Author's response – point-by-point response and marked-up version

RC1

The authors present an interesting study of the variability of the velocity predictions of a 2-D hydrodynamic model related to the uncertainty of vegetated floodplain friction parameterisation. Four parameterisation models are tested using three uncertainty analysis methods. These methods include First Order Second Moment, Monte Carlo sampling and metamodeling (Non-Intrusive Polynomial Chaos).

My main concern is the misleading formulation of the problem. Namely, the authors introduce the term 'uncertainty' based on the error between simulated and observed variables (page 5, lines 19-26) and apply it to analysing the variability of the model output in the form of velocity simulations. In other words, a sensitivity analysis is performed instead of the earlier-defined 'uncertainty' analysis. Unfortunately, the wrong use of the term 'uncertainty' leads to wrong conclusions. Four different friction parameterisation models have different numbers of parameters (from one to three). According to the authors, the model with three parameters shows smaller uncertainty than the model with only one parameter. This could be true only when the term 'uncertainty' is replaced by 'variability'. It simply shows that some parameters in that particular parameterisation scheme have a small influence on model output. Unfortunately, it does not mean that the model output has a small uncertainty (i.e. is better defined). In some way, the authors do the opposite to what Gupta and Razavi (2018) described as a sensitivity analysis using the goodness of fit criterion instead of output variables. The latter and the present papers show that a clear formulation of the problem helps to avoid drawing wrong conclusions.

In summary, the authors are asked to correct their problem formulation and apply a sensitivity method (e.g. the Global Sensitivity Analysis GSA of Saltelli et al., 2004). Berends et al. (2018) could also be helpful in dealing with the high computer time costs of hydraulic models. My specific comment regards the calibration method which is not explained.

Dear Prof. Renata Romanowicz,

thank you very much for your valuable comments to our article. We read them carefully and addressed them in the following text. An updated version of the manuscript including your suggestions is currently being prepared and will be soon available.

The use of the terms "uncertainty" vs. "sensitivity" analysis seems to be a constant discussion in the scientific community and it obviously leads to misunderstandings. For example in the references you mentioned: Saltelli et al. (2004) wrote (Box 1.1) "This is in fact an uncertainty analysis, e.g. a characterisation of the output distribution of Y given the uncertainties in its input."; Berends et al. (2018) used the Monte Carlo method and referred to the results as "uncertainty estimation /quantification"; Saltelli et al. (2008) in Section 1.1.4 described exactly what we presented in our analysis with the Monte Carlo method as "uncertainty analysis". Further examples of the use of the term "uncertainty analysis" can be seen in Hofer (1999), Maskey and Guinot (2003) and Altarejos- García et al. (2012), where the term was employed similarly to the way we did. Furthermore, Walters and Huyse (2002) described in Section 2 ("Review of Uncertainty Analysis Methods") amongst others the same three methods we used.

I understand the need for a common language and agreement in using identical names when addressing identical things. Therefore, my suggestion would be to exchange the term “uncertainty analysis” with “uncertainty quantification” in our manuscript. This would be in agreement with Berends et al. (2018) and with other studies carried out similarly to ours, e.g. Hosder and Walters (2010), Oladyshkin and Nowak (2012), and Sudret (2015).

Our goal of investigation is to quantify the uncertainties of hydrodynamic model results on floodplains with regard to different friction methods. Within the large number of different friction methods there is still no generally accepted method for large scale applications. The outcomes of the uncertainty quantification will help to choose a better suited friction method for practical use. The model was previously calibrated based on the best information available and the input parameters are perturbed within a practical range of variation, and not across the whole feasible parameter space. Analyses considering the entire parameter space are still computationally unfeasible in real engineering projects involving large models and cannot be put in practice in our case.

With respect to the problem formulation we will improve the description in Sections 1 and 3 accordingly. Furthermore, from the sensitivity methods presented in Saltelli et al. (2004), we will add scatterplots and calculate the standardised regression coefficient (SRC) to assist the evaluation of each friction formulation (see figures). With respect to the calibration method, we will emphasize in Section 4.1 the fact that previous investigations already presented good results for the hydrodynamics. This knowledge was the starting point for our study.

RC2

The authors have improved on the clarity of the description of the methods. The sensitivity plots are a good illustration of the approach taken. A minor comment: the velocity units (y-axis) in Fig. 3 are missing. Also, the linear relationship between flow velocity and a canopy permeability K requires a comment.

I understand that different definitions of the same word (sensitivity vs uncertainty) are used in different disciplines. As long as those definitions are clearly stated and we know what the discussion is about, it does not make much difference to me.

However, the statement “... the smallest prediction intervals, i.e. the most accurate results” (line 9, page 1 and line 24, page 18) in the absence of observations is not justified. It should be replaced by: ... "the smallest variance”.

Dear Prof. Renata Romanowicz,

thank you very much for your comments. I think the scatterplots improved the understanding of model behaviour in our analysis and could be a good starting point for further investigations. The missing units in Figure 3 were added. Regarding the analysis of the canopy permeability, a missing description of the approach was added in Section 2.4 and referenced in the discussion. I hope it is clear now. You are correct about our statement on the prediction intervals. It was suppose to be "most precise" and not "most accurate", of course. Nevertheless I corrected it as you suggested. Please find the corrected version of the manuscript attached as supplement.

RC3

Overview This study describes an interesting analysis on the estimation of uncertainty of hydrodynamic models on floodplains. Specifically, the variability of the velocity predictions of a 2-D hydrodynamic model related to the uncertainty of vegetated floodplain friction parameterization is investigated. Four traditional floodplain resistance formulae are considered using three different uncertainty analysis (UA) methods: i.e. First Order Second Moment, Monte Carlo sampling and metamodeling. The analysis carried on a case study selected along the Rhine River, show that the three UA methods compared gave similar results which means that First-Order Second-Moment is the less expensive one.

Comments The topic of the work is of interest for the scientific community and consistent with the aim of the journal. English is sound and the manuscript is well written. I was able to follow the analysis carried out by the authors even if I suggest some necessary modifications. One limit concerns the confusion on the used symbols: some of them are not clearly defined, both in the text and in the tables captions (e.g. H, D, t, x, y, ...), and some other are used to indicate more than one quantity (e.g., d). Moreover, the authors use acronyms before they are defined. I was wondering about the meaning of the term 'prediction interval' and if it is considered as an 'uncertainty band'. The comment of the previous reviewer and the reply of the authors shed light on this issue. I must say that, from my point of view, the term 'sensitivity analysis' would be more appropriate in this case. Minor comments: - explain what 'with a probability of occurrence larger than HQ5' means. - use always the past tense or the present tense throughout the manuscript.

Dear Referee #2,

thank you very much for your comments.

„One limit concerns the confusion on the used symbols: some of them are not clearly defined, both in the text and in the tables captions (e.g. H, D, t, x, y, ...), and some other are used to indicate more than one quantity (e.g., d). Moreover, the authors use acronyms before they are defined.“

Thank you for pointing that out. We modified the manuscript accordingly.

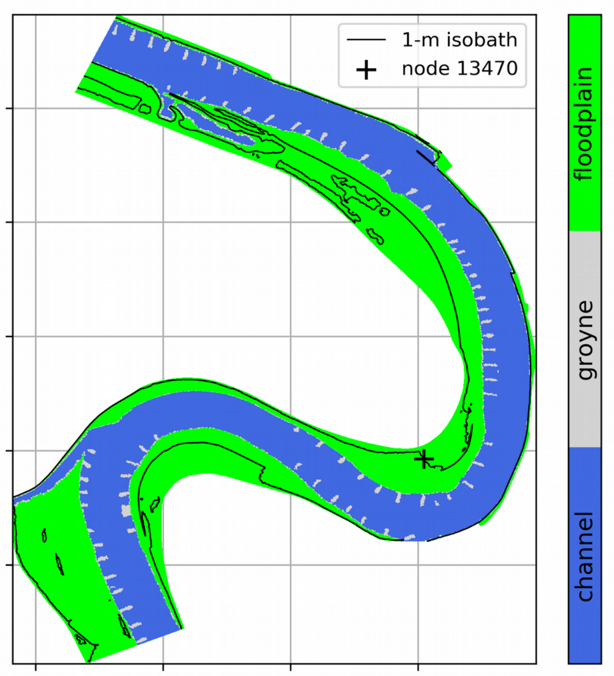
„I was wondering about the meaning of the term 'prediction interval' and if it is considered as an 'uncertainty band'. The comment of the previous reviewer and the reply of the authors shed light on this issue.“

It seems to me that the term "uncertainty band" refers to the same quantity as "prediction band" or "prediction interval". I would still stick to the latter to avoid further misunderstanding regarding the term "uncertainty", and as "prediction interval" seems to be more widely used according to Google. Nevertheless the definition given in Section 3 was improved.

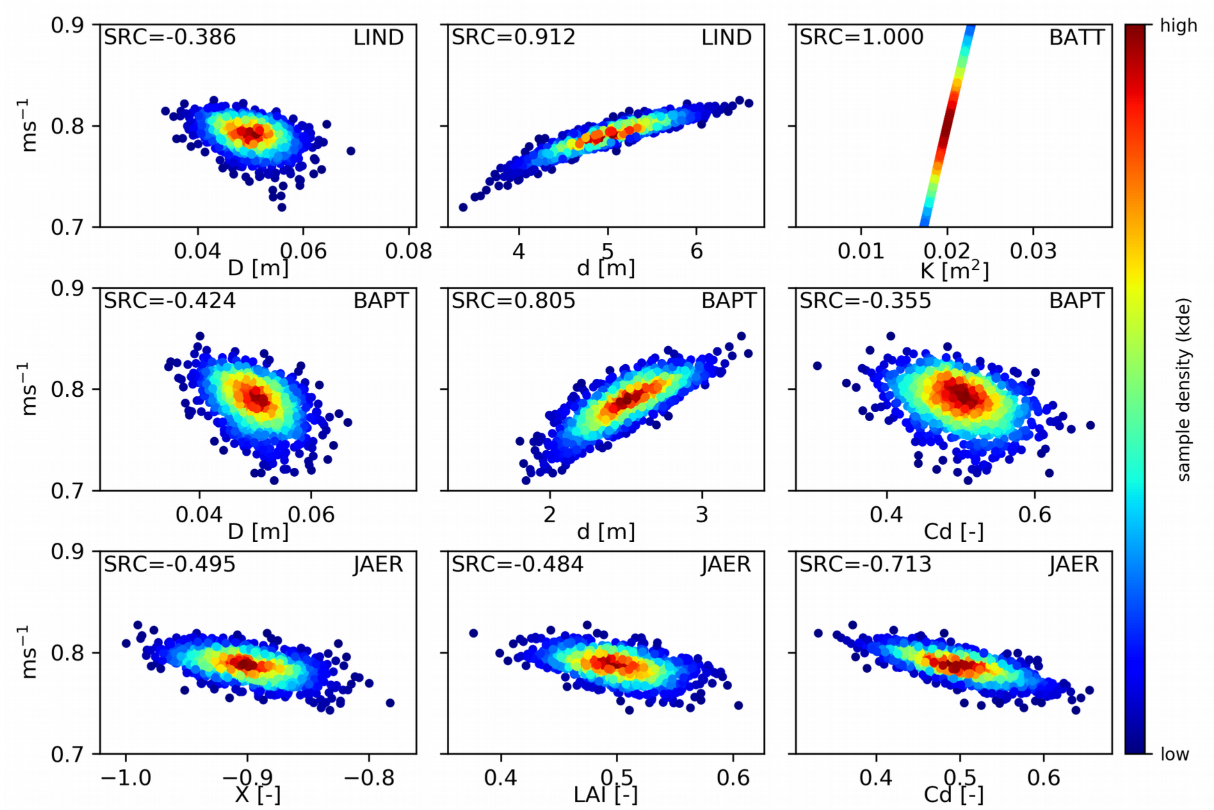
„Minor comments: - explain what 'with a probability of occurrence larger than HQ5' means. - use always the past tense or the present tense throughout the manuscript.“

We modified the manuscript accordingly.

Modified Figure 1 (right)



Added Figure 3



Uncertainty ~~analysis~~quantification of floodplain friction in hydrodynamic models

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Abstract. This study proposes a framework to estimate the uncertainty of hydrodynamic models on floodplains. The traditional floodplain resistance formula of [based on][]Lindner82 used for river modelling as well as the approaches of , , and were considered for carrying out an uncertainty ~~analysis (UA)~~quantification (UQ). The analysis was performed by means of three different methods: traditional Monte Carlo (MC), First-Order Second-Moment (FOSM) and Metamodelling. Using a two-dimensional hydrodynamic model, a 10 km reach of the River Rhine was simulated. The model was calibrated with water level measurements under steady flow conditions and then the analysis was carried out based on flow velocity results. The compared floodplain friction formulae produced qualitatively similar results, in which uncertainties in flow velocity were most significant on the floodplains. Among the tested resistance formulae the approach from Jaervelae presented on average the smallest prediction intervals i.e. the ~~most accurate results~~smallest variance. It is important to keep in mind that ~~UA~~UQ results are not only dependent on the defined input parameters deviations, but also on the number of parameters considered in the analysis. In that sense, the approach from Battiato14 is still attractive for it reduces the current analysis to a single parameter, the canopy permeability. The three ~~UA~~UQ methods compared gave similar results, which means that FOSM is the less expensive one. Nevertheless it should be used with caution as it is a first-order method (linear approximation). In studies involving dominant non-linear processes, one is advised to carry out further comparisons.

1. Introduction

Flow resistance can be considered as the contribution of four components, according to : (a) surface, (b) form, (c) wave, and (d) flow unsteadiness resistances. Not only that, it is a complex phenomenon dependent on Reynolds number, relative roughness, cross-sectional geometry, channel non-uniformity, Froude number, and degree of flow unsteadiness. Also, affirms that flow resistance interacts ``in a non-linear manner such that any linear separation and combination is artificial". There are several approaches available in the literature for determining flow resistance coefficients of vegetated floodplains in numerical models. These approaches are basically divided under four categories: rigid or flexible, and emergent or submerged vegetation. They aim to determine the resistance exerted by the vegetation on the flow based on physical properties such as vegetation height and width, stem diameter and density, etc. Recent research on flow resistance of emergent floodplain vegetation is given in and a review of vegetated flow models can be found in . For an overview of the main vegetation friction laws available the reader is referred to the review given in . Even though much work has been done in applying different approaches to include vegetation induced resistance effects in hydrodynamic calculations, the majority of these studies were verified only under laboratory scale conditions. A gap between those results and river engineering projects still exists. While free surface information on flooded areas can be well approximated from river channel measurements, flow velocity cannot. And because floodplain measurements usually are not available, model performance is neglected at those areas. That means, when flood scenarios belong to the scope of a project or study, attention should be given to this matter. A way to address this problem is to consider a probabilistic approach and to carry out an uncertainty ~~analysis (UA)~~quantification (UQ) of the floodplain friction. Uncertainty in the context of fluid dynamics is defined as a potential deficiency of the simulation process, according to . considered floodplain friction parametrization to be an important source of uncertainty. Also, compared and discussed deterministic and probabilistic approaches for floodplain mapping. They concluded that due to uncertainties related to flood-event statistics the probabilistic approach was considered to be a more correct representation. Some studies can be found in the literature involving the estimation of uncertainty related to floodplains and the resistance coefficient. presented a flood risk assessment by means of a simple hydrological flood routing model in the Lower Rhine applying a Monte Carlo (MC) framework. conducted an analysis using a one-dimensional hydraulic model using a generalised likelihood uncertainty estimation. Their results showed that many parameter sets (channel and floodplain) can perform equally well even with extreme values. showed that the deterministic approach underestimates the design flood profile in hydraulic modelling and proposed an alternative approach based on the use of uncertain flood profiles. used the Point-Estimate Method for carrying out uncertainty ~~analysis~~quantification as an alternative to MC approaches to get estimates of the mean and variance of water depth and velocity. They considered the roughness coefficient as the main source when assessing the uncertainty in river flood modelling. proposed a methodology to derive probabilistic flood maps taking into account several sources of uncertainty. concluded that hydrodynamic modelling can be improved by increasing the number of frictional surfaces; however, they draw attention to the numerical scheme choice, which might lead to much larger errors. In this context, a framework to estimate the uncertainty of hydrodynamic models on floodplains due to vegetation is proposed in the current study. Within a large number of different floodplain friction methods there is still no generally accepted choice for large scale applications. Thus, the outcomes of the uncertainty ~~analysis~~ quantification can assist to identify a well suited friction method for practical use. A two-dimensional hydrodynamic model is calibrated with floodplain friction formulations, ~~to~~with which input parameters uncertainties are associated based on a practical range of variation. After defining the variation ranges for sensitive input parameters, the ~~uncertainty analysis~~UQ is carried out with different methods for comparison. In other words, the quantification of uncertainties in flow velocity simulation is addressed by considering uncertainties in floodplain friction parameters. In the next section four chosen floodplain resistance formulae are described and analysed. Then the concept of uncertainty ~~analysis~~ quantification is briefly explained and three different methods are presented in the third part. The fourth section provides information on the case study including a brief description of the hydrodynamic model, parameters used for model calibration, and ~~a definition of~~the defined uncertainties for the selected input parameters ~~uncertainties~~ needed for carrying out the analysis. In the fifth section results are presented and discussed, from which conclusions are drawn in the last part of the manuscript.

2. Floodplain friction

Vegetation found on river banks and floodplains plays an important role on flow velocity profile and, therefore, on hydraulic roughness. Current research aims to relate vegetated floodplain properties to their hydraulic signatures and to incorporate the complex nature of vegetation characteristics into floodplain friction models. According to , there are no established practices for defining flow-dependent vegetation roughness values and incorporating them into hydrodynamic models. Additionally, model calibration usually is carried out with measurements taken in the main channel, and seldom (if ever) on floodplains. Thus, model response on floodplains cannot be verified and only relative conclusions can be made. It is under these circumstances that ~~UA~~UQ is especially useful for quantifying the probability of results. Basically the available approaches for vegetation friction formulation are subdivided in emergent/submerged and rigid/flexible. For the current study four out of several vegetation friction formulations [see][]Aberle15, Shields17 are considered for floodplains: and , , , and . The first approach is a recommended practice by the German Association for Water, Wastewater and Waste DVWK91 for hydraulic calculations and it is commonly used in the German Federal Waterways Engineering and Research Institute's (BAW) projects. The second and third approaches represent the rigid (Baptist07) and flexible (Jaervelae04) approximations. Lastly, the approach from Battiato14 is chosen for it proposes a completely different concept based on porous medium flow.

Lindner and Pasche

The modified formulation from , based on , was developed for rigid emergent vegetation. The Darcy-Weisbach friction factor for vegetation () can be obtained after the bulk drag coefficient () is iteratively calculated by the following equations:

SET OF EQUATIONS (1)

where is the hydraulic radius, is the bottom slope, is the bottom friction, is the approach velocity (upstream), is the calculated velocity (downstream), are the wake length and width resp., is the drag coefficient for a single stem, is the number of stems per m^2, is the stem diameter, is the water depth and is the gravitational acceleration.

Baptist et al.

The approach from was developed for rigid vegetation. They modelled the vegetation resistance force as the drag force on an array (random or staggered) of rigid cylinders with uniform properties. The velocity profile is calculated for two conditions: non-submerged (emergent) and submerged vegetation. For the case of emergent vegetation a uniform velocity is assumed. For the case of submerged vegetation the velocity profile is subdivided in a uniform velocity zone (within the vegetation) and logarithmic velocity zone (above the vegetation). Both conditions combined, after some algebra and use of genetic programming, give the following expression for the Chezy coefficient induced by bottom and vegetation friction ():

EQUATION

where H is the vegetation height, C_b is the Chézy coefficient of the bed and κ is the von Kármán constant. The corresponding Darcy-Weisbach friction

10

factor can be then obtained by The corresponding Darcy-Weisbach friction factor can be then obtained by

EQUATION (2)

Järvelä

The approach from was developed for flexible vegetation. It is based on the leaf area index (LAI), a dimensionless quantity that characterizes plant canopies. The LAI is defined as the one-sided leaf area per unit projected area in canopies. The Darcy-Weisbach friction factor for vegetation () can be calculated by the following relation:

EQUATION (3)

where is the species-specific vegetation parameter (Vogel exponent), is the species-specific drag coefficient, is the mean flow velocity, is a normalizing value and is defined as the lowest flow velocity used in determining . is usually 0.1 m/s and it will be considered constant.

Battiato and Rubol

The approach from developed for submerged vegetation follows the concept of coupling an incompressible fluid flow with a porous medium flow. Although it is conceptually suited for rigid vegetation, this approach was successfully validated also with flexible vegetation [see] []Rubol18. The main advantage of this approach lies in the representation of the drag force by a single parameter, i.e. the canopy permeability (). The volumetric discharge per unit width through a vegetated channel () can be determined from direct integration of the velocity over depth, obtained from the solution of the coupled log-law and Darcy-Brinkman equations:

SET OF EQUATIONS

where is the density of water, is the turbulent viscosity, is the reduced von Karman constant for vegetated channels () and is the friction velocity. Under emergent conditions (h < H) an approximation is made, in which the velocity profile is considered constant within the canopy. Thus, Qw is linearized with regard to h by applying Qw = Qw h H^{-1}. The Darcy-Weisbach friction factor can be then calculated by:

EQUATION (4)

Overall comparison

From now on the presented floodplain friction formulations will be referred to as LIND, BAPT, JAER and BATT, respectively. The formulae will be analysed in terms of the total Darcy-Weisbach friction factor calculated as , with and being the bottom and vegetation friction, respectively. The four expressions are then given by:

EQUATION (LIND)

EQUATION (BAPT)

EQUATION (JAER)

EQUATION (BATT)

In LIND and BAPT there is a direct dependency between the term and the friction factor. The same analysis is valid for in the first three formulae. The relation is found in some form in all the approaches which include submerged vegetation. Furthermore, a similar relation between the bottom friction and the friction factor in BAPT is also observed in BATT. While the first three approaches present an explicit term for the bottom friction, in BATT the expression can be rearranged so that a Chezy-like term is found as a function of H.

3. Uncertainty ~~analysis (UA)~~quantification (UQ)

Numerical models represent only an approximation of the observed process. The measured difference between the model and the observation can be considered either as error or uncertainty. defined these two concepts as: Error: a noticeable lack in the modelling process, not due to a lack of knowledge; (Deterministic) Uncertainty: a potential shortcoming in the modelling process due to a lack of knowledge. (Stochastic) Uncertainty ~~analysis~~quantification aims to describe the system reliability by combining the uncertainties in the basic components (variables) of the system. The framework of the numerical model used to represent the system characterizes the interactions of the basic components. The overall response of the system is described by the performance function :

EQUATION (5)

where is the vector of input variables of the system and is the number of variables. The analysis yields the combined effect of all input variables that significantly contribute to the performance function. The results ~~from the analysis~~ can be represented in terms of reliability or risk. Reliability refers to a prediction interval (PI)~~, i.e. the probability that Y will be found in the interval [Ya, Yb].~~ of the form [Ya, Yb] associated with a known probability P (Ya ≤ Y ≤ Yb). ~~PI is expressed as the difference |Ya − Yb| corresponding to a desired probability.~~PI can be expressed as the difference |Ya − Yb| with a probability P. Risk refers to the probability of failure (Pf) with respect to a threshold value , i.e. the probability that . Pf is directly expressed as the calculated probability. In the current study Y represents hydrodynamic model results (deterministic) and x contains the input parameters related to each friction formulation. By defining each xi through a probability distribution based on a potential uncertainty, it is possible to estimate the probability of occurrence of Y . Finally model results are not evaluated as an absolute value anymore e.g. simulated water depth or flow velocity, but either as a measure given by the absolute difference between Ya and Yb with probability P, or as a direct probability P of exceedance of a threshold Yc. Three probabilistic methods are chosen for the ~~UA~~UQ: First-Order Second-Moment, Monte Carlo (MC) and Metamodelling. The first method is based on the method of moments and requires the calculation of the model sensitivities (first-order derivatives). The MC method requires the simulation of a large number of random experiments and is the most expensive in terms of computing time. The metamodelling method is based on random experiments (MC) with the benefit that it requires far less samples. Polynomial Chaos is a type of metamodelling technique, which is chosen for the present study. Further details on each method will be given in the following sections.

First-Order Second-Moment

Moment method approximations are obtained from the truncated Taylor series expansion about the expected value of the input parameter. The First-Order Second-Moment (FOSM) method uses the first-order terms of the series and requires up to the second moments of the uncertain input variables for estimating the output variance of a system. The variance of the performance function is given by:

EQUATION (6)

It should be noted that the FOSM method is suited as long as (a) the input variables are statistically independent and (b) the linearity assumption is valid, i.e. the first-order approximation is enough to describe the sensitivity of the system. If is non-linear, e.g. hydro- and morphodynamic models, one should make sure that the value of is small. Otherwise, might be over- or underestimated. The reader is referred to for further details on FOSM.

Monte Carlo

Monte Carlo simulation is a probabilistic method in which a very large number of similar random experiments form the basis. An attempt is made to solve analytically unsolvable or complicated solvable problems with the help of probability theory. The law of large numbers makes up one of the main aspects of the method. The random experiments can be carried out in computer calculations in which (pseudo)random numbers are generated with suitable algorithms to simulate random events. The basic steps of a MC method can be described as follows: Sample the input random variables from their known or assumed probability density function times; Calculate the deterministic output for each input sample; Determine the statistics of the distribution of (e.g. mean, variance). Step (2) should be repeated times, which presents this method's main drawback. Also the input variables are considered to be statistically independent, otherwise the joint probability distribution is required. The advantage is its robustness, because independently from the nature of (linear or non-linear), the method will always deliver reliable results as long as the number of samples () is sufficiently large.

Metamodelling

Metamodelling attempts to offset the increased cost of probabilistic modelling by replacing the expensive evaluation of model calculations with a cost-effective evaluation of surrogates. Polynomial Chaos (PC) is a powerful metamodelling technique that aims to provide a functional approximation of a computational model through its spectral representation of uncertainty based on polynomial functions. A more detailed introduction to the PC method can be found in . Spectral-based methods allow for an efficient stochastic reduced basis representation of uncertain parameters in numerical modelling. By means of a truncated expansion to discretize the input random quantities it is possible to reduce the order of complexity of the system. ~~Let us consider the uncertain parameter A, representing velocity, density, or pressure in a stochastic fluid dynamics problem, as:~~Let us consider the uncertain variable A as a function of the input variable vector x, time t and the random variable vector ξ. A can represent velocity, density, or pressure in a stochastic fluid dynamics problem, and is defined as a polynomial expansion:

EQUATION

where is the deterministic component, is the random basis function corresponding to the -th mode and ξ ~~is the random variable vector characterizing~~characterizes the uncertainty in the parameter. The polynomial chaos expansion ~~in pcdef~~ is approximated by a discrete sum taken over the number of output modes ~~P~~M defined as:

EQUATION [~~d~~p]

where ~~d~~p is the degree of the polynomial and is the number of random dimensions. The statistics of the distribution for the model output at a specific position and time can be calculated using the coefficients and the basis functions. The mean and variance of the solution is given respectively by

SET OF EQUATIONS [~~p~~w] (6)

with being the weight function of the polynomial and its the support range. When the input uncertainty is Gaussian (normal) the basis function takes the form of a multi-dimensional Hermite polynomial, so that . In this study, the Non-Intrusive Polynomial Chaos method (NIPC) will be considered. The main objective of this method is to obtain the polynomial coefficients without modifying the original model. This approach considers the deterministic model as a ``black-box'' and approximates the polynomial coefficients based on model evaluations. The advantage is that this method requires much fewer evaluations of the original model (with regard to MC) for providing reliable results (at least one order of magnitude). The main disadvantage is that it is an additional approximation in the modelling framework, thus leading to further loss of information of the physical process. The reader is referred to for further details on the application of the NIPC method. The implementation of the method was done in Python with the help of the OpenTURNS package openturns.

4. Case study

The current study focuses on a reach of the river Rhine used for numerical tests by the

German Federal Waterways Engineering and Research Institute (BAW). It is an 11 km long section of the lower Rhine located between kilometres 738 and 750, nearby Düsseldorf (Germany). The model has been extensively tested and calibrated for a wide spectrum of discharges. A constant discharge of 7870 m^3/s was imposed at the upstream boundary and the corresponding free surface at the downstream boundary. These conditions represent a flood scenario with a probability of occurrence larger than HQ5 LUA02 i.e. a discharge with an annual probability of occurance of 1/5 or likely to be observed within five years (return period of five years). In recent years flood studies are receiving more and more attention as part of BAW's activities. For that reason the current motivation is to understand how sensitive numerical models are to floodplain friction under flood conditions and how this might affect the hydrodynamics of navigation channels. An overview of the study area is presented in Figure , where the red polygon delimits the boundaries of the numerical model.

FIGURE 1

Hydrodynamic model

A numerical model is used to simulate the flood scenario. In the BAW studies carried out in large scale river projects (101-102 km) usually make use of the hydrodynamic model TELEMAC-2D Galland91,Telemac17. It is a two-dimensional finite-element software (finite-volume also available) for solving the shallow water equations, a set of partial differential equations derived from the integration of the Navier-Stokes equations over the vertical axis. Thus, the equations for the conservation of mass and momentum in two dimensions should be solved.

SET OF EQUATIONS (7)

where are the ~~c~~Cartesian coordinates, is the water depth, is the bottom elevation, are the components of the velocity field, is the fluid viscosity, which may be constant or given by a turbulence model, are the shear stress components and are any additional source term components of momentum (e.g. wind stress, external forces). The bottom shear stress is bound to the depth-averaged velocity by the quadratic law first introduced by :

EQUATION

The friction coefficient () is equal to the sum of the bottom friction () and the friction due to vegetation (). The bottom friction usually can be determined by traditional friction laws relating open-channel flow velocity to resistance coefficient (e.g. Manning, Chezy, Darcy-Weisbach, Nikuradse). However, on floodplains the velocity profile strongly depends on the vegetation height and morphology. Thus, specific flow resistance formulae have been developed for determining the vegetation drag (see Section). The model consists of an unstructured triangular mesh composed by 56825 points and 112360 elements. The resolution varies from about 2.5 m in the main channel to about 30 m on the floodplains and the model mesh covers an area of ca. 8 km^2. A constant discharge upstream and a constant water level downstream are imposed at the open boundaries, as aforementioned. A time step of 1 s guarantees a Courant number below 1 and it is used to simulate 24 hours, which takes about 9 min with the LIND formulation using 160 processors of the BAW's ~~HPC~~high performance computing system. The other three formulations for floodplain friction are about three times faster (3.5 min) as there is no iteration step. This numerical model was extensively investigated from the point of view of sediment transport and morphodynamics Backhaus14,Riesterer14~~. Because water level measurements along the river channel axis are available 9for a discharge of 7870 m 3 /s, the bottom friction in the numerical model has been~~

~~calibrated under these conditions as a representation of a flood scenario.~~, from which the calibrated hydrodynamic model was taken as a starting point for the current study. Water level measurements for a discharge of 7870 m^3/s available along the river channel axis were used to calibrate the bottom friction in the numerical model, as a representation of a flood scenario. A root mean square error (RMSE) smaller than 1 cm was accepted for the water level calibration. The bottom friction in the model defined by Nikuradse's equivalent sand roughness () in the channel is set to 0.1 m. Originally the floodplains are divided basically in three categories: forest, cultivated land and meadows/pastures. In the current study, however, all the floodplain areas are considered to be covered with the same type of vegetation for the sake of simplicity (Figure).

FIGURE 2

~~It is possible to calibrate the floodplain friction in the hydrodynamic model to fit water level measurements~~The calibration of the floodplain friction with water level measurements can be achieved either with the traditionally used Lindner-Pasche friction law eq:lindner in addition to the bottom friction (Figure l, red line), or ~~only~~simply with a higher bottom friction value on the floodplains (Figure l, blue line). If the same friction value of the river channel (m) is used for the floodplains, the momentum is too high and the simulated free surface does not fit the measurements (black line). A much better result is obtained by using m on the floodplains (blue line), in which the water level RMSE is reduced ~~to less than 25% from the first result.~~by a factor of four (see values within brackets). Alternatively, a similar result is obtained when 5 cm thick stems evenly spaced by 5 m intervals are added to the floodplains with the LIND formulation, while keeping the bottom friction equal to the channel. The reader may ask himself/herself about which approach to be used. In this case it is useful to compare the absolute difference of the flow velocity with and without the floodplain friction formulation (see Figure r). It can be seen that while differences in the main channel can be neglected (m/s), those on the floodplains cannot (up to 0.4 m/s). In other words, when model calibration is based only on measurements in the river channel the hydrodynamics on floodplains is not guaranteed to be correctly simulated. It is important to point out that in case of unsteady flow conditions a friction formulation dependent on water depth is not desired. However, if flow velocity measurements are not available on the floodplains (usually the case), little can be done in terms of calibration. Furthermore, remote sensing data of vegetation characteristics (Light Detection And Ranging technology) have been used in flood modelling in the last 20 years, but the accuracy of these measurements should also be taken into account [see] []Cobby03,Antonarakis08,Dombroski17. An alternative to the deterministic approach in such situations, when there is a potential shortcoming in the modelling process due to a lack of information, is to carry out an ~~UA~~UQ. As explained in Section , this analysis can be used to ~~determine~~estimate the combined effect of all uncertain input parameters that significantly affect model results by means of a probabilistic approach.

Input parameters

The next step now is to calibrate the remaining floodplain friction formulations with water level measurements. In order to make a comparison to the LIND approach, first m is set to ensure emergent conditions in all formulations. A second scenario is then calibrated for submerged conditions, in which m. Tables and present the calibrated parameters for each one of the scenarios. After the calibration all model results presented RMSE smaller than 1 cm for water level. (The density of stems is calculated as , where is the distance between stems.) For the ~~UA~~UQ it is required that all sensitive parameters relevant to model results should be considered for the determination of the prediction intervals (PI). Once the parameters are chosen a very important step follows: an error or deviation should be carefully assigned to each parameter. This variation should be small enough to be treated as an error, but large enough to include the actual parameter uncertainty (due to the lack of knowledge). Unfortunately there is no general rule for choosing a proper value, since different aspects might contribute e.g. measurement accuracy, spatial/time variances, numerical representation of process, etc. In the current study, the chosen variations for the parameters related to the vegetation species (, LAI,) are based on values given in . For the remaining parameters (, , ,) a standard deviation of 10 of the calibrated value is assumed (). The vegetation height is only included in the analysis under submerged conditions. Input deviations are treated as errors and, therefore, represented by a Gaussian distribution. This implies that there is a 99.7 probability that the parameter value is found within .

TABLE 1

TABLE 2

TABLE 3

Finally, the ~~UA~~UQ methods presented in Section are applied with the input uncertainties given in Table . The FOSM method is evaluated through central finite difference; hence, model evaluations are necessary (refers to the number of input variables). For the MC method, a sample size of 1000 was used for the evaluation. Although MC sample sizes are usually considered in the range of 104-105, previous tests with 104 samples showed very little difference in results. The NIPC method (metamodelling) requires less samples than MC, because a polynomial function fitted to the samples is then used for the evaluation of results. In this case results with 100 samples for the metamodel were sufficient for approximating MC results.

5. Results and Discussion

The numerical model was evaluated with the four floodplain friction formulations. A constant discharge of 7870 m^3/s was imposed at the upstream boundary and at the downstream boundary a corresponding free surface based on a discharge curve. Model results were analysed after a steady state was achieved in the simulation and presented in the form of prediction interval (PI) with a 95-probability of occurrence. It should be noted that the PI represents a range of variation around the mean value, which is not necessarily symmetric (MC and metamodelling). Once Monte Carlo results are available scatterplots can be used to investigate the behaviour of the model. They represent here the projection of the values of model outputs against the values of each of the input parameters. Scatterplots are a very simple and informative way of sensitivity analysis, since they provide a visual representation of the relative importance of the input parameters Saltelli08. In order to summarize the scatterplots with a single value, standardized regression coefficients (SRC) can be determined through linear regression. The scatterplots together with the SRCs are presented in Figure , in which the sampled values of each input parameter (see Table) are plotted against the flow velocity results at node 13470 (see Figure) under emergent conditions. This node is considered representative of the hydrodynamics on vegetated floodplains. The SRC indicates whether there is a significant linear relation between input and output (values given in brackets). For instance the permeability coefficient () in BATT (1.0) is linearly related to the flow velocity, due to the approximation used under emergent conditions (see Section). The distance between stems () in LIND (0.912) and BAPT (0.805) also presents a significant linear effect on flow velocities. Interestingly the drag coefficient () presents a much stronger linear relation to the flow velocity in JAER (-0.713) than in BAPT (-0.355). In summary the permeability coefficient (K), the distance between stems (d) and the drag coefficient (C_D) in JAER were identified as inputs from the friction formulations with the largest linear effect on flow velocity. Although the remaining parameters showed no significant linear relation (|SRC| <0.5), higher order dependencies may still exist. In Figure the ~~uncertainty analysis~~UQ of the flow velocity under emergent vegetation conditions is presented. It can be observed that similar results are obtained with the three ~~UA~~UQ methods. Among the friction formulations, LIND and JAER presented smaller variations on average and the PI exceeds 0.2 m/s only at the left floodplain in the middle of the river reach. On the other hand the BATT approach appears to be the most sensitive one, followed by BAPT. The approach from Battiato14 results in PI m/s on most of the floodplains. Relative to results with calibrated values all formulations showed variations above 10 on the floodplains. The same analysis is carried out for submerged conditions (see Figure). Because the LIND formulation is only valid for emergent conditions (independent of), submerged conditions cannot be accounted for. As expected all results present on average larger PI than under emergent conditions, due to the addition of in the analysis. The floodplain PI of flow velocity is mostly above 0.2 m/s and in BATT the PI m/s is present on floodplains located at the inner bends of the river reach. In the channel the PI in BATT is the largest one and exceeds 0.05 m/s all along the upstream river section. Relative to results with calibrated values the variations exceed now 25 on the floodplains, and in BATT at shallow regions up to 100%.

FIGURE 3

As explained in Section results from the ~~UA~~UQ can also be represented in terms of risk, i.e. a probability of failure (Pf). This is a more suitable analysis for when results must not exceed a given threshold. For instance, a threshold of 0.1 m/s above the mean value is used for the analysis of the flow velocity (see Figure). In other words, the probability of exceedance of m/s was calculated. Because in the current study the difference among the ~~UA~~UQ methods was not significant, results are now presented only from metamodelling. Results indicate that there is a larger probability that velocities are found above with the BATT approach. Under submerged conditions velocities are more likely to exceed this threshold. In BAPT and BATT the probability of failure can be higher than 10 on the floodplains. Figures and show that results using the ~~UA~~UQ methods are similar for this case study. Although the FOSM method is the less expensive alternative among the ones presented (only model evaluations), it should be used with caution as it is a first-order method (linear approximation). In studies involving strongly dominant non-linear processes (e.g. turbulence modelling, sediment transport, unsteady conditions, etc.) further comparisons should be carried out. On the other hand, Monte-Carlo based methods have the advantage that the analysis under any conditions is possible. Although a large number of simulations is required for obtaining trustful results, alternatives such as the NIPC make them more feasible by reducing the sample size by at least one order of magnitude. For instance, carried out the ~~UA~~UQ of a computationally intensive morphodynamic model, to which they applied pure MC and metamodelling methods.

FIGURE 4

FIGURE 5

FIGURE 6

When compared to emergent conditions the overall uncertainty of submerged conditions is significantly larger. This is an expected result in ~~UA~~UQ as there is an additional input (vegetation height) that significantly contributes to model performance. The floodplain friction formulation Lindner-Pasche is by definition only valid for emergent conditions. Thus, a different approach is needed when submerged conditions should be taken into account. Additionally, warn that when simulating flood scenarios attention must be given to parameter compensation between floodplain and channel resistance coefficients, so that reasonable values are chosen. An important topic not only regarding ~~UA~~UQ but numerical simulation in general, is the matter of input uncertainty definition. When performing a numerical simulation that is based on physical processes one will eventually need to validate calculations with measurements. Also, initial and boundary conditions usually are based on measurements of the original process. That is to say one should know a priori how accurate the available measurements are. This is usually not a trivial task, since measurement errors may not be easily evaluated [see][]Taylor97. For instance, published a study that focused only on the uncertainty in river discharge observations. Although it was attributed a standard deviation of 2.7 for discharge measurement errors, the authors emphasize that this value is associated to their case study, thus any generalization should be attributed with care. For uncertainties related to floodplain friction there are no such reference studies known to the authors. In that case, a suggested practice is to start with commonly used value ranges in the literature and apply a six sigma range () for the total parameter variation as a rule of thumb. Of course available experience in the topic of investigation should be also taken into account.

6. Conclusions

A framework for the estimation of uncertainties of hydrodynamic models on floodplains was presented. A traditional resistance formula used for river modelling together with three more recent approaches to floodplain friction were considered for carrying out an uncertainty ~~analysis~~quantification. The analysis was performed by means of three different methods: traditional MC, FOSM and NIPC (metamodelling). A two-dimensional model of a 10 km reach of the River Rhine was calibrated under steady flow conditions and the analysis was based on flow velocity results. From the scatterplots it was identified that the permeability coefficient (K), the distance between stems (d) and the drag coefficient (C D) in JAER produce the largest linear effect on flow velocity among the inputs from the friction formulations. Altogether ~~T~~the tested floodplain friction formulae produced qualitatively similar results, in which uncertainties in flow velocity are most significant where the resistance coefficient was modified. Under emergent conditions, larger velocity variations are obtained with the formulations of BAPT and BATT. Variations from the latter also included the river channel. Under submerged conditions all approaches resulted in larger uncertainties, as the vegetation height was included in the analysis. Although the BATT approach presented once again the largest variations among the analysed methods, results were consistent not only qualitatively, but also quantitatively. In summary, among the tested floodplain friction formulae the JAER approach presented on average the smallest prediction intervals i.e. the ~~most accurate results~~smallest variance. It is important to keep in mind that ~~UA~~UQ results are not only dependent on the defined input parameters deviations, but also on the number of parameters considered in the analysis. In that sense, the BATT approach is still attractive for it reduces the current analysis to a single parameter, the canopy permeability . The three ~~UA~~UQ methods compared gave similar results, which means that FOSM is the most efficient in this case. Despite being a very simple method to apply, FOSM will only produce good results when the first-order approximation is sufficient to describe the sensitivity of the system. In the presented study this was the case, probably because all the chosen inputs are directly correlated to the resistance coefficient. Research on related topics such as floodplain mapping usually focuses on the analysis of uncertainties that relies on Monte-Carlo based methods [e.g.,][]DiBaldassarre10,Domeneghetti13. Several further topics could be listed here for future development e.g. unsteady flow, boundary conditions, not to mention sediment transport modelling. However, the most important is first to be aware of the limitations of the available information and tools. Are there enough measurements for an acceptable calibration in the study area? Is the chosen numerical model capable of correctly representing the physical process under the desired conditions? As basic as it may sound, if those questions cannot be answered, any kind of analysis involving uncertainties will fail in providing useful results.

Competing interests. The authors declare that no competing interests are present.

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