A hydraulic study on the applicability of flood rating curves

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Giuliano Di Baldassarre and Pierluigi Claps

ABSTRACT

Several hydrological studies have shown that river discharge records are affected by significant uncertainty. This uncertainty is expected to be very high for river flow data referred to flood events, when the stage–discharge rating curve is extrapolated far beyond the measurement range. This study examines the standard methodologies for the construction and extrapolation of rating curves to extreme flow depths and shows the need of proper approaches to reduce the uncertainty of flood discharge data. To this end, a comprehensive analysis is performed on a 16 km reach of the River Po (Italy) where five hydraulic models (HEC-RAS) were built. The results of five topographical surveys conducted during the last 50 years are used as geometric input. The application demonstrates that hydraulically built stage–discharge curves for the five cases differ only for ordinary flows, so that a common rating curve for flood discharges can be derived. This result confirms the validity of statistical approaches to the estimation of the so-called 'flood rating curve', a unique stage–discharge curve based on data of contemporaneous annual maxima of stage and discharge values, which appears insensitive to marginal changes in river geometry.

Key words | cross-sections, flood discharge, hydraulic models, observation uncertainty, rating curve

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INTRODUCTION

Hydrological models often disregard the fact that river flow data are affected by a significant uncertainty (e.g. Clarke 1999). This is despite the fact that it is well known that river discharges are almost never directly measured, as opposite to the water stage. Usually, observed river stage values are converted into river discharges by means of a stage–discharge relationship, the so-called rating curve (World Meteorological Organisation 1994).

The main sources of uncertainty that affect river discharge data, obtained using the rating curves, are: (1) errors in the individual stage and discharge measurements; (2) errors induced by the presence of unsteady flow conditions; and (3) errors induced by the extrapolation of the rating curve beyond the range of measurements used for its derivation. Depending on the specific case study, additional sources of uncertainty can be significant. These include the presence of relevant backwater effects (caused by downstream confluent tributaries, lakes and regulated reservoirs) and temporal changes in the hydraulic properties governing the stage–discharge relationship (e.g. scour and fill, vegetation growth and ice build-up during cold periods).

Concerning the measurement uncertainty (case 1), Pelletier (1987) reviewed 140 publications and concluded that the overall uncertainty in a single determination of river discharge can be more than 8% at the 95% condence level. More recent studies reported errors around 5–6% (e.g. Léonard *et al.* 2000) that could possibly be reduced by using appropriate discharge measurement techniques (Lintrup 1989; European ISO EN Rule 748 1997).

The errors induced by the presence of unsteady flow (case 2) can be relevant in very mild river slope conditions, where the variable energy slope leads to the formation of a

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loop rating curve (Jones 1916; Fread 1975). In order to reduce this source of uncertainty, a number of authors proposed the use of artificial neural networks to model the looped rating curve due to unsteady flow (e.g. Tawfik *et al.* 1997; Jain & Chalisgaonkar 2000; Bhattacharya & Solomatine 2005). More recently, an original approach based on simultaneous stage measurements at two adjacent cross-sections was introduced (e.g. Arico *et al.* 2008; Dottori *et al.* 2009).

Finally, the uncertainty induced by the extrapolation of the rating curve beyond the measurement range (case 3) can result in an amplification of the previous uncertainties. Given the lack of measurements during high flow conditions, indirect and extrapolated discharge measures of flood discharges turn out to be affected by relevant errors. Many authors therefore warn not to extrapolate rating curves beyond a certain range (e.g. Kuczera 1996; Clarke 1999). For instance, Di Baldassarre & Montanari (2009) performed a quantitative numerical analysis to estimate the uncertainty of river discharge observations on the River Po (Italy) and showed that the errors produced by the extrapolation of the rating curve beyond the range of measurements used for its derivation were about 14% at the 95% confidence level. They also showed that this extrapolation uncertainty strongly increases for increasing values of river discharge.

Nevertheless, river discharge data referred to high flow conditions are required for many hydrological applications, such as calibration and validation of rainfall–runoff models, flood frequency analysis, boundary conditions of flood inundation models, geomorphologic studies and river sediments management. Thus, the extrapolation of the rating curve beyond the measurement range is very often a necessity (Pappenberger *et al.* 2006) and more efforts are needed to reduce the errors and uncertainties associated with this indirect measure. These premises are the main motivations for the present study.

The standard methodology to derive a rating curve consists of carrying out field campaigns to record contemporaneous measures of water stage h and river discharge Q. Such measures allow us to identify discrete points (Q, h) that are subsequently interpolated through an analytical relationship that approximates the rating curve. The power-law function is commonly used in hydrometric practice (Herschy 1978; Dymond & Christian 1982; ISO 1998):

$$Q = a \cdot (h - b)^c \tag{1}$$

where a, b and c are calibration parameters that are usually estimated by means of the non-linear least squares method (e.g. Petersen-Øverleir 2004). Equation (1) is widely used in river hydraulics and has some physical justifications (Chow 1959; Fenton 2001; Petersen-Øverleir 2005). More recently, Reitan & Petersen-Øverleir (2008) analyzed the use of power-law (Equation (1)) segments to cope with stage–discharge relationships that change at certain flow stages.

Hydrologic measurement standards require a periodic updating of the rating curve to account for changes that may occur in the river geometry. These updates produce annual rating curves that sometimes change considerably from one year to another. The evaluation of the effects of these changes in the range of flood discharges is the main topic of this manuscript. Visual inspection of the ensemble of annual rating curves (Figure 1) gives an idea of the possible inaccuracies due to the extrapolation and of the variability in the low-flow region. Studies conducted by Claps *et al.* (2003) hypothesize that flow extremes in different years can be

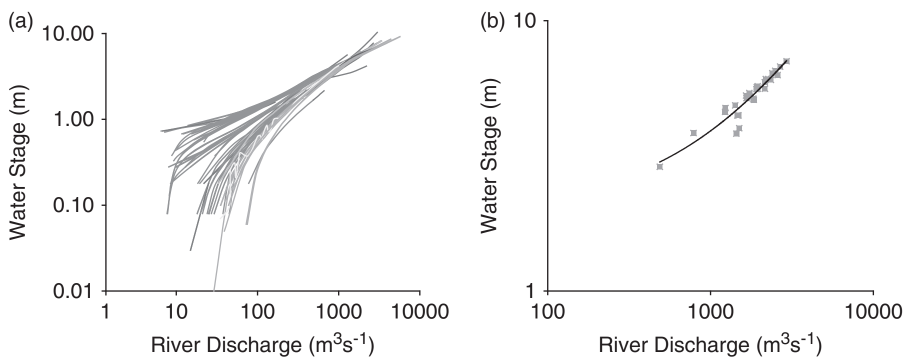

Figure 1 | Example of the methodology proposed by Claps *et al.* (2003): (a) different rating curves (from 1922 to 2004) for a River Po tributary and (b) corresponding flood rating curve interpolating annual maxima.

considered compatible with a unique so-called flood rating curve, despite changes in river geometry. The flood rating curve is estimated using only annual maxima of contemporaneous values of stage and discharge (Figure 1(b)). This approach (described below) is solely based on a statistical fitting and is quite practical to apply when data of the section geometry is lacking. However, appropriate hydraulic justification would be required to confirm the above basic assumption that the rating curve tends to be constant in the range of annual maximum discharges.

Flood rating curve

The empirical estimation of the so-called flood rating curve (Claps *et al.* 2003) is based on the assumption that available annual maximum discharge values can be used to identify a discharge range in which the rating curve is stable for a given cross-section. The study is based on data available in publications of the Italian Hydrological Survey (SII) (Ministero dei Lavori Pubblici 1937–1970), which contain annual maxima of instantaneous discharge (not of secondary peaks) as well as the annual rating curves. Peak discharges are available in the publications as determined from extrapolation of the annual rating curves, even if some expert-judgment adjustment is reported (Figure 1). Given the high variability of the annual rating curves in the low discharges range, Claps *et al.* (2003) considered the series of annual extremes and, using the published stage values, proposed the use of a separated and hydraulically based rating curve only for those series (Figure 1). In particular, the flood rating curve is obtained by parameterizing Equation (1) using the annual extremes data. This curve allowed the authors to demonstrate the inconsistency of some discharge values and to reconstruct discharge values from stage measurements made in periods where the annual rating curves were unavailable.

The present study aims to evaluate the validity of the assumptions made by Claps *et al.* (2003) and to reduce the uncertainty of flood data induced by extrapolation of the rating curve. These objectives are tackled by means of a hydraulic approach using a set of valuable data on a 16 km reach of the River Po (Northern Italy). In particular, five hydraulic models are built using five topographical ground surveys conducted in 1954, 1968, 1979, 1991 and 2000 as geometric input. These models are then used to investigate the hydraulic behaviour of the river reach and, in particular, to assess the effects of river geometry changes in the stage–discharge relationships, as described in the following sections.

DATA AND METHODS

Data related to the rating curves and used in the hydraulic modelling refers to the 16 km reach of the River Po (Northern Italy) between Cogozzo and Tagliata (Figure 2). The River Po is the longest river in Italy and its basin of about 70,000 km^2 drains a large part of the Italian alpine region. In the reach under study, the average bed slope is about 0.02% and the cross-section is formed by a main channel having a width varying from 200 to 300 m. Two lateral banks with overall width varying from 2 to 3 km are confined by continuous artificial levees. The mean annual peak discharge is equal to around 1000 m^3 s^{-1} and the 100-year flood peak is

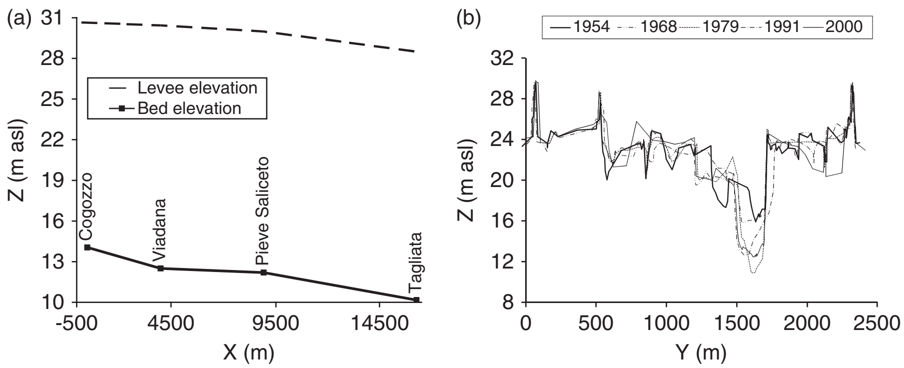

Figure 2 | Test site: (a) River Po between Cogozzo and Tagliata and (b) cross-section of Viadana surveyed in 1954, 1968, 1979, 1991 and 2000. X represents the river chainage (m), Y the distance along each cross-section (m) and Z the elevation (m asl).

about 12,000 $m^3 s^{-1}$ (Maione *et al.* 2003). Historical flood events on the River Po are characterized by flood waves with a rather long base time (Castellarin *et al.* 2009).

Five different topographical ground surveys of this river reach, conducted in 1954, 1968, 1979, 1991 and 2000, are used in this study. The right panel of Figure 2 shows an internal cross-section surveyed at Viadana. Using the above-mentioned survey data as geometric input, five different hydraulic models are built by means of the one-dimensional (1D) HEC-RAS (Hydrologic Engineering Center River Analysis System) model code (Hydrologic Engineering Center 2001). HEC-RAS is widely used for flood inundation modelling (Horritt & Bates 2002; Pappenberger *et al.* 2005; Matgen *et al.* 2007) and as a hydraulic kernel in hydrological studies (Young *et al.* 2009). It is worth noting that a number of studies showed that, when the hydraulic problem at hand is not dominated by specific 2D phenomena (e.g. inundation caused by dam breaches or levee failures), HEC-RAS is rather suitable for providing an accurate reproduction of the flood propagation and inundation extent (e.g. Horritt & Bates 2002). Concerning the Po test site, previous studies pointed out that HEC-RAS provides an accurate reproduction of the hydraulic behaviour of the River Po (Castellarin *et al.* 2009; Di Baldassarre *et al.* 2009).

The topography of the 16 km reach of the River Po is described by using 4 cross-sections (Figure 2). Despite this apparently excessive cross-section spacing, the hydraulic behaviour of this river reach is reasonably well described because of its regular geometry and very gentle slope. This is confirmed by indications in the scientific literature (e.g. Samuels 1995) as well as by the findings of the extensive numerical analysis performed in this test site (Castellarin *et al.* 2009).

River discharge at the upstream end and friction slope at the downstream end define the model boundary conditions. Concerning the roughness parameters, in order to avoid subjectivity in separating the main channel from the floodplain for each cross-section in the five different topographical ground surveys, a uniform Manning coefficient for the entire cross-section (channel and floodplain) is utilized. This assumption is justified by the findings of previous studies performed in the same river reach using HEC-RAS (Di Baldassarre *et al.* 2009). In particular, Di Baldassarre *et al.* (2009) manually calibrated a HEC-RAS model using a large amount of data from the October 2000 flood event. The calibration exercise showed that the optimal set of parameters agrees well with the values given in standard tables of Manning's coefficients (0.04 $m^{-1/3}$ s for the channel and 0.09 $m^{-1/3}$ s for the floodplain; Chow 1959). The same study demonstrated that parameter compensation, due to Manning's coefficient decrease in the floodplain and to its increase in the main channel, allows us to use a uniform Manning's coefficient for the whole section (equal to around 0.05 $m^{-1/3}$ s) while preserving almost equivalent performance of the hydraulic model. Consequently, in the present study, direct stage and discharge measurements are used to evaluate the model performance with a uniform Manning's coefficient equal to 0.05 $m^{-1/3}$ s. This additional evaluation indicated that relative errors between observed and simulated water levels did not exceed 5%.

NUMERICAL STUDY

This study focuses on the extrapolation errors of the steady rating curve and is made by means of numerical experiments. It is therefore important to note that, in steady flow conditions for this river reach, it is reasonable to assume the presence of a one-to-one correspondence between the water stage and the river discharge. This is due the minor role played by downstream disturbances and tributaries (e.g. Franchini *et al.* 1999; Di Baldassarre & Montanari 2009).

The first numerical experiment is performed to examine how the river geometry modification affects steady-state rating curves. The experiment focuses on an internal cross-section (Viadana, Figure 2) and uses two different geometries surveyed in 1954 and 1968. Specifically, steady-state simulations with the hydraulic model produces 'measured' river discharges values. This is in a range between 500 $m^3 s^{-1}$ (low flow condition) and 5000 $m^3 s^{-1}$ (ordinary flood condition), in steps of 500 $m^3 s^{-1}$. The rating curve expressed by Equation (1) is estimated by interpolating the (Q, h) points. These simulations are run using a uniform Manning's coefficient equal to 0.05 $m^{-1/3}$ s and the least-squares method is used to estimate the three parameters of Equation (1).

The choice of the mentioned discharge interval reflects the actual practice to make direct measurements of river discharge up to ordinary flow conditions (e.g. Franchini *et al.* 1999). This is obviously due to the fact that measuring discharge during extreme floods is very difficult (if not impossible).

Figure 3 shows the results of this first numerical experiment and clearly highlights that the two annual rating curves are strongly different. Differences in the interpolation zone (500–5000 $m^3 s^{-1}$) reflect the changes in the natural geometry of the River Po occurred in the period 1954–1968 (Figure 2). In contrast, the high differences in the extrapolation zone (5000–12,000 $m^3 s^{-1}$) cannot be justified by data and simply reflect the shape of the curves in the extrapolation range. More specifically, Figure 3 shows that the water stage of 30 m asl (which is the elevation of the levee system; Figure 1) would correspond to around 15,500 $m^3 s^{-1}$ according to the 1954 rating curve, or around 12,000 $m^3 s^{-1}$ according to the 1968 rating curve. This difference appears too large: it is hard to believe that the river geometry modification which occurred in the period 1954–1968 would have led to a decrease of the hydraulic capacity of the river reach from 15,500 $m^3 s^{-1}$ to 12,000 $m^3 s^{-1}$.

Finally, by analyzing Figure 3 we can observe that there is a shift of the measured points for the 1968 geometry occurring at approximately 24 m. This could indicate that a second power-law segment (Reitan & Petersen-Øverleir 2008) might be more appropriate then single-valued power-law (Equation (1)) to interpolate (and then extrapolate) the measurements. However, this numerical analysis aims at investigating the behaviour of traditional approaches to building a rating curve; the use of a unique curve is the practical result of having very few direct measurements during floods which prevent us from reliably estimating a second power-law segment for high flows. For instance, referring to this specific experiment, we would estimate the second segment using only three measurements corresponding to river discharge beyond 4000 $m^3 s^{-1}$, which is a value related to significant flood events (Figure 3).

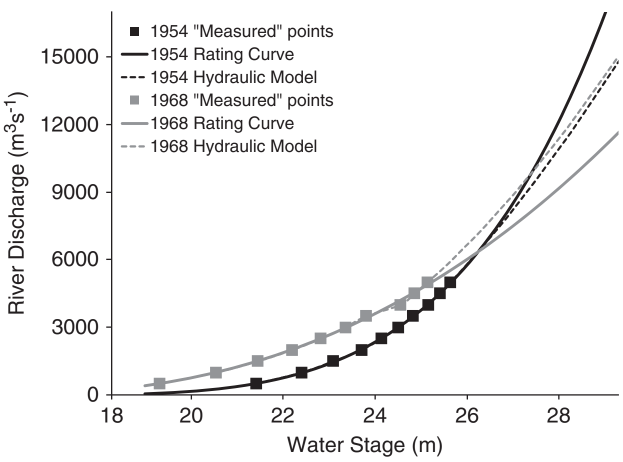

Figure 3 | Results of the first experiment in Viadana: construction of the rating curves using two different geometries (1954, black; 1968, grey). The figure also shows the hydraulic model results (dotted lines).

To better investigate the rating curve behaviour in the flood discharge range, a second set of numerical experiments is carried out where water surface profiles are reconstructed by using the five topographical ground surveys as geometric input. The hydraulic simulations are performed by imposing river discharge from 500 $m^3 s^{-1}$ to 12,000 $m^3 s^{-1}$, with steps of 500 $m^3 s^{-1}$, and uniform Manning's coefficient equal to 0.05 $m^{-1/3}$ s.

Table 1 and Figure 4 show the results of these simulations in terms of water stage corresponding to a given river discharge at Viadana. Differences in the water stage (for a given discharge) reported in Table 1 are caused by the changes in the cross-section geometry, including the cease-to-flow stage. The last column of Table 1 reports the standard deviation of the water stage values. It is interesting to note that, although considerable changes occurred in the geometry of this river reach (Figure 2), the flood stages corresponding to high discharge values remain approximately constant (Figure 4). More specifically, standard deviations of the water stage remains within the range 20–30 cm when the discharge exceeds 5000 $m^3 s^{-1}$ (Table 1). It is important to highlight that 20–30 cm represents the tolerance of results of computational hydraulic models in view of the rounding errors, topography uncertainty, etc. (e.g. Samuels 1995). Furthermore, Figure 3 also compares the hydraulic model results with the rating curves derived using the analytical relationship (1). It is interesting to note that, for high flow conditions, the hydraulic results tend to converge whereas the two rating curves diverge.

A third set of experiments is performed to take into account the uncertainty of the model parameters. For each geometry (1954, 1968, 1979, 1991 and 2000), the numerical computations are run using three values of the Manning's coefficient, i.e. 0.045 $m^{-1/3}$ s, 0.050 $m^{-1/3}$ s and 0.055 $m^{-1/3}$ s. Figure 5 shows the results obtained at the two internal

Table 1 | Results of the second experiment: simulated water stage (m) at Viadana cross-section (Figure 1) versus river discharge values ($m^3\ s^{-1}$). The last column reports the standard deviation (m) of the water stage

Q	1954	1968	1979	1991	2000	St. dev.
500	21.55	19.48	17.92	18.28	18.20	1.50
1,000	22.57	20.77	20.05	20.14	20.08	1.07
1,500	23.33	21.72	21.24	21.30	21.34	0.88
2,000	23.93	22.50	22.18	22.18	22.32	0.74
2,500	24.35	23.12	22.91	22.95	23.12	0.60
3,000	24.72	23.67	23.49	23.55	23.71	0.51
3,500	25.08	24.49	24.00	24.09	24.23	0.43
4,000	25.38	24.83	24.40	24.50	24.67	0.39
4,500	25.64	25.15	24.75	24.86	25.07	0.34
5,000	25.90	25.45	25.07	25.19	25.44	0.32
5,500	26.14	25.74	25.38	25.50	25.77	0.29
6,000	26.38	26.01	25.67	25.79	26.09	0.28
6,500	26.61	26.27	25.95	26.07	26.46	0.27
7,000	26.83	26.53	26.21	26.34	26.73	0.26
7,500	27.05	26.77	26.47	26.59	26.99	0.25
8,000	27.26	27.01	26.71	26.84	27.23	0.24
8,500	27.47	27.25	26.95	27.08	27.47	0.23
9,000	27.67	27.47	27.18	27.31	27.71	0.23
9,500	27.87	27.69	27.41	27.53	27.93	0.22
10,000	28.07	27.90	27.63	27.75	28.15	0.22
10,500	28.27	28.11	27.84	27.96	28.37	0.22
11,000	28.46	28.32	28.05	28.17	28.58	0.21
11,500	28.65	28.52	28.26	28.37	28.78	0.21
12,000	28.83	28.72	28.46	28.57	28.99	0.21

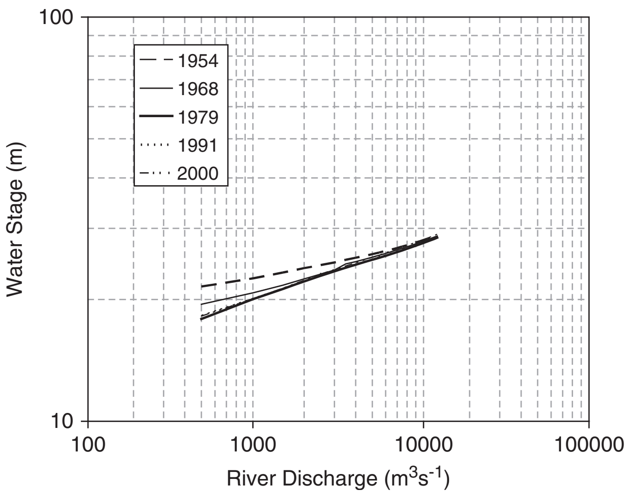

Figure 4 | Results of the second experiment: simulated water stage at Viadana versus river discharge values.

cross-sections of Viadana and Pieve Saliceto in terms of standard deviation of the water stage versus river discharge for different Manning's coefficients. This third experiment confirmed the results of the second experiment (Table 1): despite considerable modifications which have occurred in the geometry of the main channel of the River Po, the water stage corresponding to values of discharge higher than 5000 $m^3\ s^{-1}$ appears independent of the specific river geometry as the standard deviation tends to 20–30 cm (independently of the river roughness; Figure 5).

This outcome has a physical explanation: changes in the geometry of the river reach under study have mainly occurred in the main channel (Figure 2) and therefore they do not strongly affect the hydraulics of floods where the floodplain gives a relevant contribution to the flow. This hypothesis, although appropriate for many alluvial rivers, is not applicable as a general rule. For instance, if the floodplain width is not much larger than the channel width, changes in floodplain geometry due to sediment deposition cannot be neglected (e.g. Swanson *et al.* 2008). Moreover, human interventions (navigation, excavation) may produce significant alterations in the floodplain geometry. However, for the river reach under study (which has a bankfull discharge of about 3000 $m^3\ s^{-1}$) discharge values higher than 4000–5000 $m^3\ s^{-1}$ are representative of flow conditions in which floodplains provide a significant contribution to the flow and the stage–discharge relationships tend to be similar (Figure 5). Hence, these last two experiments corroborate that differences found in the extrapolation zone of the rating curves (Figure 3) find little justification from changes in river geometry.

To corroborate these findings, it can be useful to analyze the depth–width curves for the two cross-sections, obtained using the five topographical surveys (Figure 6). It is interesting to note that for high values of the water depth the top width tends to converge to a certain value. This represents a reasonable explanation of the fact that the stage–discharge relationships tend to be similar for high flow conditions. It is important to note that this type of depth–width curve is typical of rivers where the flood shoreline is constrained by slopes (or defences) bounding the floodplain and therefore large changes in water depths produce small changes in lateral flood extent (Hunter *et al.* 2007), which is the case of many alluvial rivers.

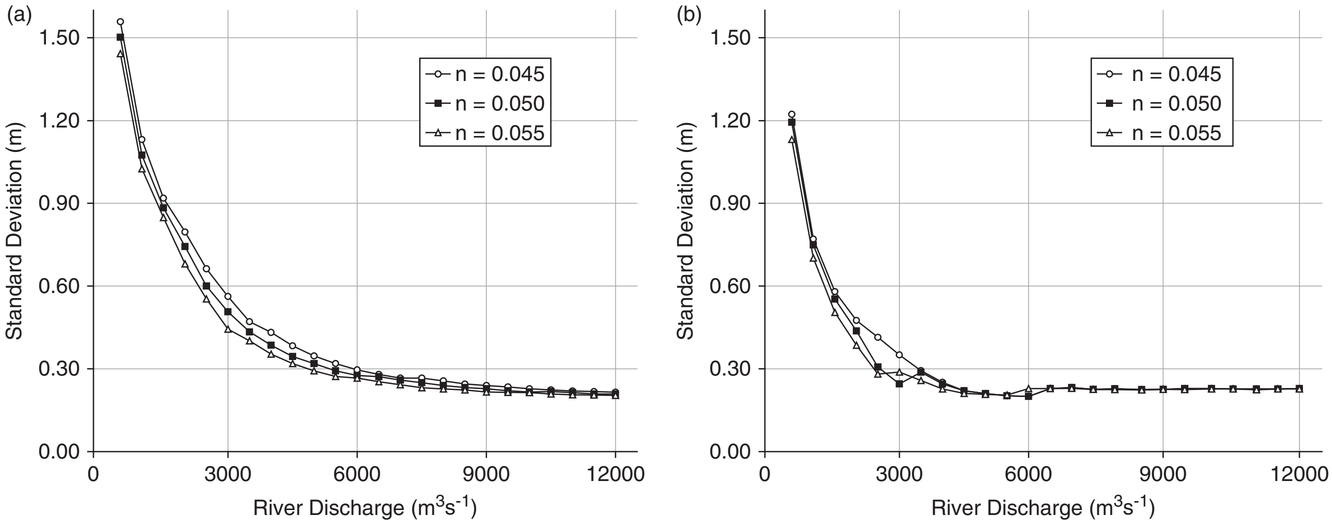

Figure 5 | Results of the third experiment: standard deviation of the water stage versus river discharge for three different Manning's coefficient values at the two internal cross-sections: (a) Viadana and (b) Pieve Saliceto.

DISCUSSION (UNCERTAINTY ESTIMATION)

The results of the numerical experiments suggest that the indirect measurement of discharges beyond the measurement range should rely on a physically based model rather than on the traditional approach of extrapolating rating curves based on analytical relationships (as that of Equation (1)). A hydraulic analysis of the river reach is allowed nowadays by the broad availability of topographic data and hydraulic model codes and may help to reduce the uncertainty in derivation of river discharge measurements, also leading to more reliable stage–discharge relationships in the extrapolation zone. A good operational strategy could be to use the stage–discharge measurements to calibrate a hydraulic model and then to use the model to extrapolate the rating curve. A hydraulic approach can also potentially include roughness variations due to changes in the state of the vegetation, which can be a relevant factor of alteration of the rating curve (e.g. Di Baldassarre & Montanari 2009). However, it must be said that the uncertainty of the hydraulic model, which is calibrated using ordinary flow data and then used to simulate extremely high flow conditions, cannot be neglected (Jarret 1987; Kirby 1987; Burnham & Davis 1990). For instance, a number of studies (e.g. Horritt & Bates 2002;

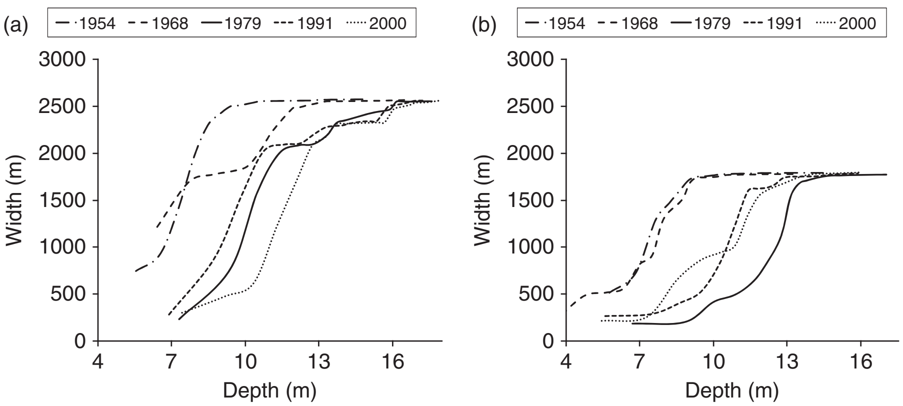

Figure 6 | Depth-width curves at (a) Viadana and (b) Pieve Saliceto.

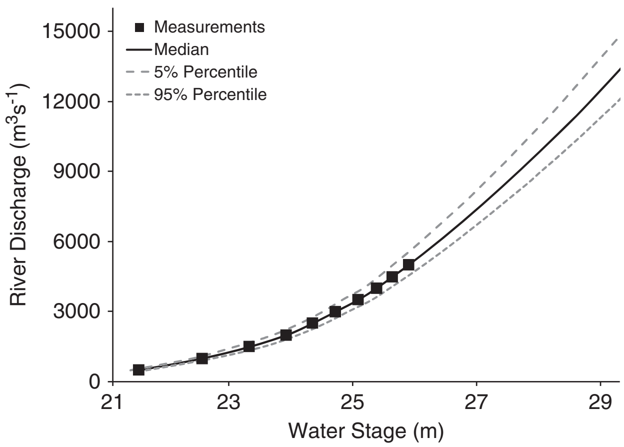

Figure 7 | Example of hydraulically derived rating curve with uncertainty bounds (Viadana 1954 geometry).

Romanowicz & Beven 2003; Horritt *et al.* 2007) have shown that the effective roughness coefficients may be different when evaluated for different flow conditions. Thus, the hydraulic extrapolation of the rating curve is affected by uncertainty that should be considered and estimated.

A rigorous and statistically consistent analysis of the uncertainty of the hydraulically derived rating curve is not an easy task and might be not be computationally feasible. We therefore set up, as an example, a simple and pragmatic approach based on the widely used Generalized Likelihood Uncertainty Estimation (GLUE, Beven & Binley 1992; Pappenberger *et al.* 2006). In this approach the uncertainty of the hydraulic model is estimated as follows. Firstly, the hydraulic model is run using uniformly distributed roughness coefficients in the range 0.04–0.07 $m^{-1/3}$ s (selected according to prior knowledge; e.g. Montanari 2007). Secondly, the simulation results are compared to the calibration data (i.e. stage–discharge measurements) and simulations with a mean absolute relative error higher than 20% are rejected as non-behavioural. Thirdly, the computed likelihoods are rescaled to produce a cumulative sum of 1, and then uncertainty bounds and the median simulation are derived by following the standard GLUE methodology (e.g. Montanari 2005).

Figure 7 shows the hydraulically derived rating curve and the corresponding uncertainty bounds. It is important to note that the uncertainty bounds derived within the GLUE framework are unavoidably affected by a number of subjective decisions and reflect only the uncertainties in the model parameters, disregarding other sources of uncertainty.

CONCLUSIONS

Several hydrological applications, such as flood frequency analysis, rainfall–runoff models and flood inundation analysis, require the use of discharge data referred to flood conditions. Unfortunately, several studies pointed out that the higher the flow the higher the uncertainty of the rating curves that, for these flow conditions, are used far beyond the actual discharge measurements range.

This study confirms that analytical functions commonly used to interpolate river discharge measurements fail to reproduce the stage–discharge relationship in the extrapolation zone and can lead to results that are not physically plausible. Hence, a hydraulic approach to derive stage–discharge curves (with uncertainty) is recommended. Alternatively, inaccuracies due to the standard estimation of rating curves can be reduced by grouping annual maxima under a unique flood rating curve, according to the methodology proposed by Claps *et al.* (2003).

This study shows also that, for river discharge values sufficiently higher than the bankfull discharge, differences in water stage due to changes of river geometry tend to vanish. This is caused by the fact that changes in the geometry of the river reach mainly occur in the main channel and therefore do not have a strong effect on the hydraulics when the floodplain gives a relevant contribution to the flow.

Although the geomorphological features of the River Po can be considered representative of many alluvial rivers in Europe and around the world, the results of this study should be further expanded in light of additional studies relative to different test sites.

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