Automatic Calibration of Bed Friction Coefficients to Reduce the Influence of Seasonal Variation: Case of the Gironde Estuary

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ABSTRACT

An automatic procedure to identify the bed friction coefficient is tested on a 2D hydrodynamic model of the Gironde estuary (France). The proposed procedure involves an optimization algorithm based on evolution strategy, namely CMA-ES (Covariance Matrix Adaptation Evolution Strategy). Without optimization, application of the same friction distribution to different hydrological conditions leads to significant relative error in water level prediction up to 20-30%. For the tested configuration, 300 runs seemed to be sufficient to reach an optimal value whereas additional 200 runs would help to gain an accuracy of few millimetres (or 0.3%). In order to reach the same level of accuracy for the different hydrological configurations, it is necessary to adapt for each configuration the bed friction coefficient. Such behaviour tends to confirm a seasonal variation of the friction coefficient and this particularly in the central part of the estuary. Different relationships of the friction coefficient according to the flowrate have been incorporated inside the 2D hydrodynamic model. These relationships effectively allow to maintain an accurate prediction of the water levels close to 10% for a wide range of hydrological configurations.

INTRODUCTION

The tide propagation inside estuary is mainly affected by the modification of the flow section and by energy loses due to bed friction (Le Floch 1961). Converging sections tend to increase the tidal amplitude whereas bottom friction rather decreases this amplitude (Le Floch 1961). In the estuarine uppest part, the interactions between tide and river discharge also impact the tidal propagation (Moldwin 2016). For instance, the flowrate magnitude influences the location of turbidity maximum (TM) and associated mud deposition (Sottolichio et al 2001). The presence of fresh mud deposit induces a modification of the bottom friction (van Rijn 2007) and thus the tide attenuation. In contrast, harmonic analysis is generally used by harbours to predict the water level (Moldwin 2016). Prediction based on harmonic analysis is valid for harbours located near the shore but it becomes less accurate for ports located inside the estuary where interaction between river and tide becomes significant. A typical example is the Port of Bordeaux located 100 km upstream the mouth of the Gironde estuary. The macrotidal Gironde Estuary is located in South-West France covering a surface of 635 km^2 from the Bay of Biscay to 170 km landward (Fig. 1). The estuary is characterized by a complex geomorphology, high turbidity levels up to 20 $g.l^{-1}$ and a heterogeneous bed composition (Allen 1972, Castaing 1981). Over the years, a large number of hydrodynamic models with different complexity levels have already been developed. These models generally aimed at tracking the turbidity maximum zone (Sottolichio et al 2001, Jalon-Rojas *et al.*, 2015) with two-dimensional vertical (2DV) or three-dimensional approaches (3D) to compute the hydrodynamics, sediment transport, and salt intrusion. Alternatively, Huybrechts *et al.* (2012) proposed a 2D depth-averaged horizontal model (2DH) that showed to be a good compromise between computational cost and accurate solution to efficiently capture the main hydrodynamic processes. Fast and robust models are indeed required in operational tools applied to various alert control systems, including flood control application (Laborie *et* al 2014) and transport processes, such as sediment matter (Huybrechts and Villaret 2013, Orseau *et al.* 2020a), or pollutants in the environment. The model developed by Huybrechts *et al.* (2012) has been further applied to forecast the ship welcoming capacity inside the Gironde estuary for an interval of 36 hours (Orseau et al 2020b). Huybrechts *et al.* (2012) calibrated the bed friction coefficients by a trial and error procedure in order to reach water level differences lower than 15 cm at the estuary mouth (Verdon, Fig. 1) and at the central part of the estuary (Pauillac, Fig. 1). The calibration and the validation of this model have been performed with field measurements acquired in August 2006 and October-November 2009. These two events are characterized by low river discharges and calm weather conditions. The hydrodynamic model included river and tidal forcing whereas storm surges were not considered. The update of the Huybrechts *et al.*'s model (2012) to recent bathymetric information coming from up-to-day bathymetric surveys makes therefore necessary to assess the validity of the previous friction calibration procedure. In contrast to a flood control application where a robust calibration is needed especially for high water levels or storm conditions, a ship route plan requires a robust calibration for a wider range of hydrological condition. Therefore, the accuracy of the model needs to be evaluated under different flow scenarios and weather conditions. Since the trial and error methodology is not suitable to build a friction calibration procedure valid for different hydrological conditions, it is rather proposed to couple the hydrodynamic model with an optimization tool. As discussed by Dung et al. (2011), automatic calibration is becoming popular for water-related applications mainly for groundwater, watershed applications. Application of the proposed methodology to large scale and unsteady hydrodynamic model, as observed for estuaries, is still rare (Dung *et al.* 2011) due to the required computational resources. The automatic calibration of physical coefficients looks for solution of an inverse problem. This solution corresponds to the minimization of the error between the experimental results (field data) and the results estimated by a numerical model (called direct model). To solve this inverse problem, two different methods have been proposed (Fletcher, 1980-1981; Holland, 1975): gradient-based and meta-heuristic methods. The first category uses the objective function gradient to search for the optimum, while the second randomly searches for the optimum in a set of solutions (called the population of individuals). The gradient-based methods require that the objective function satisfies regularity conditions (differentiability, convexity). In addition, if the function has several local optima, these methods will be more likely to converge towards a local optimum than a global one. Meta-heuristic methods have been introduced to circumvent the disadvantages of the gradient-based methods. These methods will not use the calculation of the gradient of the objective function, but will explore the global research space based on stochastic processes on a population of individuals rather than on a single individual (solution). Meta-heuristic methods have the advantage of: (**i**) they are based on a random search and are therefore able to explore the whole space of the solution; (**ii**) the objective function does not have to be continuous allowing an efficient search for discrete problems, and (**iii**) they are robust, offering the guarantee of convergence towards the global optimum. However, these methods have the disadvantage of been computational costly at reaching the optimum since they are based on an iterative procedure with slow convergence (Rudolph, 1994; Smaoui et al. 2018-2019). In Geosciences, several meta-heuristic methods have been proposed, e.g. instance genetic algorithms (GA, Goldberg, 1989); simulated annealing (SA, Kirkpatrick et al., 1982); particle swarm optimization (PSO, Eberhart and Kennedy, 1995); ant colony optimization (ACO, Dorigo and Gambardella, 1997); cat swarm optimization (CSO, Ch and Tsai, 2007), differential evolution (DE, Storn and Price, 1997) and evolution strategy (ES, Baeck et al. 2000a, 2000b)

In the present study, the Covariance Matrix Adaptation Evolution Strategy (CMA-ES, Hansen and Ostermeier 1996) is applied to the 2DH hydrodynamic model of the Gironde estuary. This meta-heuristic algorithm is first performed on six hydrological events selected between April and August 2015 with different flowrate values. The period was selected based on the availability of storm surges information provided by Météo-France. From these tests, results are analysed in term of accuracy and friction distribution. Finally, the robustness of the methodology is assessed by considering the effect of the mesh discretization and the number of friction zones.

STUDY AREA

The Gironde Estuary’s width reaches 20 km at the mouth and decreases to 3 km downstream the confluence of the Dordogne and the Garonne Rivers. The tidal range varies from 1.5 m during neap tides to 5.5 m during spring tides at the mouth. Both Dordogne and Garonne contributions to the freshwater discharge are estimated to 35% and 65%, respectively (Sottolichio, 1999). Based on the bed composition, the estuary can be decomposed in 3 different zones comprising (i) a sandy facies in the estuary mouth; (ii) a mixed facies dominated by mud along the central part and (iii) a fluvial estuary, in the most upstream parts, characterised by the presence of sand, pebbles and gravels (Allen 1972). Fine suspended-sediments observed in the Gironde Estuary compose a pronounced Turbidity Maximum Zone (TMZ) with concentrations ranging between 1 and 20 g/l (Sottolichio and Castaing, 1999). Its location along the estuary depends on hydrological conditions (Castaing, 1981; Jalón-Rojas, 2015).

For the year 2015, a harmonic analysis (Pawlowicz *et al.*, 2002) on measured water levels is performed month by month at Verdon (mouth), Pauillac (central part) and Bordeaux (Port) tidal gauge stations (Fig. 1). Variations of the M_2 amplitude according to the monthly averaged discharge at previous stations are illustrated on Fig. 2.

At the mouth, a slight increase of the M_2 amplitude from 1.44 to 1.53 m with the flowrate is observed. In the central part of the estuary, the M_2 amplitude increases progressively until a relatively constant value. Conversely, the M_2 amplitude tends to decrease at Bordeaux when flowrate is increasing from 400 to 1200 m^3/s. A maximum value is reached around 300 m^3/s. For the lowest flowrate values, M_2 amplitude is then also decreasing probably due to a migration of the turbidity maximum further upstream Bordeaux in the Garonne River (Jalón-Rojas *et al.* 2018).

MATERIALS AND METHODS

Hydrodynamic model

The hydrodynamics is computed by a two-dimensional formulation based on the solution for the depth-averaged shallow water equations (Eq. 1), with appropriate initial and boundary conditions:

$$\frac{\partial h}{\partial t} + \frac{\partial (hU)}{\partial x} + \frac{\partial (hV)}{\partial y} = 0$$

$$\frac{\partial U}{\partial t} + \frac{\partial (UU)}{\partial x} + \frac{\partial (UV)}{\partial y} = -g\frac{\partial Z}{\partial x} + \frac{1}{h}\frac{\partial}{\partial x}\left(h\nu\frac{\partial U}{\partial x}\right) + \frac{1}{h}\frac{\partial}{\partial y}\left(h\nu_t\frac{\partial U}{\partial y}\right) - \frac{g}{h}\frac{1}{K^2 h^{\frac{1}{3}}}\|\vec{U}\|U + S_x$$

$$\frac{\partial V}{\partial t} + \frac{\partial (UV)}{\partial x} + \frac{\partial (VV)}{\partial y} = -g\frac{\partial Z}{\partial y} + \frac{1}{h}\frac{\partial}{\partial x}\left(h\nu\frac{\partial V}{\partial x}\right) + \frac{1}{h}\frac{\partial}{\partial y}\left(h\nu_t\frac{\partial V}{\partial y}\right) - \frac{g}{h}\frac{1}{K^2 h^{\frac{1}{3}}}\|\vec{U}\|V + S_y$$

Eq. 1

where h is the water depth [m], $\vec{U}$ is the depth-averaged flow velocity vector [m/s] , with east-west, north-south components U and V, respectively, $\|\vec{U}\|||$ is the velocity norm, g is the gravity acceleration [m²/s], Z is the free surface elevation [m], ν_t is the momentum diffusion coefficient [m²/s], ρ is the water density [m^3/kg], K is the Strickler-Manning coefficient [m$^{1/3}$/s], Sx and Sy are additional source terms. The Strickler coefficient used for the bed friction is just the inverse of the Manning coefficient. The mathematical system is therefore composed of 3 equations and 5 unknowns (h, U, V, K and ν). Bed friction and diffusion coefficients (K and ν) are provided by additional closure relationships or imposed values. A constant value equal to 1 m²/s is imposed for the diffusion coefficient over the whole numerical domain. In the shallow water equations, the bed friction term is included in the source term of the momentum equation.

The module TELEMAC-2D of the TELEMAC-MASCARET modelling system (Hervouet 2007) is applied in this study to solve the shallow water equations (Eq. 1), with the finite element method. The computational domain is comprised from 30 km offshore the estuary mouth to 180 km landward up to the limit of the tidal dynamic and extends to 20 km from the North to the South (Fig. 1). The mesh is unstructured and composed of triangular elements. Two different meshes with different element size resolutions are used in this work: the mesh 1 containing 28000 nodes and the mesh 2 containing 76000 nodes (Fig. 3). The distance between nodes of mesh 1 ranges within 1000 - 2000 m offshore 300 m in the central part (Fig.3a), and within 75-200 m in the tributaries (Fig. 3c). Mesh 2 features an enhanced resolution along the navigation channel: within 300-2000 m offshore, within 60-300 m in the central part (Fig.3b) and within 33-100m upstream the confluence of both tributaries (Fig. 3d).

Measured river discharge is imposed at fluvial boundaries for both Gironde tributaries (Fig. 1). At the maritime boundary, astronomic tide elevation and tidal currents are reconstructed using NEA tidal atlases (North East Atlantic, Pairaud et al 2008, Huybrechts et al 2012) as a superposition of harmonic waves (Schureman 1958) for each of the nodes of the offshore boundary (Eq. 2).

$$H_{tide} = H_0 + dH_0(t) + \sum_n H_n f_n cos(\sigma_n t - g_n + V_n - u_n)$$

Eq. 2

where H_{tide} = the tidal height; H_o = the mean height of the water level; n = the harmonics number; H_n = the mean amplitude of the n-wave; f_n = the nodal correction for the amplitude; σ_n = the frequency; t = the time; g_n = the phase lag of the equilibrium tide; V_n = the astronomic argument; and u_n = the nodal correction for the phase lag. dH_0 is the storm surge contribution.

Sea levels variation due to storm surges are applied to the tidal signal to improve water level predictions. Storm surge data are provided by a Météo-France model and computed every 10 minutes at 12 nodes located along the maritime boundary. Linear interpolation is then performed to incorporate surge values for each boundary node. In the previous study, Huybrechts et al (2012) decomposed the bed friction into 4 different zones delineated as: mouth, central part and tributaries. In the present work the number of zones is firstly increased up to 7 zones K_i, (Fig. 1b) to better characterize the bed roughness of the estuary's tributaries. Finally, a configuration accounting for two additional friction zones located at the central part of the estuary is considered (Fig. 1c). The delineation between the mouth and the central part of the estuary (respectively zone 1 and zone 2, Fig. 1b) corresponds to a change in the bed material from sand to mud, respectively. Other remaining delineations are arbitrarily defined mainly based on the geometrical features of the water body.

Optimization algorithm

The optimization algorithm implemented in this work is based on the evolutionary strategy algorithm (ESA, Baeck et al. 2000a, 2000b, Dréo et al. 2005). According to the Darwin's theory, evolution will produce at the long-term organisms more adapted to their environment (Dréo et al. 2005). Thus, in order to achieve better results, ESAs evolve in a set (called *population*) of solutions (called *individuals*) and a searching root on a random population instead of an individual. Research on a population increases the probability to find the optimum among individuals. During the iterative process (called generation) leading to the optimal solution, the populations evolve according to selection and variation cycles. From the ESA family, we have adopted the CMA-ES algorithm. This algorithm, due to Hansen and Ostermeier (1996), has been proposed to improve several aspects of the others ESA but specially to overcome the main issues of the optimization solvers based on genetic algorithms (Espana *et* al 2017). CMA-ES offers good performance in optimizing functions that are not regular enough or even undefined explicitly. The CMA-ES research space has the advantage of evolving real numbers set, thus avoiding the coding/decoding steps that characterize the genetic algorithms (GA). However, a complete description of the CMA-ES is out of the present scope. It is worth noting that metaheuristic optimization methods such CMA-ES can be effectively coupled with other numerical models to identify some parameters model not accessible from measurements (Bayer and Finkel, 2004; Elshall et al. 2015; Smaoui et al. 2018 and Smaoui et al., 2019). Additional details are provided in the Appendix whereas full descriptions of the algorithm are available in Hansen and Ostermeier (2001); Hansen et al. (2003), Dréo et al. (2005) or Hansen (2006 &2016).

Coupling between the hydrodynamics module and the optimization algorithm

The coupling interface between the optimization algorithm (CMA-ES) and the hydrodynamic module (TELEMAC-2D) is performed with the multi-paradigm numerical computing environment and proprietary programming language Matlab©, developed by MathWorks (Moler and Little 2020). The specificity of each application relies on the way of building the objective function. In our application involving 2D hydrodynamic modelling, the unknowns are the values of the different bed friction coefficients and the variable to optimize is the difference between measured and computed water levels. The coupling flowchart between the hydrodynamics module and the optimization algorithm is illustrated on Fig. 4.

An initial distribution of the bed friction coefficient is provided. A steering subroutine is implemented to build the objective function. This subroutine calls the module TELEMAC-2D for launching the numerical simulations, it post-processes the numerical results and it evaluates the RMSRE (Root Mean Square Relative Error, Eq .4) between the computed water level depending on the friction distribution (Zc, Fig. 4) and the measurement (Zm, Fig. 4). The RMSRE is estimated at 8 tidal gauge stations (Fig. 1): Verdon, Laména, Pauillac, Medoc, Ambes, Bordeaux, Cadillac, Libourne. The first six stations are located along the navigation channel. Cadillac station located more upstream in the Garonne River, while Libourne station located in the Dordogne River.

The CMA-ES algorithm searches for minimizing the mean value of the RMSRE of the 8 stations. The minimized value is referred as RMSREm (m for mean between the 8 stations). For each station, the RMSRE is computed by (Eq. 3):

$$RMSRE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Z_{mi} - Z_{ci})^2}}{Z_m}$$

Eq. 3

Where Z_{mi} is the measured water levels [m] at a gage station and $\boldsymbol{Z_{ci}}$ is the computed values, n the number of "i" observations and Z_m the mean measured value.

RESULTS

Convergence of the algorithm depending hydrological conditions

Six hydrological events are selected from April to August 2015 with flowrate varying from 150 to 1300 m^3/s in the Garonne River and from 200 to 1500 m^3/s in the central part considering the Dordogne contribution. Each event is simulated with 500 runs covering a period of 6 days. The same initial friction distribution defined from Huybrechts et al (2012) is applied to all configurations. The configuration with 7 friction zones is firstly tested. The evolution of the mean error for the 8 stations during the optimization procedure is illustrated on Fig. 5a for the four events from April to June. Similar evolutions are also plotted on Fig. 5b for Pauillac station.

As shown in Fig 5a most of the gain is reached within the first 250 runs. The accuracy gain is more evident with the evolution of the relative error at Pauillac station (Fig. 5b). RMSRE starts around 0.18, then it is decreasing down to lower than 0.1 and it may even reach 0.06 (Fig. 5b). At Pauillac for a mean tidal range of 1.6m, a decrease of 12% in relative error coincides with an absolute gain of 0.19 m. The results with 7 zones (Fig 1b) are summarized in Table 1.

Relative error is within the range [0.14 - 0.18] before optimization and [0.09 - 0.12] after optimization (Table 1, Fig. 5a). The global gain is thus within 3 and 8 % and the accuracy gain is increasing with the flowrate. For the 6 hydrological configurations, the mean ratio between final and initial error is 0.7. Along the different station, the mean ratio is almost equal to 1 at Verdon, between 0.51 and 0.59 at Laména, Pauillac and Medoc and within 0.73-0.84 at Ambes, Bordeaux, Cadillac and Libourne. At Verdon, no accuracy gain is observed. It might suggest that improving the accuracy at Verdon through bottom friction coefficient leads to deteriorate the accuracies of the other upstream stations. Improvement at the mouth may probably require enhanced offshore boundary conditions which is a combination of tidal atlases (Huybrechts et al 2012) and prediction of the storm surges. Less accuracy gain could also be expected at the uppest estuarine part due to a sparse bathymetry dataset. However, for an application related to ship route and underkeel clearance management inside the estuarine configuration (Orseau et al., 2020b), it is crucial to attain an efficient prediction of water levels at the central part where navigable depths are more restricted.

Variation of the bed friction distribution related to the flowrate

The algorithm allows to reach a mean error relatively constant for the different hydrological conditions. Nonetheless, it requires for each case an adaptation of the values for bed friction coefficient. As suggested in Fig. 2, the flowrate variation might be responsible of the TM migration of the fluid mud deposits, and it thus has an influence on the bottom roughness. Friction coefficients are plotted as a function of the flowrate to find a relationship that could be used to set an operational model. It is performed on Figs. 6 for the distribution with 7 friction zones. The zones are gathered as downstream part of the estuary for K1 and K2 (Fig. 6a), as Dordogne river for K3 and K4 (Fig. 6b) and as Garonne river for K5-K6 and K7 (Fig. 6c).

The evolution of the K1 coefficient (mouth, Fig. 6a) is in agreement with the evolution of M_2 amplitude in Verdon: slight linear increase according to the flowrate. Similar patterns are also observed between evolution of K2 and M_2 amplitude at Pauillac.

For the Dordogne river (Fig. 6b), a parabolic distribution is obtained for K3 and a third polynomial curve accurately describes the K4 evolution. For the Garonne river (Fig. 6c), K5 and K6 describe a second order decreasing curve according to the flowrate. It means that the friction increases due to the seaward migration of the TM which is in line with M_2 evolution at Bordeaux. Similarly, for the lowest flowrates, the friction coefficient seems to reach a maximum value as observed with M2 amplitude. The most upstream coefficient K7 describes an inverse behaviour with maximum value around 700 m^3/s. The plotted regression curves show the general tendencies of the friction evolution. Nonetheless, extrema values for K5 and K6 are not well captured by the simple second order equations. For the operational model, it would be rather suggested to use piecewise linear equations between the 6 optimized values.

Applicability of the methodology to finer mesh discretization and friction distribution

The proposed methodology requires between 250-500 TELEMAC-2D runs to reach the optimized friction distribution. For a 12 cores of 2.4 GHz RAM 48 Go workstation, 500 runs are performed in approximately one-day wall-clock time. Computational efficiently can be gained by avoiding some repetitive steps inside each individual run, by reducing the number of runs or by increasing the computing resources. Nevertheless, alternative way can be suggested to avoid a rough application of the methodology to a finer mesh.

The optimized distribution of bed friction obtained on a 28000 nodes is assessed on a finer grid resolution (76000 nodes). The finer mesh is characterized by a better resolution along the navigation channel and upstream the confluence. Table 2 summarises the averaged RMSRE at each station along the navigation channel obtained with the 6 hydrological events after an optimization of the coarser mesh. It reaches values ranging from 7.7% (Pauillac) to 13% (Bordeaux) with a mean value of 9.8 %. Direct application of the optimized values to the finer grid leads to RMSE within 6.9 to 11% with a mean value of 8.7%. It means that the optimized values and associated abacuses are also valid on this finer mesh. As an alternative, the optimized value obtained from the coarse mesh could be used as initial solution for a second optimization with a finer mesh and a shorter number of runs.

To address the sensitivity to the number of friction zone, the optimization methodology is applied to the same 6 hydrological events, but with 9 zones (Fig. 1c) on Mesh 1. As detailed in Table 1, no significant differences can be noticed in term of accuracy. However, the values of the friction distributions are different in the central part. To distinguish the friction zone between the methodologies accounting for 7 or 9 zones, friction coefficients for the 9 zone distributions are noted as KK1 to KK9. In fact, K2 extension covers the area sum of KK2, KK3 and KK4 whereas KK1 is the same zone as K1. The evolution of the bed friction coefficients in the central part is shown in Fig. 7.

KK1 describes a linear relationship whereas KK2 and KK3 describe a parabolic relationship with a maximum value around 800 - 900 m^3/s. KK4 rather describes a parabolic relationship with a minimum value. It should be noted that KK1 is smaller than K1 and KK2 higher than K2. It results in a more abrupt transition occurring between the two zones which may affect the numerical results if the model is coupled to a sediment transport and bed evolution module.

Application of time-varying friction coefficients to a medium-term simulation (6 months).

From Fig. 6, a relationship can be built between the friction coefficient and the flowrate for all the 7 friction zones. Concerning the regression, piecewise linear relationships are selected to interpolate the values for all flowrate values. Three simulations are conducted from April 1st to the end of October 2015. The first two simulations are based on steady friction coefficients extracted from the optimization step. The first one corresponds to friction coefficient representative of low flowrate configuration (200 m^3/s) and the second one rather corresponds to a configuration representative of mean discharge configuration (800 m^3/s). The last and third simulation tests the piecewise linear relationships (PWL).

Time series of storm surges and flowrate are imposed at the boundary conditions. The time step of flowrates is equal to 2 hours whereas it is equal to 10 min for the storm surge. Flowrate ranges within 130 and 2700 m^3/s during this period. At Verdon, Pauillac and Bordeaux, the RMSRE are evaluated every two tidal cycles (25 hours) to provide an averaged estimation of the accuracy. Values of RMSRE at Bordeaux and Pauillac stations are plotted in regards to flowrate also averaged every 25 hours. At the Verdon station, the accuracy for each simulation is equivalent (not showed here).

For the simulation 2 referred as “mean”, the values of friction coefficients are not suited for low flowrates. The RMSRE can increase up to more than 20% (> 30 cm) at Pauillac. A similar behaviour is observed at Bordeaux. In contrast, for the simulation 1 referred as “Low”, the accuracy tends to decrease at Pauillac once values are higher than 500 m^3/s, while, at Bordeaux, the accuracy is more variable. However even if the prediction is correct at Bordeaux, the accuracy is not sufficient in the central part. The advantage of the PWL simulation is to maintain a constant accuracy for a wider range of flowrate since it combines the advantage of the two previous simulations.

CONCLUSIONS AND PERSPECTIVES

The CMA-ES algorithm has been coupled to the hydrodynamic module TELEMAC-2D applied to optimize the distribution of the bed friction coefficient inside the Gironde estuary. For the tested configuration, 300 runs seemed to be sufficient to reach an optimal value. Additional 200 runs would help to gain an accuracy of few millimetres (or 0.3%). For simulations performed on a 12 core workstation), 500 runs are completed in approximately one-day wall-clock time for 12 tidal cycles. The application of the proposed methodology shows that it is necessary to modify the bed friction coefficient in order to reach the same level of accuracy for the different hydrological configurations. It also confirms a seasonal variation of the friction coefficient and this particularly in the central part of the estuary. Different relationships of the friction coefficient according to the flowrate have been incorporated inside the operational model. These relationships effectively allow to maintain an accurate prediction of the water levels for a wide range of hydrological configurations. However, further investigations on more extreme events, such as flood, storm and long dry periods, are still needed to provide more robust bed friction relationships.

For operational models, it would be interesting to further apply the methodology with several flow configurations in order to build a surrogate model providing the friction distribution according to hydro-meteorological forcing (flowrate, tidal range, storm surge) and to compare such variation to data related to the bed texture or water column as bed sample or satellite images of suspended matters.

DATA AVAILABILITY

Data, models, and code scripts used for coupling CMA-ES and TELEMAC-2D developed in this study are available from the corresponding author upon request. Water levels data are available at www.vigicrues.gouv.fr.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the Connecting Europe Facility (CEF) – Transport Sector under agreement (Innovation and Networks Executive Agency) No INEA/CEF/TRAN/M2014/1049680 through the project Gironde XL. The authors thank the National Hydrographic Service (SHOM) and the National Weather Agency (Météo-France) for providing bathymetric datasets, and predictions of tide-surge interactions. Dr. Tom Benson is kindly acknowleged for providing the Matlab toolbox used to post-processTELEMAC-2D results.

NOTATIONS

g = gravity acceleration [m/s^2] ;

h = water depth in [m] ;

K = Strickler coefficient for the bed friction in [$m^{1/3}/s$];

RMSRE = Root Mean Square Relative Error [-]

$\vec{U}$= depth-averaged flow velocity vector, with east-west U, north-south V components [m/s].

Z = free surface elevation [m];

ν_t = momentum diffusion coefficient [m²/s];

ρ = density [m^3/kg];

APPENDIX: BRIEF DESCRIPTION OF THE CMA-ES ALGORITHM

CMA-ES is a meta-heuristic optimization algorithm. It belongs to the class of algorithms called "Evolution Strategies". The research step of these algorithms is carried out in a stochastic way without any gradient calculation. The CMA-ES algorithm operates on a population of individuals rather than on a single individual (as in the case of gradient algorithms).

Like all meta-heuristic algorithms, CMA-ES starts from an initial population randomly chosen. To build a new generation of individuals, the CMA-ES algorithm follows on from the selection step in which the new candidate solutions are sampled using a multivariate normal distribution. Then individuals of this generation are evaluated via the objective function and selected according to their fitness (or objective function value) to be part of the next generation. Then comes the recombination stage to select a new mean value for the distribution. The penultimate step of the CMA-ES algorithm is the mutation which consists in adding a random vector acting as a perturbation with zero mean. The adaptation step terminates the algorithm by updating the various parameters involved in the construction of the covariance matrix. From this brief description of CMA-ES algorithm, we conclude that it is the mutation and adaptation stages that make this algorithm a robust and powerful tool for complex numerical optimization. In order to not burden the text and given their importance, we will briefly describe these two stages.

Mutation

The mutation is a step in the CMA-ES algorithm which allows generation of a new population with the aim of improving the one generated by the selection and recombination steps. It is certainly the most important step in the algorithm. It adds a random vector deduced from the multivariate distribution based on the previous generation (selection and recombination). The mutation guides CMA-ES to move in the search space by rotation and by scaling the adapted covariance matrix of the generated population. The evolution of this iterative process is controlled by different parameters (called strategy) which update automatically from information from previous generations. This process is called “evolution path’’. It's this automatic parameter update that makes this algorithm the most powerful in its class. The user does not set any parameters for the correct execution of the algorithm.

As explained above, the ES algorithms are considered to be slow to converge towards the global optimum. To accelerate this convergence, the CMA-ES algorithm offers an intermediate recombination which averages a few vector individuals from the parent population. This combination is noted by $\left(\frac{\mu}{\mu_I},\lambda\right)$-CMA-ES where $\left(\frac{\mu}{\mu_I}\right)$ designates the recombination of μ_I among μ parents and λ is the number of individuals in the initial population. Thus, for the algorithm $\left(\frac{\mu}{\mu},\lambda\right)$-CMA-ES the λ individuals of the generation $(g+1)$ are calculated by:

$$p_i^{(g+1)} = \langle p\rangle_\mu^{(g)} + \sigma^{(g)} N\left(0, C^{(g)}\right) \ , \qquad i = 1, \ldots\ldots \lambda$$

Eq. 4

With $p_i^{(g+1)}$ is the ith individual of the population of the generation $(g+1)$, $\langle p\rangle_\mu^{(g)}$ is the mean value of $p^{(g)}$ at generation (g) computed by

$$\langle p\rangle_\mu^{(g)} = \frac{1}{\mu}\sum_{k=1}^{\mu} p_k^{(g)}$$

$\sigma^{(g)}$ is the standard deviation at generation (g) (but for CMA-ES, it is also called step size), $N(0, C^{(g)})$ note the normal distribution with center 0 and covariance $C^{(g)}$ at generation (g). It should be noted that the covariance matrix is a symmetric definite positive matrix, therefore diagonalizable. In this case the covariance matrix $C^{(g)}$ can be written as:

$$C^{(g)} = B^{(g)} D^{(g)} \left(B^{(g)} D^{(g)}\right)^T$$

Eq. 5

Where the columns of the matrix $B^{(g)}$ are exactly the eigenvectors of $C^{(g)}$ and $D^{(g)}$ is a diagonal matrix whose diagonal elements are the square root of the eigenvalues of $C^{(g)}$. The combination of expressions (1) and (2) allows to rewrite (1) in the new form as:

$$p_i^{(g+1)} = \langle p \rangle_\mu^{(g)} + \sigma^{(g)} B^{(g)} D^{(g)} z_i, \qquad i = 1, \dots .. \lambda$$

Eq. 6

With $z_i = \left(B^{(g)} D^{(g)}\right)^T N(0, I)$, $\quad i = 1, \dots .. \lambda$

Finally, the calculation of the covariance matrix at generation $(g + 1)$ is based on the calculation of the evolution of the path p_t at generation $(g + 1)$ according to the following scheme:

$$p_t^{(g+1)} = (1 - c).p_t^{(g)} + \; c_u \frac{\sqrt{\mu}}{\sigma^{(g)}} \left(\langle p \rangle_\mu^{(g+1)} - \langle p \rangle_\mu^{(g)}\right)$$

Eq. 7

$$C^{(g+1)} = (1 - c_{cov}).C^{(g)} + \; c_{cov} \; p_t^{(g+1)}.\left(p_t^{(g+1)}\right)^T$$

Eq. 8

Where $\frac{1}{c}$ is the cumulative time of the evolution path. The parameter c can be interpreted a weight allowing the smoothing of p_t and can be normalized by $c_u = \sqrt{c(2 - c)}$. $\frac{1}{c_{cov}}$ denotes the average time for the covariance matrix. In the other word, c_{cov} allows the updating of the covariance matrix and it can be considered as the learning rate.

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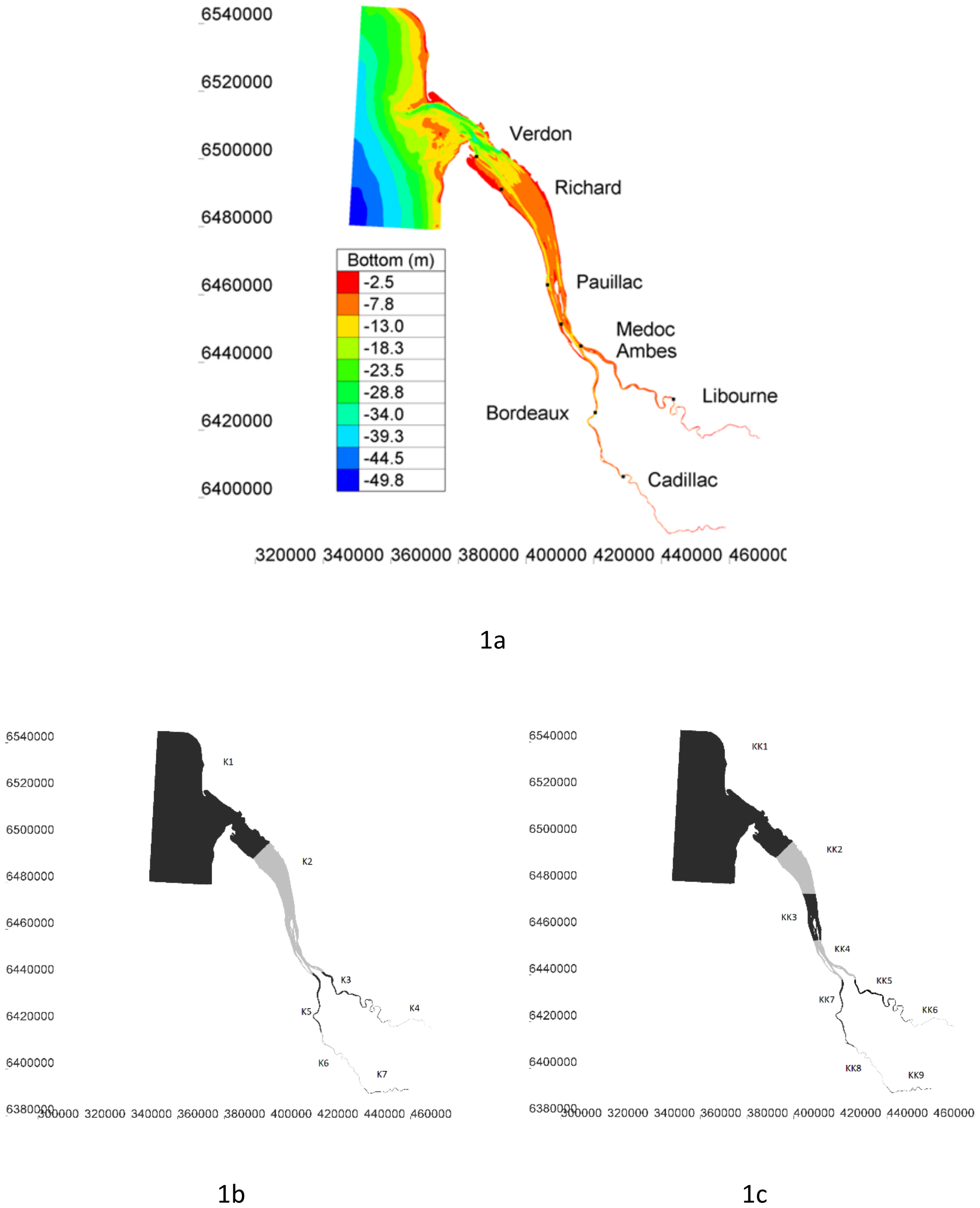


Figure 1 Model extension (1a) and bottom friction zones with 7 zones (1b) or 9 zones (1c)

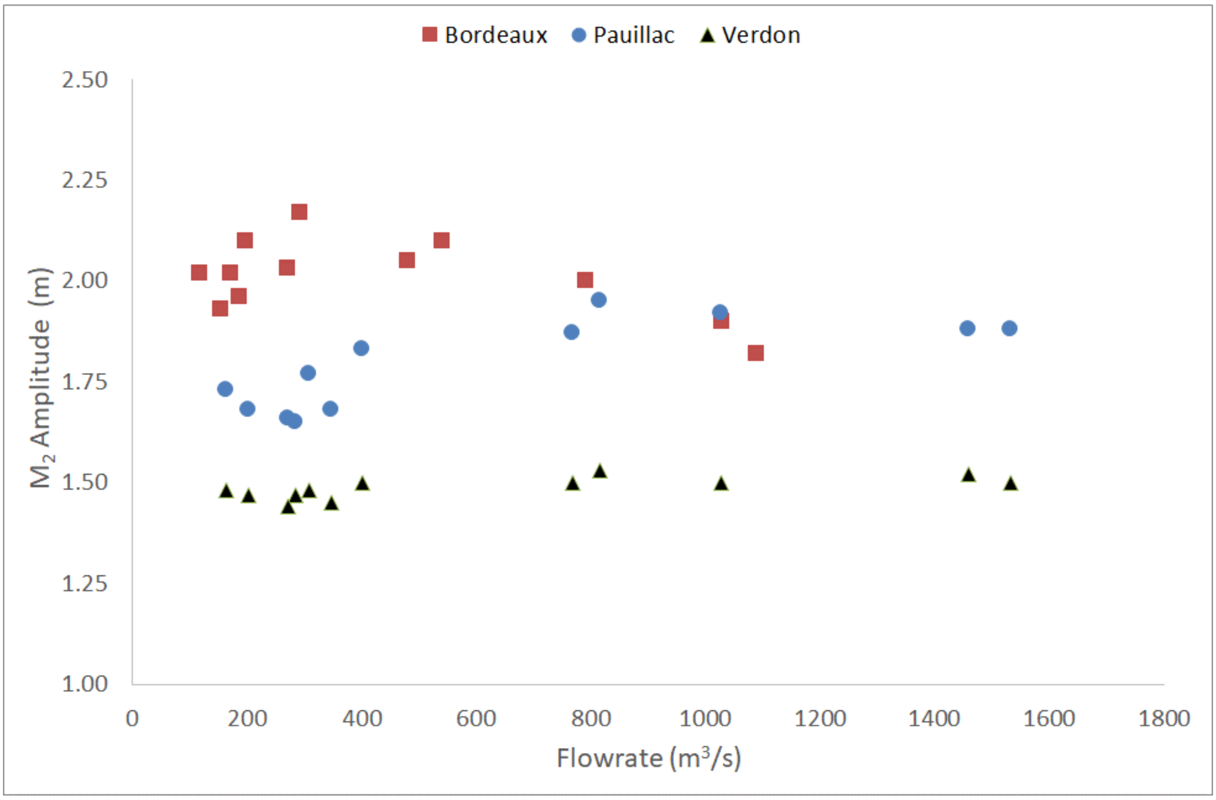
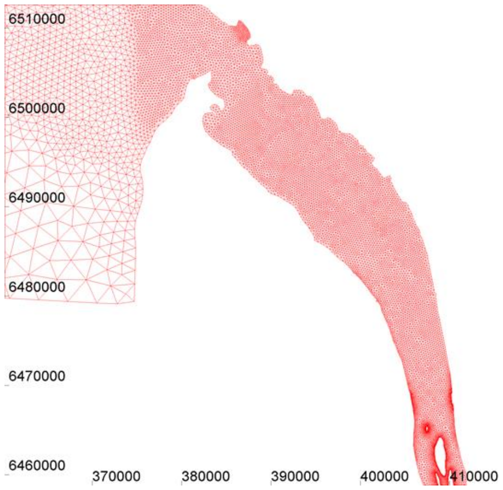
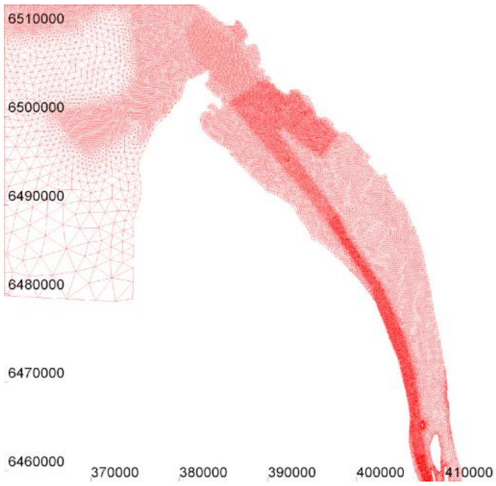


Figure 2 Seasonal variation of M_2 amplitude with the total flowrate at Le Verdon, Pauillac station and with Garonne flowrate at Bordeaux station (Fig. 1).



3a



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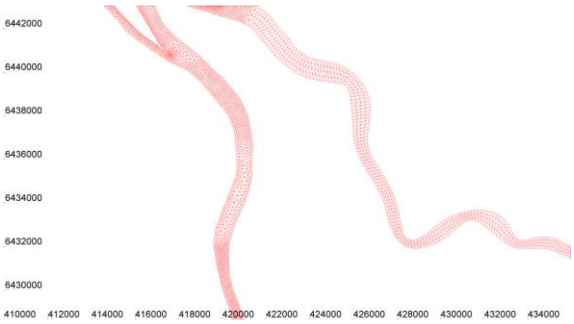

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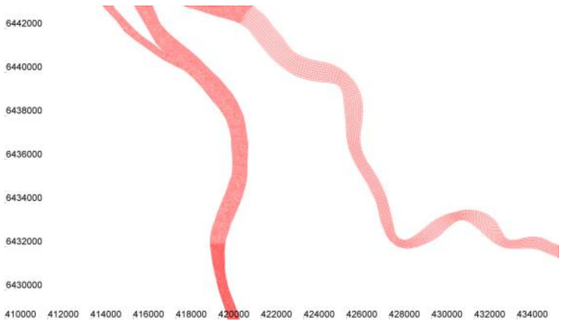


3d

Figure 3 Mesh distribution: (3a) mesh 1 with 28000 nodes in the downstream area, (3b) mesh 2 with 78000 nodes in the downstream area, (3c) mesh 1upstream the junction, (3d) mesh 2 upstream the junction.

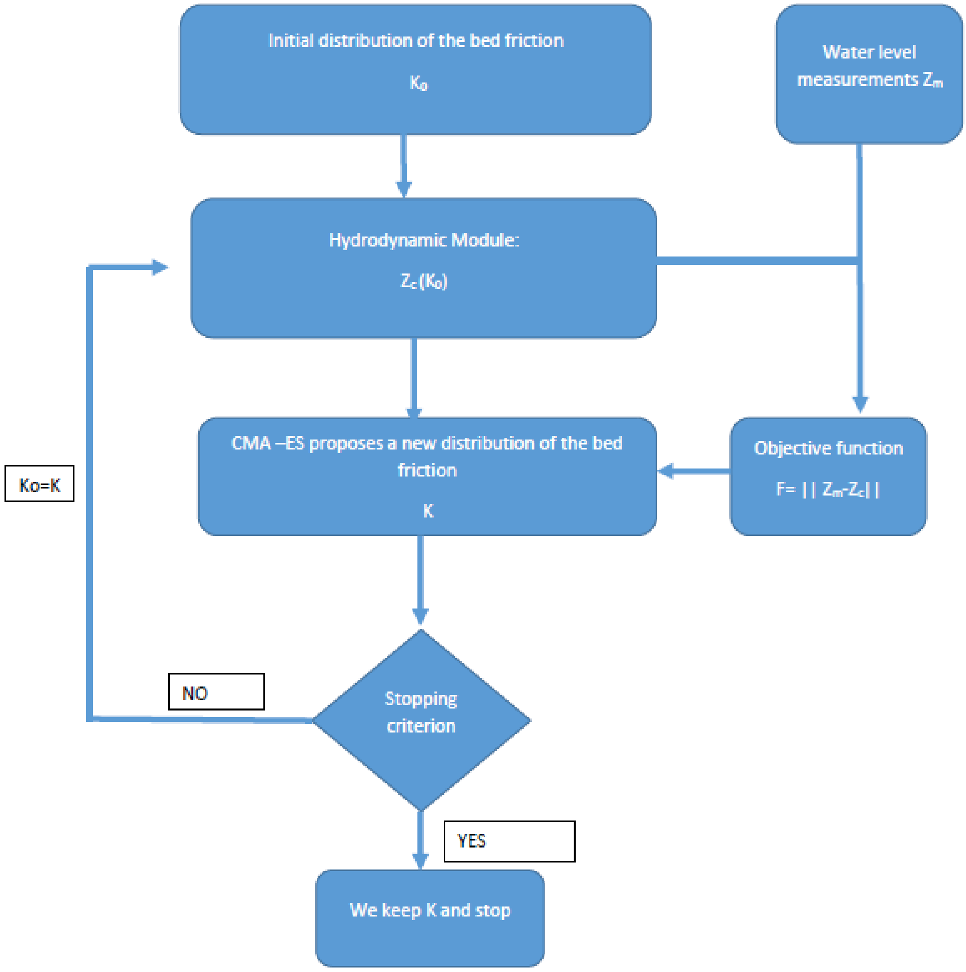
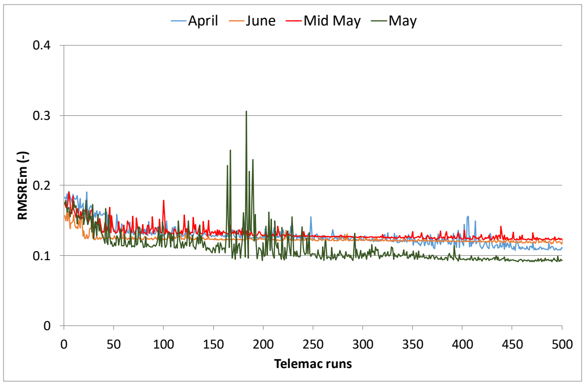
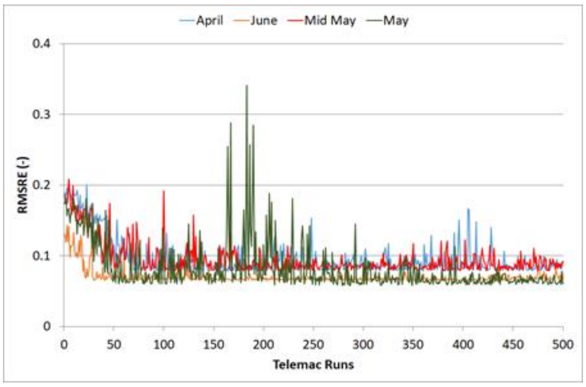


Figure 4 Flowchart of the coupling between the hydrodynamics module and the optimization algorithm

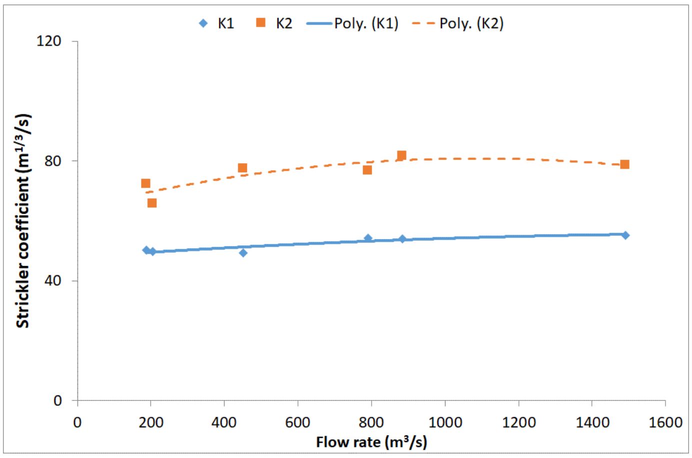


5a

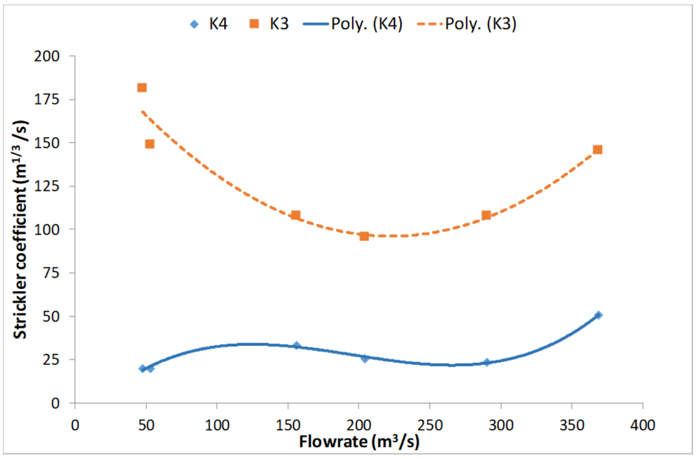


5b

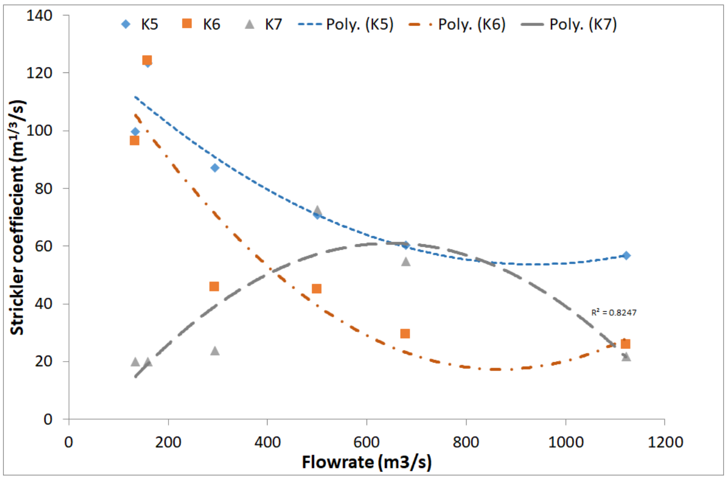
Figure 5 Convergence of the algorithm. 5a mean RMSRE for the 8 stations. 5b RSMRE at Pauillac



6a



6b



6c

Figure 6 Evolution of the values for friction coefficient according to the total flowrate (Garonne and Dordogne). 6a in the central part with 7 zones distribution. 6b Distribution in the Garonne with 7 zones distribution. 6c in the Garonne for the 7 zones distribution

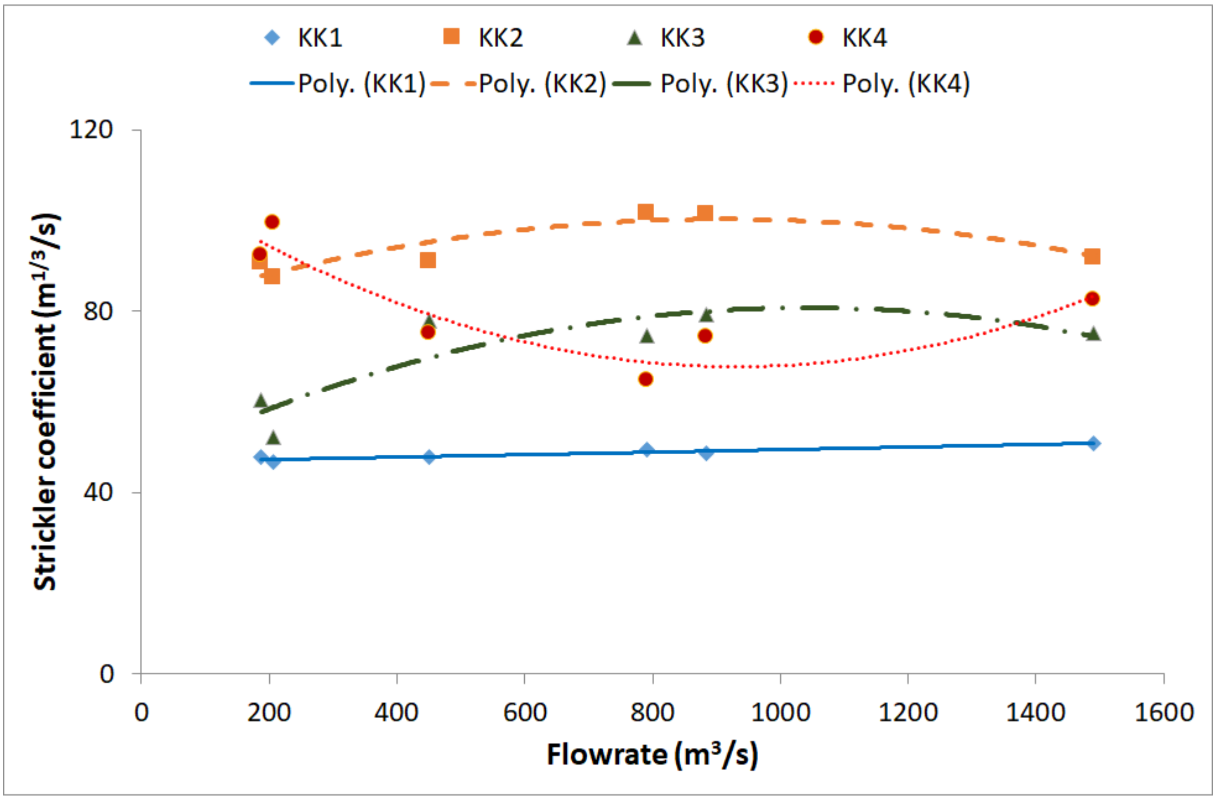
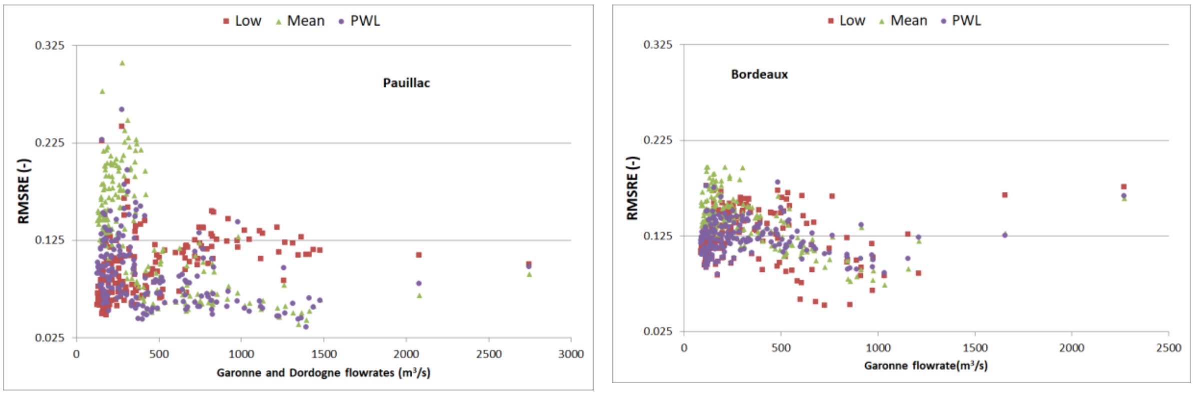


Figure 7 Evolution of the values for friction coefficient according to the flowrate in the central part with the 9 zones distribution, Strikler coefficients are noted as KK to distinguish them from the 7 zones distribution.



8a 8b

Figure 8. Evolution of the daily RMSRE with the flowrate at Pauillac (8a) and Bordeaux (8b). Daily tidal range are using to estimate the relative accuracy. Flowrate is the sum of Garonne and Dordogne contribution at Pauillac and only Garonne contribution at Bordeaux.

Table 1 RMSREm for the different configurations for different flowrate (Garonne and Dordogne contribution)

Total flowrate (m3/s)	RMSREm - 7 zones		RMSREm - 9 zones	
	Before optimization	After Optimization	Before optimization	After optimization
187	0.149	0.119	0.152	0.121
205	0.142	0.123	0.142	0.122
450	0.157	0.117	0.153	0.116
790	0.176	0.122	0.167	0.118
883	0.183	0.107	0.173	0.111
1490	0.173	0.091	0.163	0.089

Table 2 Reached RMSE for two different mesh sizes

Mesh	Mean RMSE	Verdon	Laména	Pauillac	Medoc	Ambes	Bordeaux
M1 - 28000 nodes	0.098	0.089	0.094	0.077	0.106	0.092	0.13
M2 - 76000 nodes	0.087	0.090	0.070	0.069	0.100	0.085	0.11