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Global Sensitivity Analysis for the Gironde Estuary Hydrodynamics with TELEMAC2D

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Abstract

This paper presents a global sensitivity analysis study applied to a TELEMAC2D numerical flood forecast model of Gironde estuary which aims at identifying which input variables should be better described for water levels to be better simulated and forecasted. A variance sensitivity study (ANOVA) was carried out, by calculating Sobol' indices for all numerical parameters (wind influence coefficient, Strickler friction coefficients for 4 zones) and time-dependent forcings of the model (rivers discharges and maritime boundary conditions). It led to the identification of parameters and forcings to which the model is most sensitive for each area of the estuary. Sobol' indices for 2003 event show a predominance of the influence of the maritime boundary conditions and of Strickler coefficients all along the estuary. A mesh convergence study shows that the results don't depend on the mesh. Moreover, a special focus on the eigenvalues of the tide signal correlation error function shows no predominance of one mode on the other. These first results are currently used to implement a sequential ensemble Kalman filter improving both the state of the system and the maritime boundary condition and optimizing the friction coefficients over the Gironde estuary.

1 Introduction

Hydrodynamic numerical softwares based on shallow-water equations are commonly used for management and protection of urban infrastructures located near rivers or coasts. They are also used for operational flood forecasting with strong computational constraints. Yet, these numerical codes remain imperfect as uncertainties in the model (numerical schemes, time and space resolution, etc.) and its inputs (model parameters, boundary conditions, geometry, etc.) translate into uncertainties in the outputs. Quantifying uncertainties goes beyond the limits of deterministic forecast and represent a great challenge for Decision Support Systems for risk

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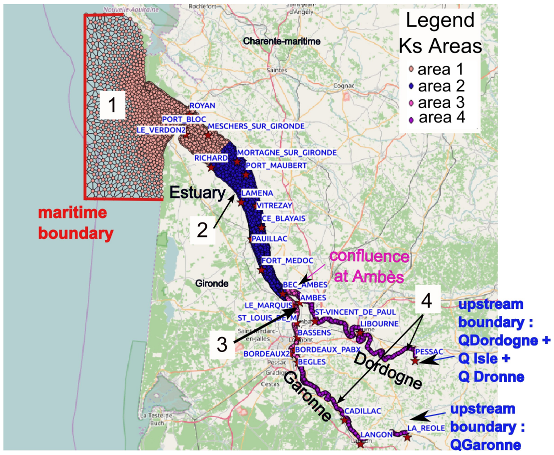


Figure 1: extension and location of the numerical model of the Gironde estuary and delimitation of the Strickler coefficient areas 1 to 4. Circles represent the nodes of the numerical model based on a mesh built with finite elements (in black). Red stars show the main measurement stations of interest for the water levels forecast.

assessment or crisis management.

This paper presents a Sensitivity Analysis (SA) study in the context of flood forecasting in the Gironde estuary. It aims at identifying the major sources of uncertainties for water levels' simulation and, thus, which input variables should be better described for water levels to be better simulated and forecasted in the estuary. A multivariate GSA method (ANOVA) is presented, consisting in the Quantity of Interest (QoI - water levels here) variance decomposition in terms of elementary variances associated to the different parameters and their interactions. This decomposition is obtained from an orthogonal decomposition of the uncertain QoI over the probabilized parameter space [1]. A set of sensitivity indices, called Sobol' indices [9], is estimated. They represent the contribution of each parameter and their interactions to the model output variance. Once identified and quantified, these uncertainties can be reduced with data assimilation methods, such as Ensemble Kalman Filter currently implemented, thus improving water level forecast in the context of flood forecasting on the Gironde estuary.

The structure of the paper is as follows: in a first section, the Gironde estuary hydrodynamic model implemented with TELEMAC2D is presented. In the following section, the experimental settings for the GSA (ANOVA for grouped modes of time-dependent variables and eigenmodes taken one after the other for the tide signal) study are presented. Results are then described and discussed. Conclusions and perspectives in terms of ensemble Kalman filter implementation for the study are finally given.

2 Gironde estuary numerical model

A hydrodynamics numerical model for the Gironde estuary (presented in [3] and shown on Figure 1) implemented with TELEMAC2D [2] is used to compute water depths and velocities in the estuary and on Garonne and Dordogne rivers. The maritime boundary is located in the Bay of Biscay, 35 km away from le Verdon. The upstream boundaries are located on the Garonne River (at La Réole) and on the Dordogne River (at Pessac).

Table 1: Calibrated Strickler (K) parameters computed from the NASH_HT and RMSE criteria.

Input variable	Updated Strickler coefficients with NASH_HT criterion	Updated Strickler coefficients with RMSE criterion	Uniform distribution over
Ks1	55	70	[50 ; 70]
Ks2	70	70	[45 ; 75]
Ks3	75	65	[25 ; 75]
Ks4	50	55	[40 ; 80]
CDz	2.57.10-6	2.57.10-6	[0.678.10-6 ; 3.016.10-6]

Surface forcing wind velocity and pressure fields from the regional meteorological model ALADIN and water levels at the maritime boundary, which are the sum of the predicted astronomical tide and surge levels, are provided by Meteo-France. Hydrological upstream forcings for the Dordogne and Garonne rivers are provided by DREAL (Direction Régionale de l'Environnement, de l'Aménagement des Territoires et du Logement) Nouvelle Aquitaine.
The friction coefficient Ks is described over 4 homogeneous areas as shown in Figure 1. The wind influence coefficient formulates the wind shear stress at the free surface from the wind velocity [5]. A uniform and constant value was chosen here (Cdz = 2.14 10^{-3}) [6].

3 Methodology for sensitivity analysis

Eight uncertain input variables are considered for ANOVA in the following: the 4-zone distributed friction coefficients (K1, K2, K3, K4), the wind influence coefficient CDZ and time-dependent boundary conditions at the hydrological limits (QDOR and QGAR for the Dordogne and Garonne rivers respectively) and at the maritime boundary (CLMAR). The uncertain input vector is denoted by X, of components X_i with i in [1;8]. The QoI is the water level at a specific node and a specific time. It is a scalar and denoted by Y in the following. The GSA is applied for water level at the 26 observing stations in Figure 1, over time. For each X_i, a Sobol' sequence is used for space filling in a normalized space and the sample is then mapped onto the physical space.

Scalar uncertain variables are described by their Probability Density Function (PDF). Here, wind influence coefficient and friction coefficient PDFs are supposed to be uniform with ranges described in Table 1. The critical point is the description of the ensemble from which sensitivity indices are stochastically estimated. For ANOVA, all physical variables should be mapped onto a unit hypercube.
When uncertainty relates to time dependent variables (hydrological time vectors for this study), the dimension of the input space should be reduced for computational reasons. This applies to the time-dependent upstream discharge forcings (Dordogne and Garonne), downstream water level forcing and wind and pressure surface forcing (not treated in this paper). The sampling procedure for these quantities aims at preserving temporal correlation of errors. The discharge chronicles q_T are supposed to be Gaussian Processes with Gaussian correlation function f_T with a correlation length scale L_T, estimated from observed chronicles over the $1981 - 2016$ period and a Karhunen Loeve decomposition is used to obtain the main eigenmodes for each time-dependent forcing.
A set of N_e boundary condition time dependent vectors are then generated with the amplitude of the perturbation set proportional to the observed chronicle. This leads to a maximum discharge variance of 20 % and a maximum water level variance of 50 cm for the maritime boundary. A perturbed forcing for the Dordogne boundary conditions (resp. for the tide signal) is shown in

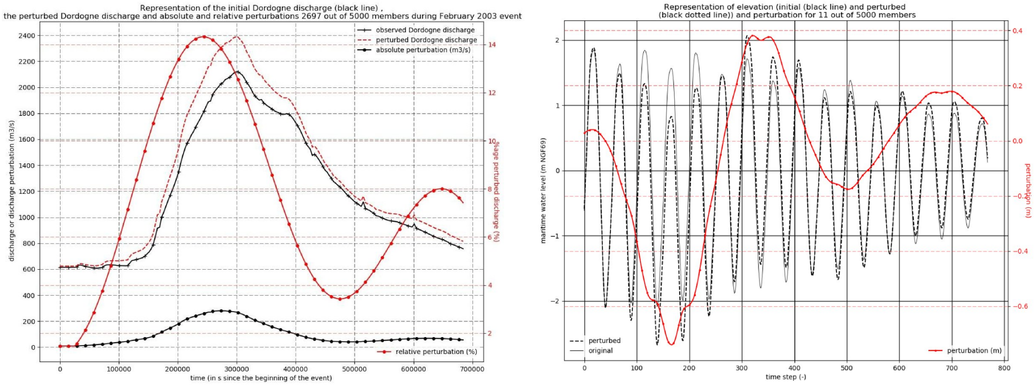


Figure 2: perturbed forcing member for maritime boundary condition (on the left) and Garonne river discharge (on the right)

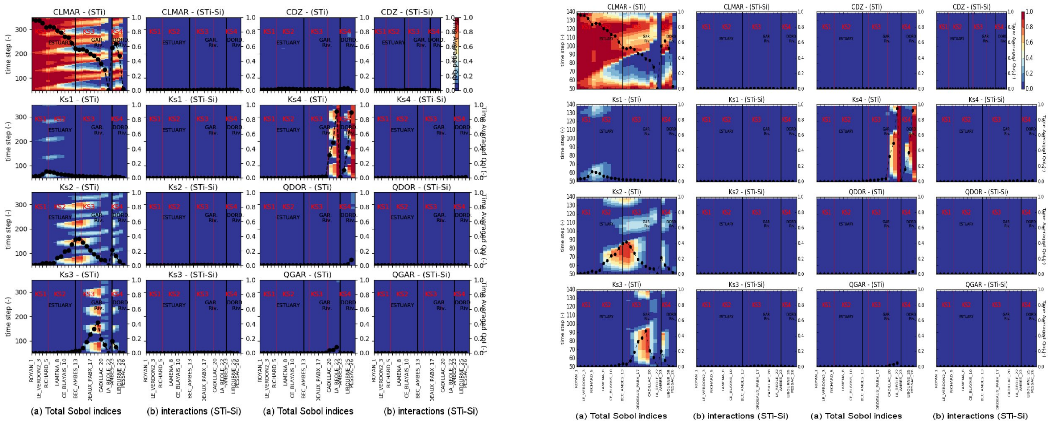
Figure 2 on the left (resp. on the right).
The GSA is thus carried out in an uncertain space described by 20 variables: 4 Strickler coefficients, the wind influence coefficient Cdz, the 4 principal modes for each river discharge QDOR and QGAR and the 7 principal modes for the maritime boundary tide signal. However, for each time-dependent variables (river discharges and tide signal at the maritime boundary), perturbations for each mode are then aggregated by to the physical input space if grouped modes are considered. Total and first order Sobol' indices (S_{Ti} and S_i) are then computed according to [8], [4] and [7].

4 Results and discussions

4.1 GSA results and mesh convergence

The ANOVA GSA study was carried for $2nd - 9th$ February 2003 event, characterized by a tide coefficient in the range of [43 ; 90] and Dordogne (resp. Garonne) discharge of [600 ; 2200] m^3/s (resp. [1200 ; 5900] m^3/s). For each input variable, a sample of 5000 perturbed realisations was generated.
Sobol' indices are displayed in Figure 3 with a blue-red color bar for the 8 uncertain inputs Xi, over time and along the curvilinear abscissa. The x-axis represents the 26 observing stations classified from left to right for downstream to upstream. The red vertical lines represent the limits between the 4 friction coefficients areas. The black vertical lines represent the limits between the estuary, the confluence and the Garonne and Dordogne rivers. For each input variable, the total Sobol' indices are plotted in panels –a and the difference between total and first order indices are plotted in panels –b. For panels –a, blue/red means small/large Sobol' indices; for panels –b, blue/red means small/large interactions of Xi with other uncertain variables. The thick dashed line represents time-averaged Sobol' indices.

Figure 3 on the left clearly shows the predominance of the maritime boundary condition and the dependency of all variable impact on the tidal signal. As previously mentioned, the wind influence coefficient, the hydrological boundary conditions and the friction coefficient in area 4



(a) Total Sobol indices (b) interactions (STi-Si) (a) Total Sobol indices (b) interactions (STi-Si) (a) Total Sobol indices (b) interactions (STi-Si) (a) Total Sobol indices (b) interactions (STi-Si)

Figure 3: For the original mesh (on the left) and a more refined one (more than 400000 nodes on the right): Total Sobol' indices (STi) in panels a- (resp. interactions STi - Si in panels b-) along Gironde estuary during february 2003 storm for 8 uncertain input variables (maritime boundary conditions (CLMAR), friction coefficients (Ks1, Ks2, Ks3, Ks4), the wind influence coefficient Cdz and hydrological boundary conditions (Dordogne river discharge: QDOR ; Garonne river discharge: QGAR).

have no influence on the water level variability except at the upstream location of Garonne and Dordogne.

It should be noticed that these results have been confirmed for the first tide cycle on a much more refined mesh (more than 400.000 nodes) than the operational one (see Figure 3 on the right).

Moreover maps of Sobol' indices over the complete mesh for all variables at each time step have also been produced (see Figure 4 for the mapping of Total Sobol' indices for maritime boundary conditions at high tide). Figure 4 shows (at high tide) the homogeneity of Total Sobol' indices geographical repartition and confirm that the conclusions brought previously for the 26 locations of interest can be generalized for areas they are located in. It should be noticed that the same maps have been provided at other times during 2003 storm, leading to the same conclusions and making able to visualize the evolution of influences of each variable during the event.

4.2 Influence of each eigenmodes on the system variability

The ANOVA GSA studying each eigenmode one by one was also carried for $2^{nd} - 9^{th}$ February 2003 event, characterized by a tide coefficient of [43 ; 90] and Dordogne (resp. Garonne) discharge of [600 ; 2200] m^3/s (resp. [1200 ; 5900] m^3/s). For each eigenmode, a sample of 5000 perturbed realizations is generated.

The same methodology was used considering the eigen modes of all time-dependent variables separately, i.e hydrological and tide forcings. However, as already shown formerly, the contribution of hydrological forcings (the discharges of Garonne and Dordogne rivers) is very low except at the upstream part of both rivers, considering grouped eigen modes. That's why no further investigation was led to study separately the contribution of the modes of hydrological

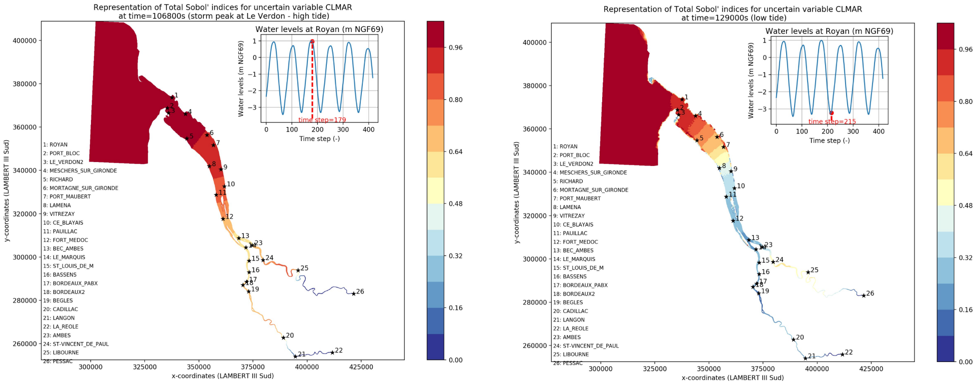


Figure 4: spatial variability at low tide and high tide: Total Sobol' indices (STi) in Gironde estuary during february 2003 storm for the maritime boundary uncertain input variables (CLMAR).

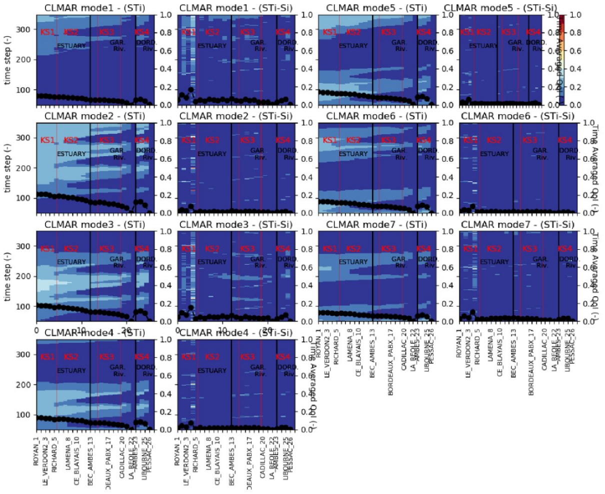
forcings.

As introduced in the former section, the sampling procedure for maritime boundary conditions aims at preserving temporal correlation of errors. The tide signal chronicles q_T are supposed to be Gaussian Processes with Gaussian correlation function f_T with a correlation length scale L_T, set to 6 hours (half-tide) at the maritime boundary. q_T is written by a Karhunen-Loève decomposition, as the truncated sum of n_p orthogonal functions where ϵ_i coefficients (modes) are independent standard normal variables.

In our case, the 9 first modes explain 50 % of the variance of the tide-signal chronicle, as the variance of q_t is simply the sum of the eigenvalues of the correlation function. However, it also shows that the 4 first modes nearly explain the same percentage of total variance, i.e around 6 %. Moreover, until the 23^{rd} eigenvalue, each explains more than 1 % of the total variance. It should therefore be noticed no real predominant impact of the 1^{st} mode on the total variance of input data. It almost has the same contribution as the 4 modes behind it.

In this study, 7 modes of the correlation function have been perturbated. The results are confirmed considering 12 modes. They are displayed in Figure 5 with respect to time. Therefore, only 45 % of the input data variance can be caught and perturbated.

Considering the contribution of each eigenmode of the maritime signal separately leads to the results displayed on Figure 5, in the same way as explained in section 3 for grouped modes. According to the ebb or flood tide, all 7 modes considered don't contribute at the same time during february 2003 storm event. Modes are only significative contributors at ebb tide, with quite a great difficulty to draw a hierarchy between them. Several remarks can be made. As for the former study and as expected, the influence of the eigenmodes decreases from the mouth of the estuary to the upstream part of rivers with respect to the periodic tide signal. Modes 2, 3, 4 and 5 have major contributions, their respective Sobol' indices reaching 30 % according to the time step. Modes 6 and 7 have a lower influence during the second part of the storm event; Finally, mode 1 has no great influence on water levels except at the end of the event as its total Sobol' index reaches 20 %. Moreover it mainly contributes from the mouth of the estuary to the confluence between Dordogne and Garonne rivers.



(a) Total Sobol indices (b) interactions (STi-Si) (a) Total Sobol indices (b) interactions (STi-Si)

Figure 5: Total Sobol' indices (STi) in panels a- (resp. interactions STi - Si in panels b-) along Gironde estuary during february 2003 storm for maritime boundary conditions eigenmodes (CLMAR).

Therefore, it should be noticed that, in this study, only 7 modes of the correlation function for the maritime signal have been perturbated and the correlation duration is set to 6 hours (half a tide). However, only 45 % of the input data variance can then be caught and perturbated. As expected, Figure 5 shows no predominance of one eigenmode on the other, as they all represent around 5 % of the input variancy.

It allows us to conclude that, considering tide as a deterministic process and surge levels as the uncertainty source of the maritime boundary condition, correlation lengths equal to several days should be studied.

5 Conclusions and perspectives : Ensemble Kalman filter implementation

The numerical T2D model operationally used by SPC GAD to forecast water levels along the Gironde estuary was studied through a global sensitivity analysis based of variance decomposition (ANOVA) to provide Sobol' indices. The ANOVA over the 2003 event enables to quantify the contribution of each variable during the storm and the part of the variance linked to interactions between variables. SA shows that the tidal signal imposed at the maritime boundary condition and provided by a more extended surge levels model is the key input variable. Moving from the mouth to the upstream part of the Garonne and Dordogne rivers, the influence of the friction coefficient increases and the hydrological forcing have a very local influence upstream the rivers. A perspective for this study is to use a bootstrap method to compute the confidence interval for Sobol' indices. Moreover, time and spatial dependent uncertain input variables such as the meteorological forcings associated to a tide signal should also be included in the SA.

Finally, this SA approach allows to identify the significant sources of uncertainty that should be reduced with data assimilation, for instance with an ensemble Kalman Filter, in order to improve the water level at key location on the estuary in simulation and forecast mode. Based on GSA results, an ensemble Kalman filter is currently implemented including the maritime boundary condition and friction coefficients in the control vector, trying both to improve water levels forecast and to update surge levels at the boundary and friction coefficients with time.

6 Acknowledgments

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