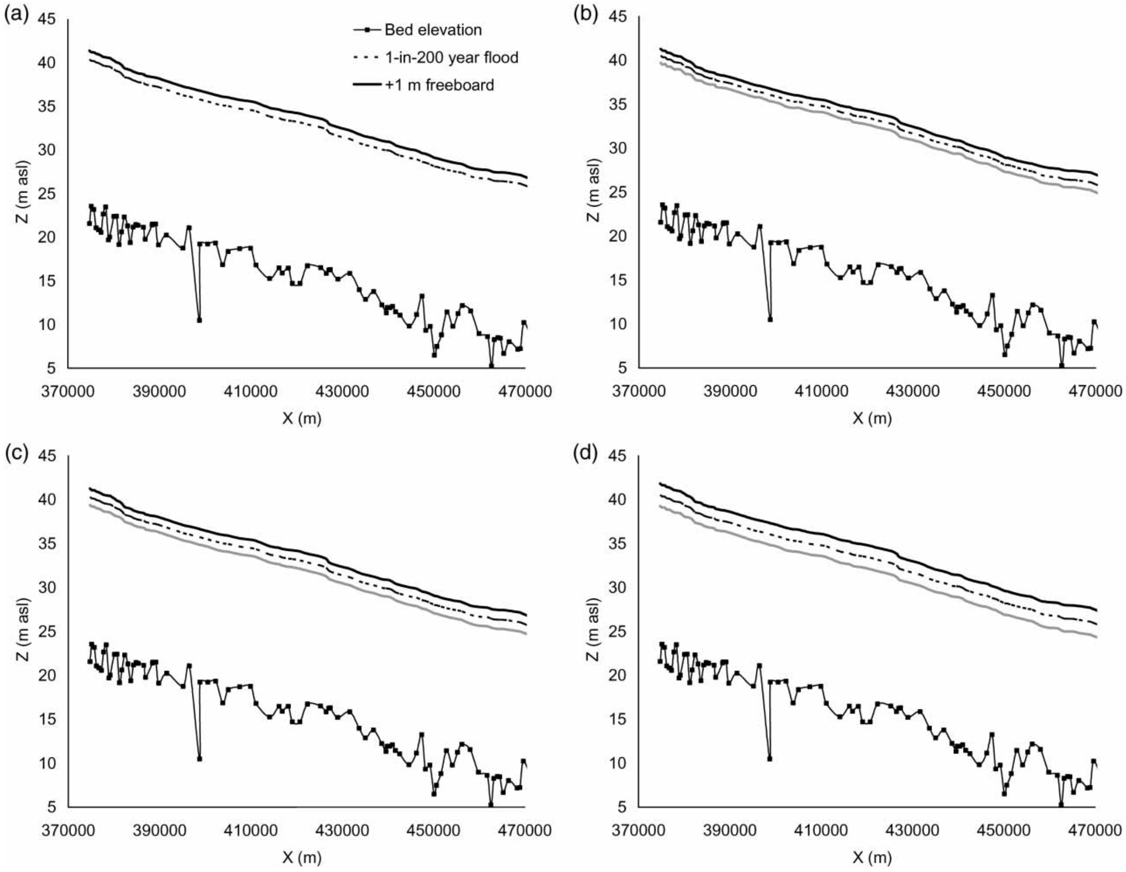

Figure 4 | Design flood profiles: (a) traditional design flood profile (single simulation with best fit model plus 1 m freeboard); Parts b–d show uncertain design flood profiles by considering the: (b) model parameter uncertainty only; (c) design flood uncertainty only; (d) model parameter and design flood uncertainty (5th, 50th, and 95th percentiles; solid gray, dotted and solid black line, respectively).

nature of the statistical properties of the residuals can generate very similar estimates of total predictive uncertainty as informal Bayesian approaches, such as GLUE.

To estimate the uncertainty in design flood profiles, only a few sources of uncertainty were selected. Concerning hydraulic modelling, the scientific literature indicates inflow and model parameters as the most affecting sources of uncertainty (Pappenberger *et al.* 2008; Di Baldassarre *et al.* 2010). Hence, it was assumed that topography and model structural uncertainties provide a minor contribution to the overall uncertainty. As a matter of fact, for this specific case study, neglecting the topographic uncertainty was supported by the high quality (i.e. resolution and accuracy) of the DTM. Moreover, the HEC-RAS model was shown to be able to properly simulate the hydraulics of the River Po during high magnitude events (e.g. Castellarin *et al.* 2009; Di Baldassarre *et al.* 2009d).

As mentioned, many sources of inaccuracy affect the estimation of the design flood. In this study, we focused on the uncertainty caused by the sample size. This is justified by the fact that often high return period quantiles (i.e. 1-in-200 year) are estimated using time series of annual maximum flows of limited extension (30–50 years; Di Baldassarre *et al.* 2009b) and therefore sample size has a major impact on the uncertainty in design flood estimation.

A first hydraulic modelling exercise was performed by focusing on the uncertainty in model parameters. To this end, a subset of behavioral models (Beven 2006) satisfying a threshold criterion has been selected from the results of the sensitivity analysis. This step has a clear subjective nature. Thus, this decision has to be transparent and unambiguous (Montanari 2005). However, it should be noted that transparency in the decision making does not eliminate this subjectivity (Hunter *et al.* 2005). For this exercise, given the accuracy of the used calibration data, all the couples of Manning's channel and floodplain coefficients giving a mean absolute error higher than 1 m (Pappenberger *et al.* 2008) have been rejected, while the others considered as behavioral models. Thus, only the models satisfying this threshold condition were used to simulate the 1-in-200 year flood.

Within the GLUE framework (Beven & Binley 1992), each simulation, i, was associated to a likelihood weight, W_i ranging from 0 to 1. The weight W_i is expressed as a function of the measure of fit, ε_i, of the behavioral models:

$$W_i = \frac{\max(\varepsilon_i) - \varepsilon_i}{\max(\varepsilon_i) - \min(\varepsilon_i)} \tag{1}$$

where $\max(\varepsilon_i)$ and $\min(\varepsilon_i)$ are the maximum and minimum value of the mean absolute error of the behavioral models. Then, the likelihood weights were rescaled to a cumulative sum of 1 and the weighted 5th, 50th and 95th percentiles, representing the likelihood weighted uncertainty bounds, were computed (Figure 4(b)).

Another important source of uncertainty is given by the estimation of the design flood. To account for uncertainty in the design flood estimation only, we generated 100 random values normally distributed, with mean value, Q_{200}, equal to the 1-in-200 year flood estimated by applying the Extreme Value Distribution type I (EVI) (see above) and standard deviation, σ_{200}, evaluated by means of the Kite formula (Chow *et al.* 1988), for the standard error of estimate for the EVI distribution:

$$S_e = s\left[\frac{1}{m}\left(1 + 1.1396K_T + 1.1000K_T^2\right)\right]^{1/2} \tag{2}$$

where s is the standard deviation of the original sample, having size m, and K_T is the frequency factor that, for the EVI distribution, can be expressed as a function of the return period, T, as (Chow *et al.* 1988):

$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + \ln\left[\ln\left(\frac{T}{T-1}\right)\right]\right\} \tag{3}$$

Thus, 100 simulations of the best fit model were run with the 100 random discharge values. From the ensemble simulations, the 5th, 50th and 95th percentiles were computed (Figure 4(c)).

Lastly, the combined uncertainty in the model parameters and inflow data has been assessed. To this end, we ran a total of 3,000 simulations by feeding all the behavioral models using the 100 discharge values generated using the Kite formula (Equations (2) and (3)). Each simulation was assigned a weight corresponding to its behavioral model (Equation (1)) and the weighted percentiles were evaluated. A sensitivity analysis pointed out that additional model runs would not significantly change the weighted percentiles. Figure 4(d) shows the plot of the weighted 5th, 50th and 95th percentiles of the 1-in-200 year flood profile, obtained by taking into account both sources of uncertainty, applying the GLUE procedure.

By comparing the flood profiles obtained in the three cases analyzed (Figure 4(b)–(d)), one can see that taking into account the uncertainty in the design flood only (Figure 4(c)) gives wider uncertainty bounds than the uncertainty in the model parameters only (Figure 4(b)). The combined effect of the uncertainty in the model parameters and inflow data further enlarges the uncertainty bound of the water surface profile (Figure 4(d)). Table 1 also reports the average value and standard deviation of the width of the uncertainty bounds, for the three cases analyzed.

DISCUSSION

As mentioned above, conceiving inundation hazard as a probability has been encouraged more recently (Aronica *et al.* 1998; Romanowicz & Beven 1998, 2003; Bates *et al.* 2004; Hall *et al.* 2005; Pappenberger *et al.* 2005, 2006). In fact, visualizing flood hazard as a probability is a more correct representation of the subject since deterministic predictions of flood profile and design flood, which use the single best fit model and best estimate design flood,

Table 1 | Average value and standard deviation of the width of the uncertainty bounds estimated in the three cases

	Mean (m)	Standard deviation (m)
Model parameters	1.57	0.17
Design flood	1.90	0.14
Model parameters and design flood	2.61	0.19

might misrepresent the uncertainty in the modelling process and give a result that is only spuriously precise (Beven & Freer 2001; Bates *et al*. 2004; Beven 2006; Di Baldassarre *et al*. 2010). Thus, theoretically speaking, the use of an uncertain design flood profile (Figure 4(b)–(d)) is more appropriate than the traditional approach (Figure 4(a)).

In particular, the traditional approach for the construction of design flood profiles (Figure 4(a)) is based on the deterministic assumption that the hydraulic model, calibrated on the 2000 flood event, is able to predict the 1-in-200 year flood profile. Then, all the uncertainties in the modelling process are included by using a constant freeboard. One of the issues of such an approach is that the definition of the freeboard is very often arbitrary. Moreover, this method may not be appropriate in terms of risk communication (Demeritt *et al*. 2010). For instance, the fact that in the Po river the levee system is designed by using 1-in-200 design flood profile plus 1 m may lead to the false perception that the levee system would be able to defend flood-prone areas also in case of extreme floods more severe than the 1-in-200 year flood (e.g. 1-in-500 year flood). This is obviously not the case. In such an approach, it is important to bear in mind that the freeboard does not give an additional level of safety, but simply attempts to account the overall uncertainty in hydraulic modelling.

By referring to the specific case considered in this paper, we can see that if the uncertainty in model parameters and design flood is considered (Figure 4(d)), the difference between the 95% percentile and the median is around 1.2–1.5 m and therefore higher than the standard 1 m freeboard (Figure 4(a)). Thus, the standard freeboard underestimates the overall uncertainty. This is particularly true if one considers that this example application estimated the uncertainty bounds by neglecting the presence of many other sources of uncertainty (e.g. topographical data, model structure). Furthermore, the uncertainty in the design flood may be underestimated as this exercise did not take into account the additional uncertainty caused by the subjective selection of a certain probabilistic model: a different probabilistic model may have led to a relatively different design flood estimation (e.g. Laio *et al*. 2009; Di Baldassarre *et al*. 2009c).

Finally, this study did not consider the presence of errors in the flood data used for the frequency analysis, which have been shown to be significant, especially for flood data when stage-discharge rating curves are extrapolated beyond the measurement range (e.g. Dymond & Christian 1982; Kuczera 1992; Petersen-Øverleir 2004, 2005; Di Baldassarre & Claps 2011).

CONCLUSIONS

Traditional methodologies for the design of flood defense structures are based on the application of calibrated (and, in exceptional occasions, also validated) models to produce deterministic flood design profiles. The uncertainty in the hydraulic modelling exercise is then implicitly considered by using a certain freeboard, which is usually arbitrarily defined.

This paper is a first attempt to develop methods and provide example applications for the diffusion of probabilistic approaches for flood defense design, and, more in general, for flood management. In particular, we proposed a simple and pragmatic approach, which is based on the use of uncertain flood profile, where the most significant sources of uncertainty are explicitly considered.

The application example enabled: (1) the illustration of the proposed framework for the derivation of uncertain flood profiles, and (2) the comparison of the proposed methodology to the traditional approach (deterministic flood profile plus freeboard).

This study focused on the uncertainty in hydraulic modelling due to model parameters and design flood estimation. It was shown that the latter has a strong influence on the overall uncertainty. It was also discussed that standard freeboards should not be viewed as an additional safety, but as a rough estimation of the overall uncertainty. More specifically, for the test site analyzed, this study also showed that the standardly used freeboard seems to underestimate the overall uncertainty.

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