Comparison between two hydraulic models (1d and 2d) of the Garonne river: application to uncertainty propagations and sensitivity analyses of levee breach parameters

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COMPARISON BETWEEN TWO HYDRAULIC MODELS (1D AND 2D) OF THE GARONNE RIVER: APPLICATION TO UNCERTAINTY PROPAGATIONS AND SENSITIVITY ANALYSES OF LEVEE BREACH PARAMETERS

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KEY WORDS

Levee breach, Uncertainty Quantification, Global Sensitivity Analysis, Flood risk, Meta-modelling

ABSTRACT

In recent years, flooding hazard is usually assessed through numerical modelling. However, depending on the nature (e.g. 1D, 2D) and the breach characteristics (e.g. river geometry, bottom roughness, levees geometry) of the numerical model, the uncertainties on the corresponding parameters should be taken into account in a rigorous way, for improving the assessment of the simulated flooding hazard. In fact, levee behaviour during a flooding event is one of the major sources of uncertainties impacting the water level at a given location.
In this context, the objective of our work is to better understand the impact of uncertain parameters related to levee breaches, on the generated overflows, through Uncertainty Quantification (UQ) and Global Sensitivity Analysis (GSA) of these parameters.
With this purpose, two numerical models of the Garonne River were built and validated, between Tonneins and La Réole sections (for a river length of nearly 50 km): a 1D hydraulic model with storage areas, developed with HEC-RAS and a 2D model with TELEMAC-2D. These modelling approaches (1D and 2D) are classically used to carry inundation studies. Moreover, the simulated river reach is of interest as protected by a levee system to reduce the flood risk. These levees have been damaged during flood periods, by physical mechanisms as erosion due to overtopping for instance, such as during the 1981 historical flood event. The study evaluates the influence of levee breach parameters (breach triggering parameter, breach length and breach depth) on the maximum water level at four points located within the upper part of the study area, through UQ and GSA. These approaches are carried out with a meta-model built with 200 simulations runs using a Monte-Carlo approach for both models. In both cases, the breach parameters are uniformly distributed and randomly sampled in order to generate a large number of breach scenarios.
Globally, the Monte-Carlo and FAST (Fourier Analysis Sensitivity Test) analyses performed have shown some differences between the results coming from both meta-models and between the upstream and the downstream storage areas, more sensitive to levee breaches. These analyses also indicated the slight effect of the breach length parameter contrary to the triggering and depth breach parameters.

1. INTRODUCTION

Nowadays, flooding hazard is assessed through numerical modelling. The estimation of flooded areas is very complex as it is dependent to many parameters such as the flood event itself (extreme flood hydrograph), levee physical characteristics which will generate different failure modes (*eg.* overflowing, piping), river geometry, roughness coefficients and so on.

In particular, flood risk evaluation related to levee breaches needs to be assessed in order to protect population and facilities presented in flood plains. Many complex models have been proposed to study levee breach behaviour during a flooding event, integrating different failure mechanisms. Nevertheless, from an engineering point of view, the actual practice of hazard assessment consists in a simplified modelling of levee breaches, usually generated by overflowing. For these cases, depending to the modelling approach (1D or 2D), a simple empirical equation (for 1D models) or an adjustment of the bottom topography (for 2D models), can be used to model the impact of the breach on the flood plain.

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Depending on the modelling approach (*e.g.* 1D, 1D/2D, 2D, 3D) and the way in which levee physical characteristics and breaches are considered within the model, uncertainties should be taken into account in a rigorous way, to improve the assessment of the simulated flooding hazard. As mentioned in [1-4], the prediction of breach parameters (*e.g.* breach location, formation time, breach geometry) is an important source of uncertainty, impacting the water level at a given location. Therefore, there is a need to better understand the impact of uncertain parameters related to levee breaches, on the generated overflows.

To deal with uncertainties in hydraulic model, methods based on statistical techniques have been developed [5]. Current method to validate models and identify the influencing parameters is to perform an Uncertainty Quantification (UQ) as well as a Global Sensitivity Analysis (GSA), in deterministic models [6-8]. Regarding method to consider sources of breach parameters uncertainties, the Monte Carlo method, also called uncertainty propagation, is commonly used in the hydraulic community [1, 3, 9, 10]. Such methods require a large number of simulations and can demand large computation time when a 2D model is used. Therefore, alternative methods to speed up the analysis can be chosen, such as meta-model approaches. Moreover, meta-models are suitable for UQ and GSA approaches and computational times are drastically reduced.

Regarding levee breaches, so far UQ and GSA analyses have been conducted to evaluate the influences of breach parameters on the water level within the flood plains. Therefore, there is a need to carry out UQ and GSA on levee breach parameters to fill this gap. Previous studies have been carried out to investigate levee breach influences on flooded areas with HEC-RAS 1D model along the Garonne River, between Tonneins and La Réole [11-13]. First, local sensitivity analysis has been conducted to assess the influence on five breach parameters related to overtopping (triggering water depth above levee crest, final length, formation time, crest lowering and breach weir coefficient). Influences of breach parameters on the water levels within each storage area have been investigated [12]. Then, uncertainty quantification on the assessment of the flood hazard, generated by a flooded watershed, has been conducted to evaluate the sensitivity of flooding associated to levee breaches, modelled with a 1D hydraulic model [11]. Finally, a methodology relying on an uncertainty propagation of the breach parameters was performed to generate a large number of breach scenarios uniformly distributed and randomly sampled, through the coupling of HEC-RAS and the computational environment Promethee, developed by IRSN. The Monte-Carlo and FAST (Fourier Analysis Sensitivity Test) analyses, performed in this study, show the strong influence of the overflow parameter and the one of the breach geometry, on the water height in a given storage area. The study also highlights the major difference between upstream and downstream parts of the river. Indeed, the upstream area is much more sensitive to levee breaches than the downstream area, so the uncertainties on maximum water levels are higher [13]. The study identified the need to carry out similar analysis with a 2D hydraulic model in order to improve the GSA analysis and better understand the influence of each breach parameter.

In this context, the aim of the study is to compare uncertainties related to levee breach parameters within 1D and 2D hydraulic models. To do so, HEC-RAS 1D (www.hec.usace.army.mil) and TELEMAC-2D (www.opentelemac.org) codes have been used to simulate a flood scenario which generates one levee breach along the Garonne River, between Tonneins and La Réole. A methodology has been designed to evaluate and rank the influences of each levee breach parameter between the two models, based on meta-modelling. This paper is divided in the following parts: the second part presents the study case and the two hydraulics models, the third part introduces the methodology, and the fourth part reviews the UQ and GSA results.

2. PRESENTATION AND MODELLING OF THE CASE STUDY: THE GARONNE

2.1. Generalities and common features of the 1D and 2D hydraulic models

The study area is a 50 km long reach of the Garonne River between Tonneins and La Réole. This reach is largely embanked. Between 1760 and 1850, many earthen levees were built to canalize the river and to protect harvest against inundations. The typical cross-section of the Garonne River is composed by a main channel and on both sides of the river, by a floodplain, levees and Storage Areas (SA) (**Figure 1**). Numerous breaches, of a 300 m maximum length, occurred between 1975 and 1981. The main levee breach scenario was by overflowing. Previous studies showed that flooding occur for low return period, *i.e.* from the 10-year flood, as a result Garonne floodplains are currently inundated. The characteristic flows of the Garonne are presented in

Figure 1. The largest observed flood event happened in 1875 (estimated to be a 1,000-year flood event) and the flow discharge reached 8,350 m^3/s.

As part of the "Benchmark Garonne" project, induced by EDF [14] and in which IRSN took part, data were recovered and two models (1D and 2D) were built. As our objective is to compare the models regarding the UQ and GSA, common characteristics for both models were chosen. The common features of the models were as follows:

- Strickler coefficient: 20 $m^{1/3}s^{-1}$;
- initial condition: initial steady flow discharge of 1,830 m^3/s;
- upstream boundary condition: triangular hydrograph with a 3,081 m^3/s flow peak in Tonneins (peak discharge achieved after 18 hours and simulation ended after 5 days);
- downstream boundary condition: rating curve in La Réole (provided by EDF);
- empty SA at the beginning of the simulations.

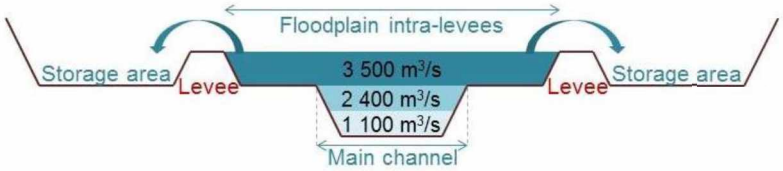

Figure 1: Typical cross section of the Garonne River between Tonneins and La Réole, with flow characteristics.

This study focuses on the upstream part of the studied reach (first 15 km), where four SA are located in the 1D model (SA1 to SA4), and one breach occurred (red star in **Figure 2** and **Figure 4**). Knowing the Garonne basin characteristics, a slightly overtopping flow was considered, in order to better appreciate the breach modelling sensitivity. Moreover, considering the differences between the models conception (*e.g.* equations, geometry), the breach location is not strictly identical.

2.2. 1D Hydraulic modelling with HEC-RAS

The 1D numerical model (**Figure 2**) was developed by IRSN, as part of the "Benchmark Garonne", with HEC-RAS which solves the 1D Saint-Venant equations. This modelling software is commonly used and integrates a levee breach module. The model construction is detailed in [12]; therefore here we only describe the main aspects.

The study reach was built from 83 cross sections and 15 curves describing the relation between water level and associated volume in each SA. In addition, 73 hydraulic connections allow linking the various components of the numerical model in the following way:

- 63 connections reach/SA (57 weir connections representing levee sections, with a length between 300 and 1,683 m, modelled with a weir equation and 6 culvert connections representing the hydraulic infrastructures (bridges, culverts, *etc.*), modelled with a modified Bernoulli's equation;
- 10 connections SA/SA (4 weir connections based on a weir equation and 6 culvert connections based on a modified Bernoulli's equation).

It is important to specify that in this model, the crests of levee sections are horizontal. Each of the 57 levee sections has the same altitude along its length.

In reality, this altitude is much more fluctuating. In HEC-RAS, breaches can occur in different ways. Here we chose to generate breaches by overflowing beyond a given threshold. In the numerical model, it is necessary to provide the following parameters (illustrated in **Figure 3**):

- the breach centre position, corresponding to the levee centre in this case;
- the breach final depth (D);
- the breach final length (L);
- the left and right side slopes of the breach, considered vertical in this case study;
- the breach weir coefficient, which could be different from the one of the levee (but considered equal in this study, with a constant value of 1.2);
- the breach formation time, here equal to 0 because the breaches occur instantly.

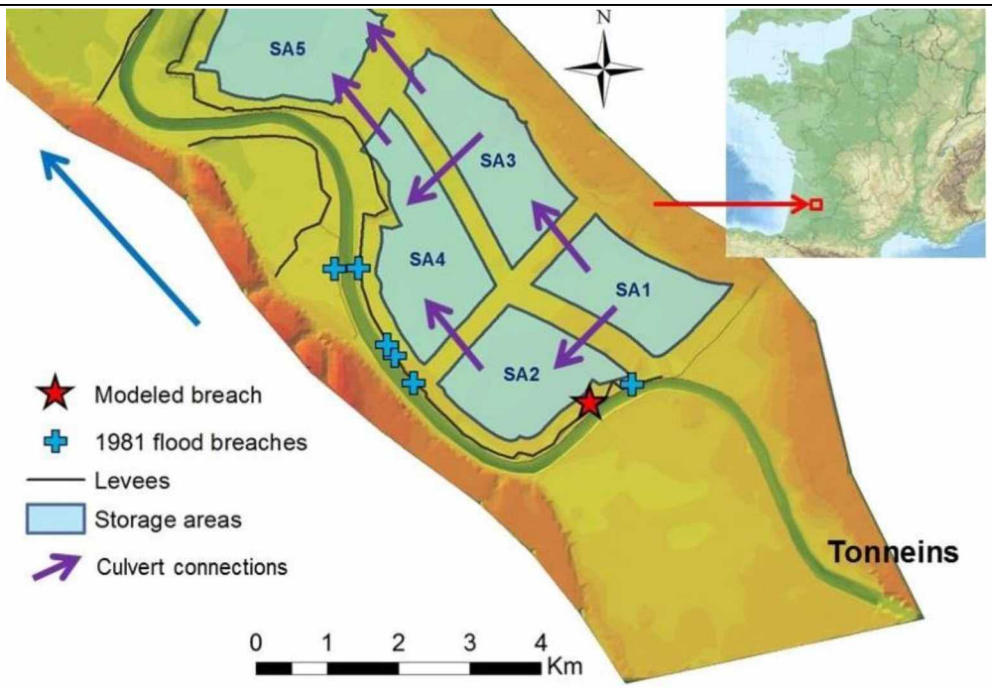

Figure 2: Case study modelling with HEC-RAS. Focus on the upper part of the Garonne River.

The breach initiation occurs when the overflow criteria (Hw), defined by the user, is reached on one side or the other of the levee, that means inside the reach or inside the SA. It should be noted that, in the model, Hw may be higher or lower than the levee crest, therefore a breach can occur even without overflow. When the breach is formed, the model computes the overflowing flow Q through the breach, according to equations 1 and 2:

$$Q = CLH^{\frac{3}{2}} \quad (1)$$

$$C = \frac{2}{3} C_d \sqrt{2g} \quad (2)$$

where C_d is the weir coefficient equal to 1.2, H is the water depth and g is the gravity acceleration. As mentioned previously, we chose to model only one breach in the study area and we evaluated the water level in the four upstream SA (**Figure 2**). This study focuses on the following uncertain levee breach parameters: the final length (L), the final depth (D) and the water level above the levee crest, corresponding to the overflow (Hw) (**Figure 3**).

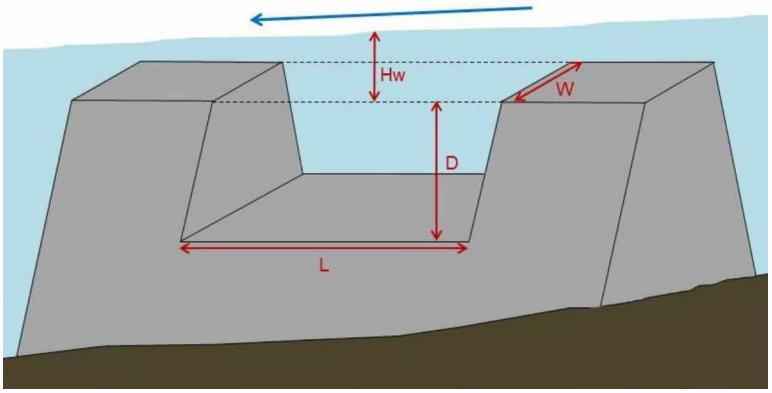

Figure 3: Levee breach diagram with length (L), depth (D), width (W) and overflow (Hw), as input parameters.

2.3. 2D Hydraulic modelling with TELEMAC-2D

A bi-dimensional model of the study area was constructed by EDF and provided to us in the framework of the "Benchmark Garonne" [14]. The model solves the Saint-Venant equations with the finite elements

approximation and it is composed of nearly 82,000 cells of different lengths, from 10 (for the levee crest or the main channel) to 300 m (for the inundated areas) (**Figure 4**). The floodplain topography and the bathymetry are represented by the interpolation of the triangular mesh coming from the photogrammetry data (downstream part of the study area) and the national topographic map (upstream part).

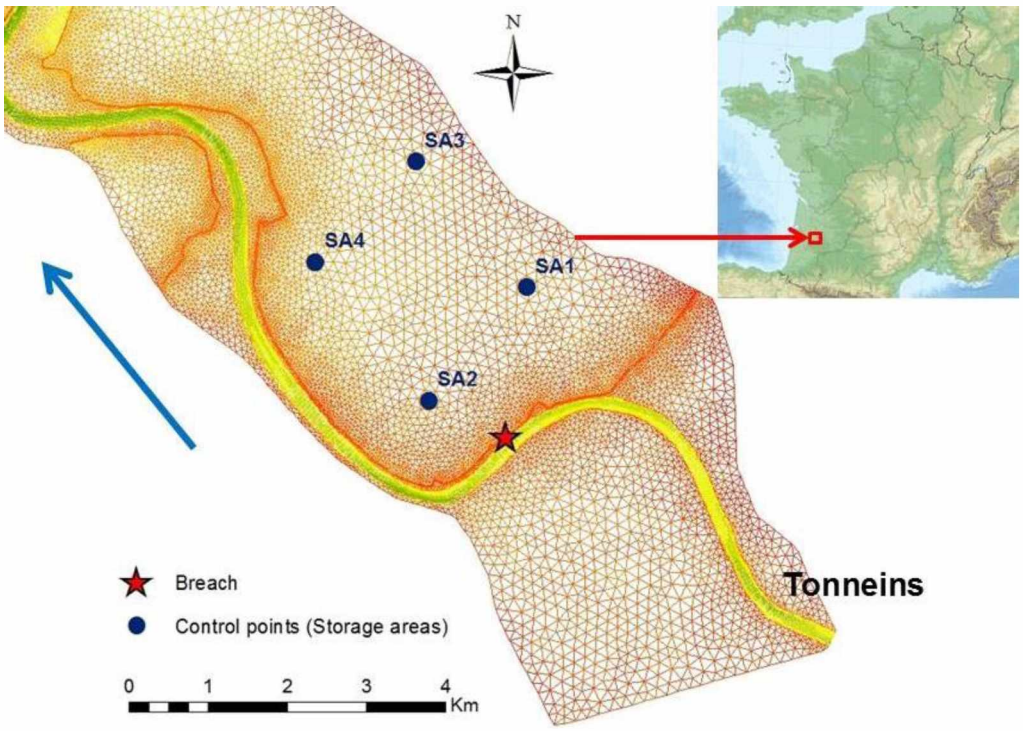

Figure 4: Case study modelling with TELEMAC-2D. Focus on the upper part of the Garonne River.

Contrary to the 1D model, the levees crests are not flat. The topography changes along the levees as shown in **Figure 5**. Therefore the quantity of water which flows on the levees can be different in each model.

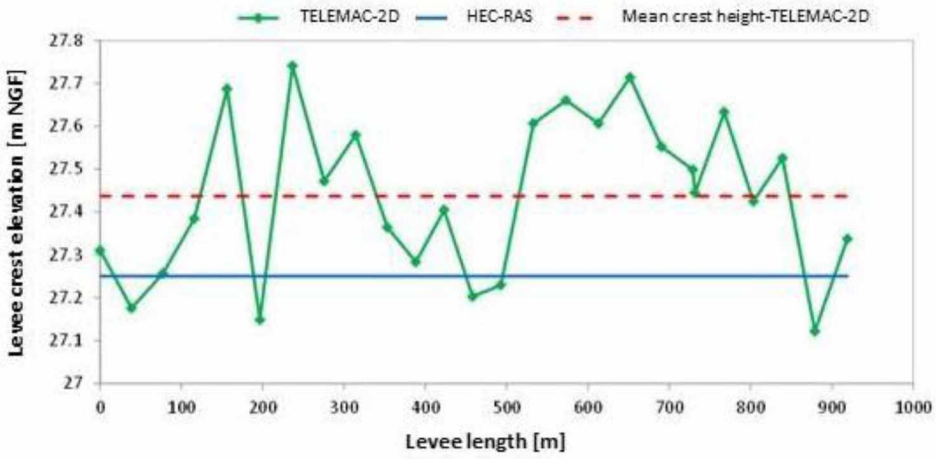

Figure 5: Differences between levee modelling in HEC-RAS and TELEMAC-2D.

The model covers nearly 136 km² of the Garonne River Basin. It is forced upstream (the "Tonneins" section) and downstream (the "La Réole" section) with the flow conditions reported in the section 2.1. The model has been calibrated against EDF observations [14].

As reported in the user manual, TELEMAC-2D simulates levee breaching by suddenly or gradually lowering the altitude of some points of the numerical grid. The breaching zone is defined by a polyline of several points associated to a bandwidth. The final situation is characterized by a bottom altitude that will be

reached by all the points located in the breaching zone. In this study, we consider a breach which is formed instantaneously, when the water level at a given point reaches a given value. The uncertain parameters describing the breaching process are the same geometrical parameters than in the 1D model (depth (D) and length (L) of the breach) and the breach triggering parameter which corresponds to the water level inside the reach (Hwr) and which slightly differs from the overflow parameter considered in the 1D model. The width parameter (W) is considered to be constant and is equal to 50 m. Again, only one breach, located almost in the same place than the one in the 1D model, was modelled.

3. METHODOLOGY

As indicated in the introduction, the aim of the study is to compare uncertainties related to levee breach parameters within 1D and 2D hydraulic models. Especially, according to the numerical model employed, the study of uncertainties related to levee breach, mainly corresponds to the study of uncertainties related to breach characteristics (*i.e.* breach geometry) and to the failure mechanisms implemented in the models.

Nowadays, there is a large number of methods and tools available to assess uncertainties related to model parameters [7]. In recent years, IRSN has developed a specific methodology for UQ and GSA applied to hydraulic studies [5, 15-17]. The proposed methodology, with some examples of application, is fully detailed in [5]. It is based on the standard steps of an uncertainty study, by using a Monte-Carlo sampling for the uncertainty quantification [18] and the computation of Sobol' indices using the methodology proposed by [19] for the GSA. These methods have the advantage to be robust, but are numerically expensive (very time consuming and requiring a large capacity for data storage). As a consequence, other techniques are suitable for real case applications such as meta-modelling, especially in the field of tsunamis [20-22], for coastal application involving breaches processes [23] and, more recently, in fluvial context [24]. In this study, we chose to perform UQ and GSA by using a kriging meta-model (or emulator).

A meta-model is a mathematical approximation of the numerical model, built on a learning basis [25]. It is currently used for engineering practice to estimate sensitivity indices [26]. The meta-model is well suited for UQ and GSA approaches as it allows to drastically reduce the computational time yet preserving the quality of the statistical results of the original model. For our analysis, a Gaussian process meta-model, also called kriging has been selected [27] for its good predictive capacities ever demonstrated (as seen in [28]). The methodology employed for the construction and the validation of the meta-models is fully detailed in previous studies (*i.e.* [4, 6, 29]).

Hereafter the four main steps of the methodology are briefly described and the applications for both models are reported in section 4.

3.1. Step 1: Design database building using coupling tools

Selecting a design database (or space filling design) is a key issue in building an efficient and informative meta-model [30]. The experience design consists of choosing the input parameters to use, in order to build the most accurate meta-model at a minimum computational coast (minimum number of model simulations). It can depend on the chosen meta-model [31]. In this paper, we use the Monte-Carlo sampling technique which permits a regular and uniform exploration of the input parameters space.

To launch a number of simulations and build this design database, we used the Promethee environment for parametric computation, developed by IRSN (http://promethee.irsn.fr/doku.php). Coupled with a hydraulic code, Promethee allows carrying out uncertainty propagation studies.

3.2. Step 2: Meta-model building

The kriging meta-model was used both for GSA and UQ applied to the 1D and 2D numerical models. The theoretical background for kriging meta-model design used in this study is fully detailed in [32]. The associated equations are implemented in the R-packages *DiceKriging* and *DiceOptim* which were used in this work.

3.3 Step 3: The validation/accuracy of the meta-model

After building a meta-model, it is generally interesting to assess the accuracy of this model on predicting outcomes for observations not used in the model building; this step is called prediction error. To do that, probably the simplest and most widely used method is the cross-validation or K-fold cross-validation method [33]. The principle of cross-validation is to split the data into K folds of approximately equal size $A_1A_1,\ldots,A_KA_K$. For $k = 1$ to K, a model $\hat{Y}^{(-k)}$ is fitted from the data $U_{j\neq k}A_k$ (all the data except the A_k fold) and this model is validated on the fold A_k. Given a criterion of quality L as the Mean Square Error (MSE):

$$L = MSE = \frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2 \quad (3)$$

the quantity used for the "evaluation" of the model is computed as follow:

$$L_k = \frac{1}{n/K}\sum_{i\epsilon A_K} L\left(y_i Y^{(-k)}(x_i)\right) \quad (4)$$

where $\hat{y}_i$ and y_i are, respectively, the meta-model and the model response and n is the number of simulations in the kth sample. Finally, the cross-validation used in this study is evaluated through the mean of the quantity L_k computed for each fold:

$$L\_CV = \frac{1}{K}\sum_{k=1}^{K} L_k \quad (5)$$

when K is equal to the number of simulations of the training set, the cross-validation method corresponds to the leave-one-out technique also used in this study.

The methodology employed is described in the *DiceEval* R-package reference-manual [34]. In our application case, we considered $K = 10$.

Finally, the accuracy of the meta-model is evaluated through several statistical metrics permitting to quantify the overall quality of regression models. This includes:

- **R-squared (R^2)**, representing the squared correlation between the observed outcome values and the values predicted by the model. The higher the adjusted R^2 is, the better the model is;
- **Root Mean Squared Error (RMSE)**, which measures the average prediction error made by the model in predicting the outcome for an observation. It corresponds to the average difference between the observed known outcomes and the values predicted by the model. The lower the RMSE is, the better the model is;
- **Mean Absolute Error (MAE)**, which is an alternative metric to the RMSE, less sensitive to outliers. It corresponds to the average absolute difference between observed and predicted outcomes. The lower the MAE is, the better the model is.

These statistical indices are used to measure the regression model performance during cross validation and leave-one-out validation.

3.4. Step 4: Uncertainty Quantification (UQ) and Global Sensitivity Analysis (GSA)

From the meta-models simulations, the last step involves carrying out UQ to determine the uncertainty margins, the output distributions, *etc.* and GSA to identify, for instance, the most contributing input variables to an output behaviour, as the non-influential ones.

One way to make a GSA is to compute sensitivity indices which allow quantifying the contribution of the output variance of the main effect of each input parameter. The methodology used in this study is the computation of the Sobol' indices (ranging from 0 to 1) with the Jansen method; the closer they are to 1, the more influential the input (or the group of inputs) is. The Jansen method gives two Sobol' indices: the first order index which corresponds to the effect of the single input and provides the output sensitivity due to the single variations of this input variable and the total order index which is the sum of all sensitivity indices relative to the studied variable. It represents the sensitivity of this variable by itself and the sensitivity to the interactions with other variables.

4. UNCERTAINTY ANALYSIS OF LEVEE BREACH PARAMETERS

4.1. Design database building

As the objective is to analyse breach parameter uncertainties, it is first necessary to define the uncertain parameters and their associated bounds. As mentioned previously, we remind that in this study, levees can break even if the flow does not reach the levee crest. Thus, for both models, the uncertain parameters are:

- the triggering parameter which corresponds to the overflow (Hw) for the 1D model (from 50 cm below levee crest to 10 cm above) and to the water level inside the reach (Hwr) for the 2D model (from 26.90 m to 27.50 m corresponding to almost 50 cm below the crest of the closest levee to 10 cm above);
- the two geometrical parameters of the breach:
  - the depth (D): from 0 to 100% of the levee height;
  - the length (L): between 40 and 200 m.

For each model, 200 parameter combinations were randomly sampled with the Monte-Carlo method and supposing uniform distributions, in the bounds previously defined. Therefore, 200 simulations were launched with TELEMAC-2D, on one hand, and 200 with HEC-RAS, on the other hand.

The outputs of interest are the maximum water levels in the 4 first SA (**Figure 2** and **Figure 4**). In the HEC-RAS model the water level in a SA is considered to be the same over the whole surface of the SA, therefore the extraction of the maximum water level is simple. However, in the TELEMAC-2D model, it is necessary to choose one location for each SA where the maximum water level is extracted. To do so, the lowest point of the SA is selected.

Two databases of 200 simulations (with 3 uncertain inputs and 4 outputs of interest) are available to build the meta-models.

4.2. Construction and validation of the meta-models

Meta-models were built from the two databases previously mentioned using the open-source R-package *DiceKriging*. Each meta-model is a function able to compute the maximum water level at a given location for a given set of breach parameters (length, depth and triggering parameter).

Once constructed, the meta-models were validated using the statistical parameters reported in section 3.3. As reported in **Table 1**, the RMSE and the MAE computed are very low and the R^2 very high, indicating that the kriging meta-model is a good emulator choice for reproducing both the HEC-RAS and the TELEMAC-2D code behaviour.

Storage Area	Statistical Index	k-fold cross validation		LOO validation	
		TELEMAC-2D	HEC-RAS	TELEMAC-2D	HEC-RAS
SA1	R^2	0.91	0.99	0.91	0.99
	RMSE	0.023	0.002	0.014	0.001
	MAE	0.14	0.001	0.014	0.001
SA2	R^2	0.94	0.99	0.94	0.99
	RMSE	0.027	0.002	0.016	0.001
	MAE	0.015	0.001	0.016	0.001
SA3	R^2	0.89	0.99	0.92	0.99
	RMSE	0.097	0.027	0.053	0.016
	MAE	0.058	0.015	0.053	0.016
SA4	R^2	0.93	0.98	0.94	0.98
	RMSE	0.093	0.040	0.054	0.016
	MAE	0.056	0.019	0.054	0.016

Table 1: Validation criteria of the meta-models

Finally, from the 200 simulations of each model, 5,000 simulations were made using the meta-models. As a reminder, we consider that only one breach is formed in the upper part of the reach and we evaluate the uncertainties in the four surrounding SA.

4.3. Uncertainty Quantification

The frequency distributions, the boxplots and the empirical cumulative distributions functions of the outputs, coming from the 5,000 simulations of each meta-model, are presented in **Figure 6**.

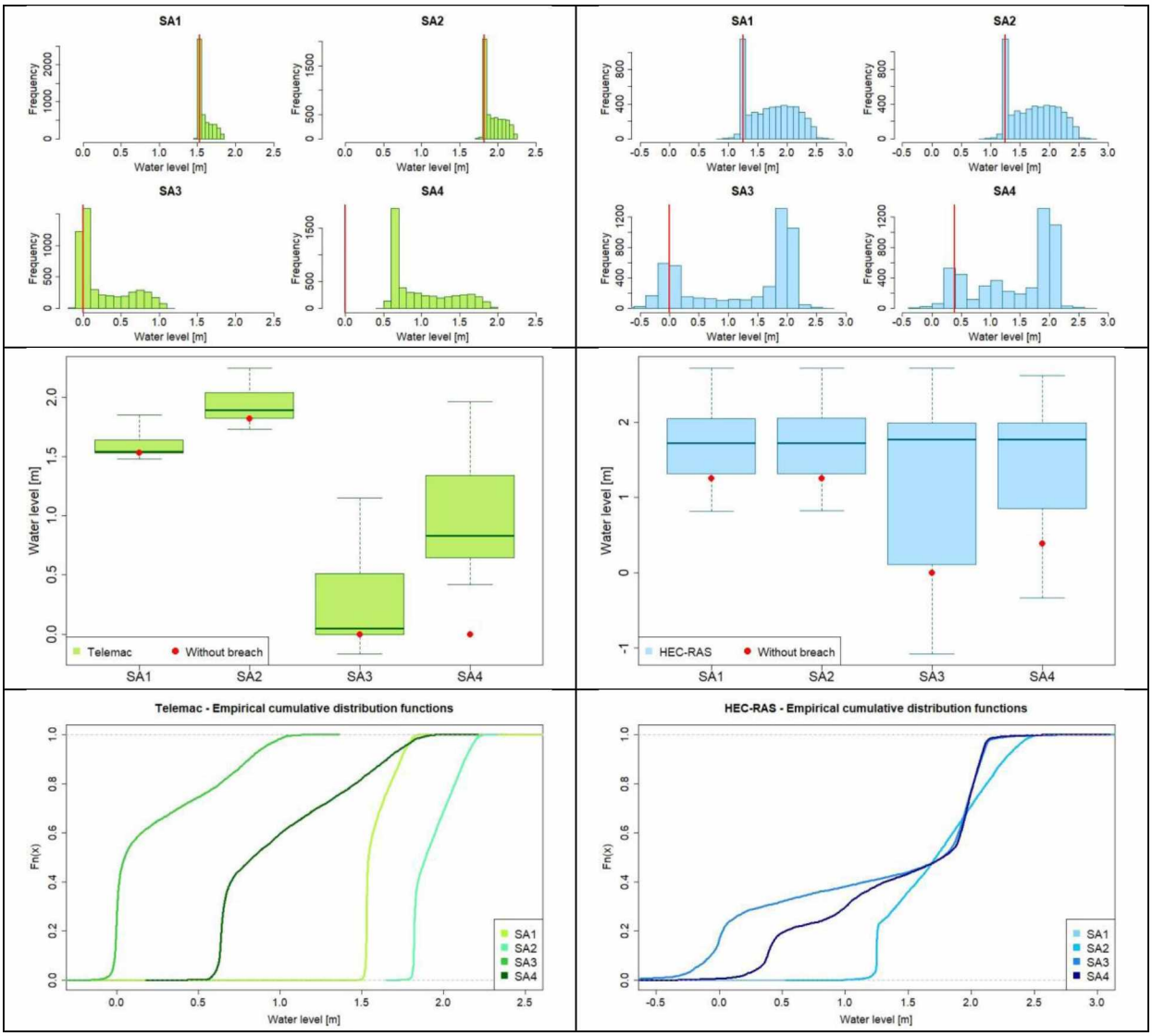

Figure 6: Frequency distributions, boxplots and empirical cumulative distributions functions of both meta-models outputs (TELEMAC-2D on the left and HEC-RAS on the right). The red lines/dots represent the simulations without breach.

For each SA and each meta-model, we represented the case without breach by a red line. In some cases, there are a few non-physical negative values. There are produced by the meta-models and are considered non-significant. From these results, we can highlight the following points:

- without breach, the SA maximum water level is different from one model to another. These differences are due to the gaps between the SA minimum elevations. In fact, in the 1D model, the minimum elevation is the same all over the SA surface while it is not the case in the 2D model which is more representative of the real topography of the inundated area;
- in both models, the upstream SA (SA1 and SA2) react in the same way but differently from the downstream SA (SA3 and SA4);
- in both models, the output variation is more pronounced in the downstream SA (SA3 and SA4) than in the upstream SA (SA1 and SA2). It suggests that breach parameters have more influence on the

water levels downstream than upstream. Generally, the scenarios generating high water level (around 2 m) coincides with long and depth breaches;

- in the 2D model, the distributions shapes are similar for the four outputs: the values are almost uniformly distributed on one side of the case without breach (except for SA4). However, in the 1D model, some differences are observed between SA1 and SA2 on one hand and SA3 and SA4, on the other hand: for SA1 and SA2 the distributions shapes is almost the same than for the 2D model but for SA3 and SA4, there are two distribution peaks. It could be due to the culvert connections between the four SA in the 1D model which do not exist in the 2D model (*cf.* section 5).

4.4. Global Sensitivity Analysis

Meta-models also permit to compute the first and total order Sobol' indices to determine the most influential parameters (**Figure 7**). Some conclusions can be drawn from these computations:

- the parameters ranking is similar for all SA of a same model;
- in both models, the breach width is the less influential parameter;
- in the 2D model, the breach depth is the most influential parameter and in the 1D model it is the triggering parameter (overflow). This difference between both models could be due to the fact that the triggering parameters are different from one model to another (water level at a given point in the 1D model and overflow in the 2D model).

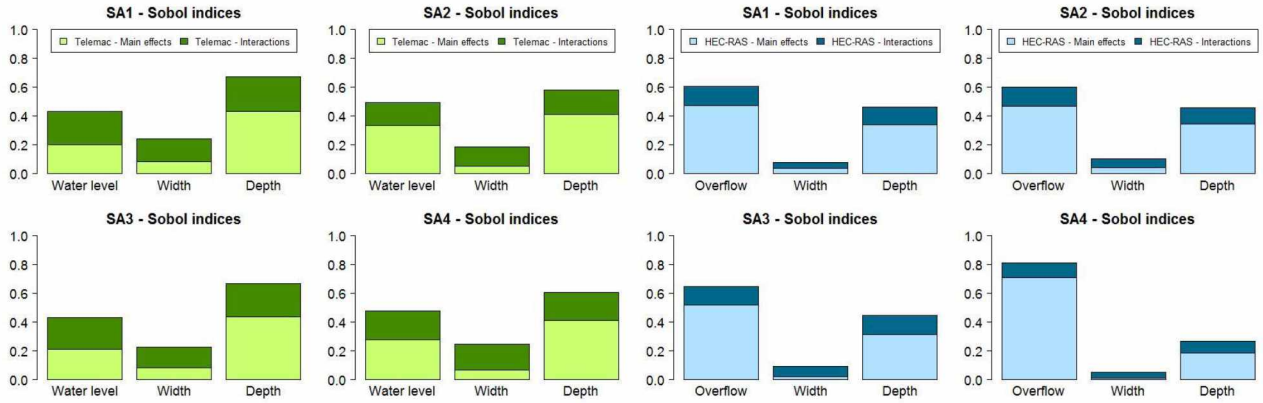

Figure 7: Sobol' indices for the four SA and for both models (TELEMAC-2D on the left side and HEC-RAS 1D on the right side). The main effects correspond to the first order Sobol' indices and the whole columns (main effects + interactions) correspond to the total Sobol' indices.

5. DISCUSSION AND CONCLUSIONS

This study permitted to show how UQ and GSA could be used to evaluate the influence of levee breach parameters (triggering parameter, length and depth) on the maximum water level at four points located in the upper part of the Garonne River for both 1D (HEC-RAS) and 2D (TELEMAC-2D) hydrodynamic models. These techniques, computationally demanding, were carried out with two meta-models built with 200 simulations each one, with a Monte-Carlo approach for both models. The meta-models properly fit the models according to the validation step. It allows reducing drastically the computational time which is very useful for the large 2D model, whereas it is not necessary for the 1D model which runs more rapidly.

Results from UQ indicate strong differences between the frequency distributions of the water levels for the 1D and the 2D simulations. Differences between both models are also observed in the GSA results, regarding the most influent parameter. These differences can be related to the following facts:

- the flow simulation in the inundated areas differs in both models: in the 1D model the connections between the SA are modelled with culverts. Therefore, when the upstream SA are in charge, the water runs off through the culverts to reach the downstream SA. This could explain the high water levels in SA3 and SA4. In the 2D model, the water runs off slowly in the floodplain from upstream to downstream according to the topography and the Saint-Venant equations, without

any artificial parametrization. In this sense, the results obtained with TELEMAC-2D appear to be more realistic;

- in the 1D model, the levees crests are flat while in the 2D model the maximum altitude change all along the levee, which is more realistic;
- the breach triggering parameter is different: it corresponds to the water level above the levee crest in the 1D model and to the water level at a given point inside the reach in the 2D model. In a future work, it could be more accurate to consider the same triggering parameter;
- the outputs are slightly different in both models. In fact, in the 1D model, the outputs are the maximum water levels inside the four SA. As in this case the SA bottom is considered to be flat, the water levels do not change inside a given SA. However, in the 2D model the SA are fictive, their limits are not well defined, and their bottoms are not flat. So we had to select, as outputs, the lowest points in the four fictive SA.

In conclusion, this preliminary work investigates which methods are suitable to compute UQ and GSA to study levee breaching. Our approach was rather simple: only one flood event, one type of failure mode and three failure parameters have been considered. Therefore, further works could be carry out to investigate more complex failure scenario. For instance, the overflowing breach is one of the most common breach mode. Indeed, breaches can be formed by internal erosion and it could be interesting to take into account this mode of failure in the models. Moreover, only three breach parameters have been considered within our uncertainty investigations. Other parameters should be taken into account such as time formation, weir coefficient, flow, *etc*. in the future studies, to complete our analysis. Then, uncertain input parameters of the models are considered independent which is not necessarily the case. Therefore, dependence between inputs parameters must be considered to compute UQ and GSA. Finally, further researches should also be focused on the parameters describing the flooding events (*e.g.* peak discharge, duration).

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