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Validation of a 1D simplified model of Gironde Estuary based on a database of TELEMAC simulations

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***Abstract*—Within THESEUS European project, on the one hand, an overflowing model of Gironde Estuary, based on TELEMAC software, has been used to create a database of water lines along the estuary depending on a large range of hydrometeorological situations. In this study, no breaching and no modification in the elevation of the dikes were considered in TELEMAC model. This database was then used to validate the construction of a 1D numerical model whose aim is to provide in less than one minute both water heights and propagation of tide along the Estuary.**

The model based on TELEMAC-2D was fed by several data sources, a tide signal at Le Verdon and a large range of discharges of the Garonne (at La Réole), the Dordogne (at Pessac), the Dronne (at Coutras) and the Isle (at Libourne). Simulations were led without considering any wind in the Estuary. The tide signal imposed at the mouth of the Estuary, near Le Verdon, was divided into two parts: a sinusoidal signal characterized by its amplitude added to a hydrometeorological surge level. Both amplitudes and surge levels belonged to a large physical range of values. Water levels along the axis of Gironde Estuary were then analyzed with a FFT decomposition to extract the tide amplitude and phase at each point along the axis and also to obtain the value of mean water levels.

On the second hand, a permanent 1D shallow water numerical model and a 1D numerical model of tide propagation were obtained developing shallow water equations with the assumption of Gironde Estuary having an exponential increasing width. Its results are mean water depths and tide amplitude along Gironde Estuary from Le Verdon to Ambes. Overflows are supposed to have an influence only on tide amplitudes.

Results were compared with TELEMAC database both for mean water levels along Gironde Estuary and tide amplitude. Results for mean water levels along Gironde Estuary show the necessity to complete the equations taken into account. For several hydrometeorological scenarios, the simplified tide amplitude model well represent tide amplitudes along the estuary as overflows occur.

I. INTRODUCTION

Within THESEUS European project [1], on the one hand, an overflowing model of Gironde Estuary, based on TELEMAC software, has been used to create a database of water levels along the estuary depending on a large range of hydrometeorological situations.

This database was then used to validate the construction of a 1D numerical model whose aim is to provide in less than one minute both water heights and propagation of tide along the Estuary to evaluate the efficience of mitigation options towards climate change.

II. STUDY SITE AND DESCRIPTION OF THE TELEMAC NUMERICAL MODEL

A. The study site

Gironde Estuary is the study site. To establish a database giving mean water levels and the first harmonic tide at specific locations along the Estuary, a bidimensional numerical model of Gironde Estuary based on shallow water equations has been used [2]. This model is currently integrated in the inundations repository of Gironde. It permits to test the impact of new buildings in the estuary and is based on TELEMAC-2D.

B. TELEMAC numerical model of Gironde Estuary

The model covers the entire estuary from La Réole on the Garonne River and Pessac on the Dordogne River [3]. Its maritime boundary is located at Le Verdon. Upstream, the model takes into account the flow rates of the river Isle at Libourne (at its confluence with the Dordogne River) and extents on the Isle River downstream of its confluence with the river Dronne.

The particularity of this bidimensional model is to take into account overflows from the minor bed of the rivers Dordogne, Garonne, Isle and Dronne into the floodplain. The model has 21304 finite elements and is composed of 13621 nodes. Its mesh is represented on Fig. 1 just below. It is about 115 km long from east to west.

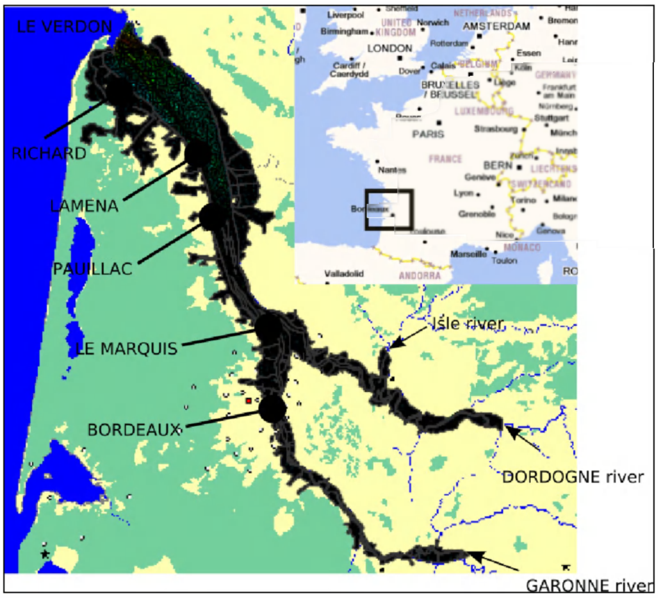

Figure 1. extension and location of the numerical model of Gironde Estuary

III. CONSTRUCTION OF A DATABASE BASED ON TELEMAC RESULTS

A. Parameters of simulaions

The model has to be fed by several kinds of data [4]:

- at the upper part of the model, the flow rates of the Garonne and the Dordogne rivers, as well as those of the Isle;
- the global signal at the maritime boundary of the model located at Le Verdon. It is the sum of two components: the predicted tide, characterized by the amplitude and the period of the signal and the meteorological surge level.

The impact of winds and pressure fields has not been considered in this study.

B. Data used for simulations

A large range of data has been used to evaluate mean water levels from Le Verdon to Bordeaux obtained with the TELEMAC numerical model.

For all simulations, flow rates of the Isle and the Dronne rivers are maintained constant, respectively equal to 37.4 and 24.6 m^3/s, which correspond to the mean discharges for these rivers.

Three flow rates have been chosen for each mean river, i.e. the Garonne and Dordogne rivers (respectively [20 m^3/s; 634.5 m^3/s; 5666.0 m^3/s] and [23.6 m^3/s; 253.10 m^3/s; 1640 m^3/s]. These values respectively correspond to the minimum, the average and the maximum discharges observed on these rivers.

Tide amplitudes at le Verdon mostly belong to the n-uplet [1.15 m; 1.30 m; 1.7 m; 1.9 m; 2.125 m]. For average flow rates of the Garonne and the Dordogne rivers, tide amplitudes were chosen between 1.15 m and 2.10 m using an increment of 0.05 m. The value of 2.125 m was also considered in this case.

The mean sea level was considered at Le Verdon. At this mean sea level was added a storm surge whose value belongs to the range [-0.1 m ; 0 m ; 0.2 m ; 0.4 m ; 0.5 m]. For the Garonne and the Dordogne rivers' average flow rates, storm surges between -0.1 m and 0.5 m were considered with an increment of 0.05 m.

The combination of those boundary conditions led to 465 simulations with the Gironde Estuary's TELEMAC-2D numerical model.

C. Extraction and analysis of results

For each simulation, TELEMAC-2D water levels were extracted at 48 nodes (24 nodes along in the Estuary, 19 along the Garonne River and 5 along the Dordogne River).

For each hydraulic scenario and each of these 48 nodes:

- the mean water level was calculated and the mean water profile along the estuary thus obtained (cf. Fig. 2 below);
- a FFT analysis was realised to obtain the tide first harmonic amplitude and its evolution along the estuary (cf. Fig. 3 below).

Fig. 2 and Fig. 3 also show mean water levels and tide amplitudes from Le Verdon to Ambès for the scenario 95, for which flow rates of Garonne and Dordogne rivers are respectively 5666 m^3/s and 1640 m^3/s, tide amplitude equals 1.9 m and the storm surge equals 0.5 m.

These results constitute the TELEMAC-2D database for mean water levels' and tide amplitude' propagation along Gironde Estuary.

In this study, this database is considered as a reference for the construction of a simplified decision support system, based on a 1D numerical model described in the following paragraphs, whose aim is to quantify effects of mitigation solutions towards climate change in a few minutes.

IV. CONSTRUCTION OF THE 1D NUMERICAL MODEL OF GIRONDE ESTUARY

A. Equations implemented in the decision support system dedicated to Gironde Estuary

Considering the following assumptions ([5]):

- the width of the estuary follows a decreasing exponential law :

$$B(\xi) = B_0\, \varepsilon\xi\pi(\xi/\beta) \quad (1)$$

where *x* is the curvilinear abscissa along Gironde Estuary (upstream to downstream), *B(x)* is the width of the estuary, *B0* the width of the Estuary at Ambès and *b* is a shape parameter characterizing Gironde Estuary.

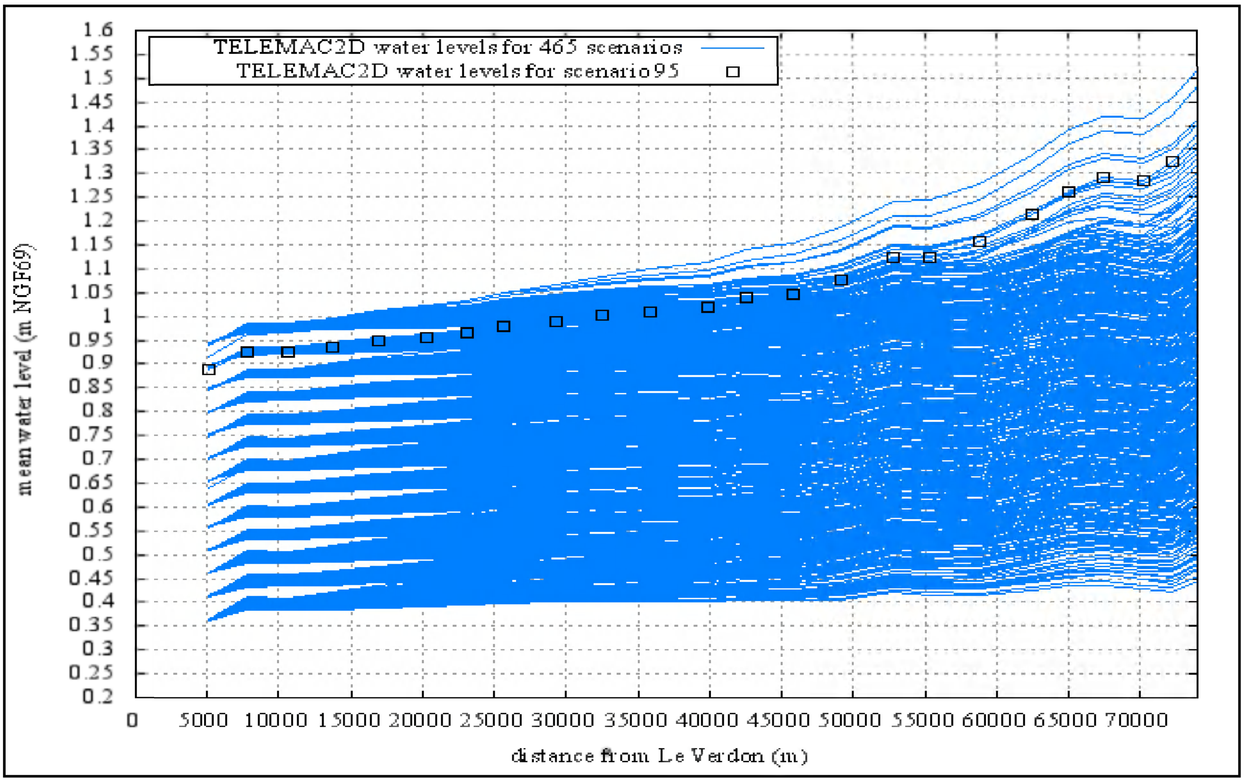

Figure 2. Water level profiles along the estuary (from Le Verdon to Ambès) for 465 hydraulic scenarios computed with TELEMAC-2D – scenario 95 constitute identification marks

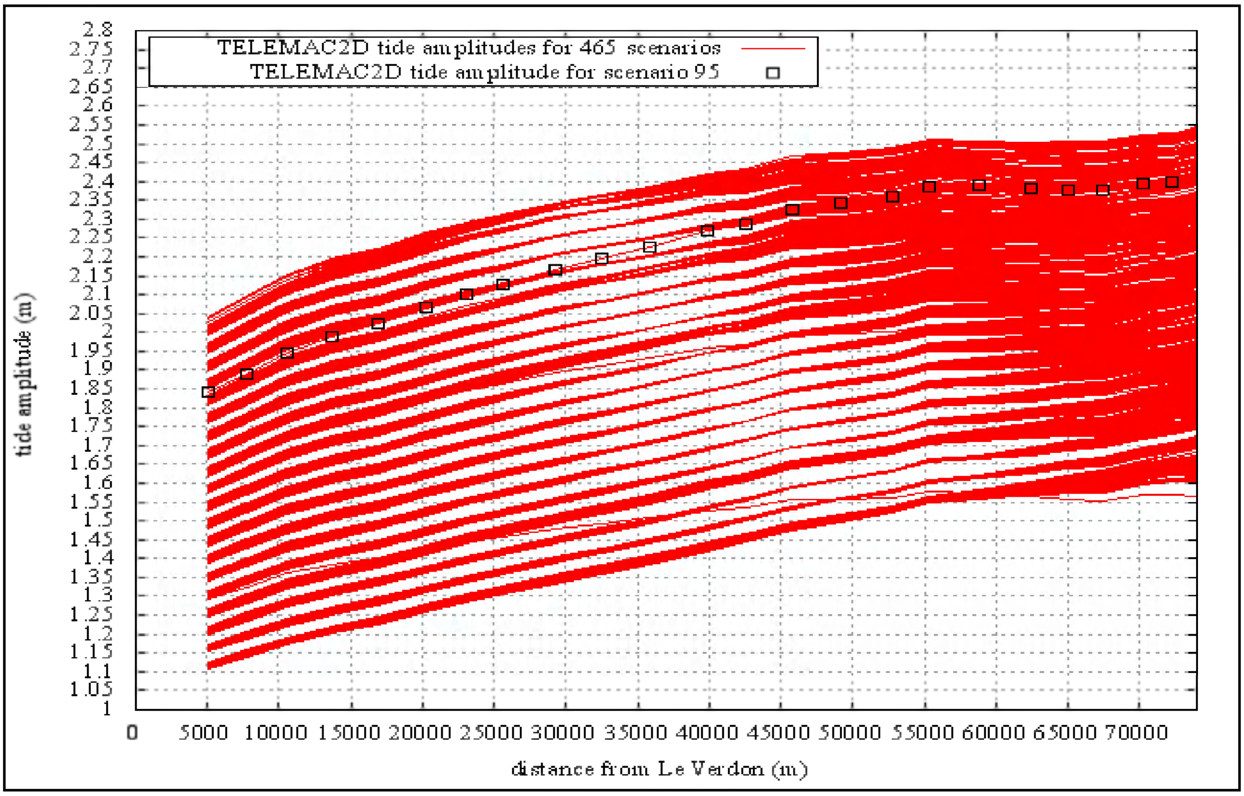

Figure 3. Tide harmonic amplitudes along the estuary (from Le Verdon to Ambès) for 465 hydraulic scenarios obtained with T2D

- the bottom of the estuary follows a 1/x law :

$$\zeta(\xi) = \zeta 0 + \delta/(\Lambda - \xi) \quad (2)$$

- where $z(x)$ is the bottom elevation at the curvilinear abscissa x, z_0 and d are constant and L is the distance between Ambès and Le Verdon,

A 1D permanent numerical model based on 1D shallow water equations and the 1D momentum equation of has then been developed in Gironde Estuary.

B. Mean Sea level

Mean water levels along the estuary are obtained with the following equation:

$$\frac{\partial h}{\partial x}(x) = \frac{\frac{-q^2}{gbh^2} + sin(\gamma) - \frac{q^2}{K^2 h^{10/3}}}{cos(\gamma) - \frac{q^2}{gh^3}} \quad (3)$$

where $h(x)$ is the water depth (m), g the gravity, γ the bottom slope (-), K the Strickler coefficient and q the averaged linear discharge (m²/s).

From Ambès to Bordeaux, the same assumptions and equations have been used, except for the bottom supposed, in this part of the estuary, to be a linear function of the curvilinear abscissa.

C. Amplitude of the first tide harmonic and overflows

To calculate tide amplitudes along the estuary, a first attempt of Fourier decomposition of water levels' and flow rates' signal has aborted.

Hence, as Fig. 3 above shows that curves representing tide amplitudes nearly remain parallel, tide amplitudes in Gironde Estuary have been calculated using an interpolation function.

In this study, it has been considered that overflows over dikes only affect tide amplitude at the curvilinear abscissa considered. If $h_1(x)$ is the tide amplitude at x and $h_2(x)$ the tide amplitude after overflows, it can be shown that:

$$\begin{aligned}\hat{h}_2(x) = \hat{h}_1(x) &- \frac{\omega}{sin(\omega T_2') - sin(\omega T_1')} \frac{V_{\text{overflow}}}{\hat{u}(x)B(x)} \\ &+ \hat{h}_1 \frac{(x)}{\omega} \left(sin(\omega T_1') - sin(\omega T_1) \right) \\ &+ (T_1' - T_1)(h(x) + z_f(x) - Z_c)\end{aligned} \quad (4)$$

where ω is the pulsation of Gironde Estuary, $V_{overflow}$ the overflowing volume and $\hat{u}(x)$ is the periodic velocity, T_1 is the time at which the initial periodic signal equals Z_c, the dike crest level; T'_1 and T'_2 have the same definition for the signal obtained after overflows.

Considering the following assumptions:

$$h = \bar{h} + \hat{h} e^{(i\omega t)} \quad (5)$$

where $\bar{h}$ is the time-averaged water depth, $\hat{h}$ is the tide first harmonic

$$q = \bar{q} + \hat{q} e^{(i\omega t)} \quad (6)$$

where $\bar{q}$ is the time-averaged flow rate, $\hat{q}$ is the flow rate first harmonic.

If $q = u \cdot h$, where u is the velocity, using the momentum equation:

$$\begin{aligned}\frac{-\partial u}{\partial t} + g\,sin(\gamma) - g\,cos(\gamma) \left(\frac{\partial \bar{h}}{\partial x} + \frac{\bar{h}}{2b} \right) \\ + \frac{B\bar{h}\,sin(\gamma)}{2} g \frac{\partial \gamma}{\partial x} = 0\end{aligned} \quad (7)$$

leads to:

$$\begin{aligned}-i\omega \hat{q}\bar{h} + -i\omega \bar{q}\hat{h} + 2g\,sin(\gamma)\bar{h}\hat{h} - 2g\,cos(\gamma)\bar{h}\hat{h}\frac{\partial \bar{h}}{\partial x} \\ -g\,cos(\gamma)\bar{h}^2 \frac{\partial \hat{h}}{\partial x} = 0\end{aligned} \quad (8)$$

Neglecting bottom friction and convection gives:

$$\begin{aligned}+g\,sin(\gamma) - g\,cos(\gamma)\frac{\partial \bar{h}}{\partial x} = 0 \\ \frac{\partial \bar{h}}{\partial x} = tan(\gamma)\end{aligned} \quad (9)$$

Injecting (9) in (8) gives:

$$\frac{\partial h}{\partial x} + \frac{i\omega}{g\,cos(\gamma)} \frac{\hat{q}}{\bar{h}} - \frac{i\omega}{g\,cos(\gamma)} \frac{\bar{q}}{\bar{h}^2} \hat{h} = 0 \quad (10)$$

and

$$\frac{\partial \bar{q}}{\partial x} - \frac{\bar{q}}{b} = 0$$

with

$$\frac{\partial \hat{q}}{\partial x} - \frac{\hat{q}}{b} + i\omega \hat{h} = 0 \quad (11)$$

Finally,

$$|\hat{u}| = \frac{1}{\bar{h}}|\hat{q} - \bar{u}\hat{h}| \tag{12}$$

can be obtained by solving the following linear set of equations:

$$\frac{\partial X}{\partial x} = \begin{bmatrix} 0 & -\frac{\bar{q}}{\bar{h}}\frac{\omega}{g\,cos(\gamma)\bar{h}} & 0 & \frac{\omega}{g\,cos(\gamma)\bar{h}} \\ \frac{\bar{q}}{\bar{h}}\frac{\omega}{g\,cos(\gamma)\bar{h}} & 0 & -\frac{\omega}{g\,cos(\gamma)\bar{h}} & 0 \\ 0 & \omega & \frac{1}{b} & 0 \\ -\omega & 0 & 0 & \frac{1}{b} \end{bmatrix} .X \tag{13}$$

with:

$$X = \begin{bmatrix} \Re(\hat{h}) \\ \Im(\hat{h}) \\ \Re(\hat{q}) \\ \Im(\hat{q}) \end{bmatrix} \tag{14}$$

Overflows are calculated using the usual weir expression:

$$q_{\text{overflowing}}(x) = \mu\,(h(x,t))^{\frac{3}{2}}\,(2g)^{0.5} \tag{15}$$

where $q_{overflowing}(x)$ is the overflowing flow rate above dikes at x and μ is a flow rate coefficient.

V. VALIDATION OF THE 1D NUMERICAL MODEL OF GIRONDE ESTUARY

A. Mean sea levels

Absolute errors on mean water levels between the results obtained with the simplified model and the TELEMAC-2D database are represented on Fig. 4.

Even after the calibration of the model, the maximum absolute error is still about 30 cm at Ambès, with a mean absolute error which equals 15 cm. Nevertheless, the distribution of scenarios gives a predominant weight to hydraulic situations where the flow rate of the Garonne River equals 634.5 m^3/s. However, it appears that for this range the calibration of a part of scenarios has negative impacts on the results obtained with other scenarios.

Moreover, in the maritime part of the Estuary, the influence of tide on mean sea levels should be considered ; this is not the case here, where water level have been divided into a mean water level and a periodic signal.

Fig. 5 below represents absolute errors between the simplified model and the database from Bordeaux to Ambès, using the exact mean water level at Ambès.

The maximum absolute error is less than 0.15 m at Bordeaux, which would be quite acceptable. Ttherefore it is necessary to improve results in the maritime part of the estuary. Indeed, the propagation of the error calculated by the model from Le Verdon to Ambès leads to errors between -0.30 m and 0.30 m at Bordeaux, even after a global calibration.

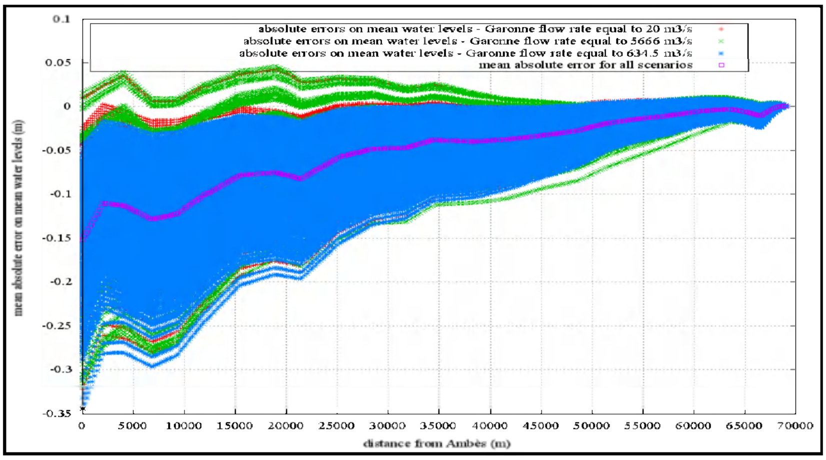

Figure 4. Absolute mean error on time-averaged water levels between the simplified model and TELEMAC-2D results from Le Verdon to Ambès

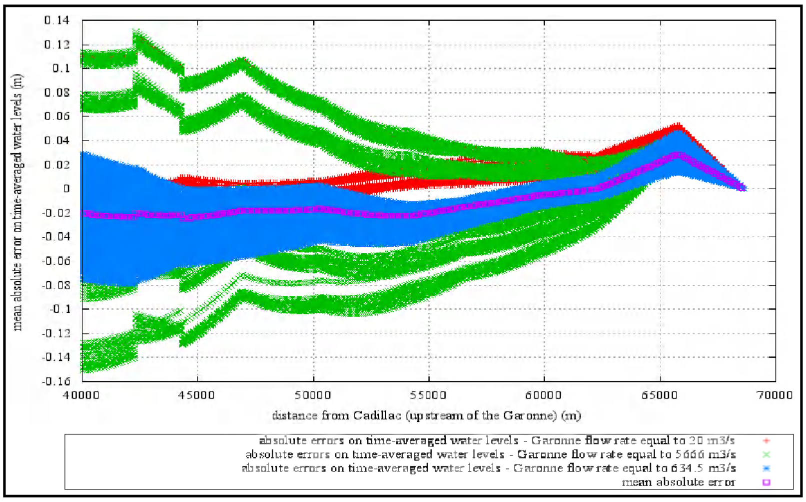

Figure 5. Absolute mean error on time-averaged water levels between the simplified model and TELEMAC-2D results from Bordeaux (x=44000 m) to Ambès (x=68000 m)

B. Tide amplitude and overflows

The flow rate coefficient has been calibrated and tide amplitude has been calculated for scenario 95 described in § III.C.

Fig. 6 represents both tide amplitudes along Gironde Estuary obtained with the simplified model in which overflows have been implemented and obtained with TELEMAC-2D for scenario95.

In this case, differences are less than 0.10 m.

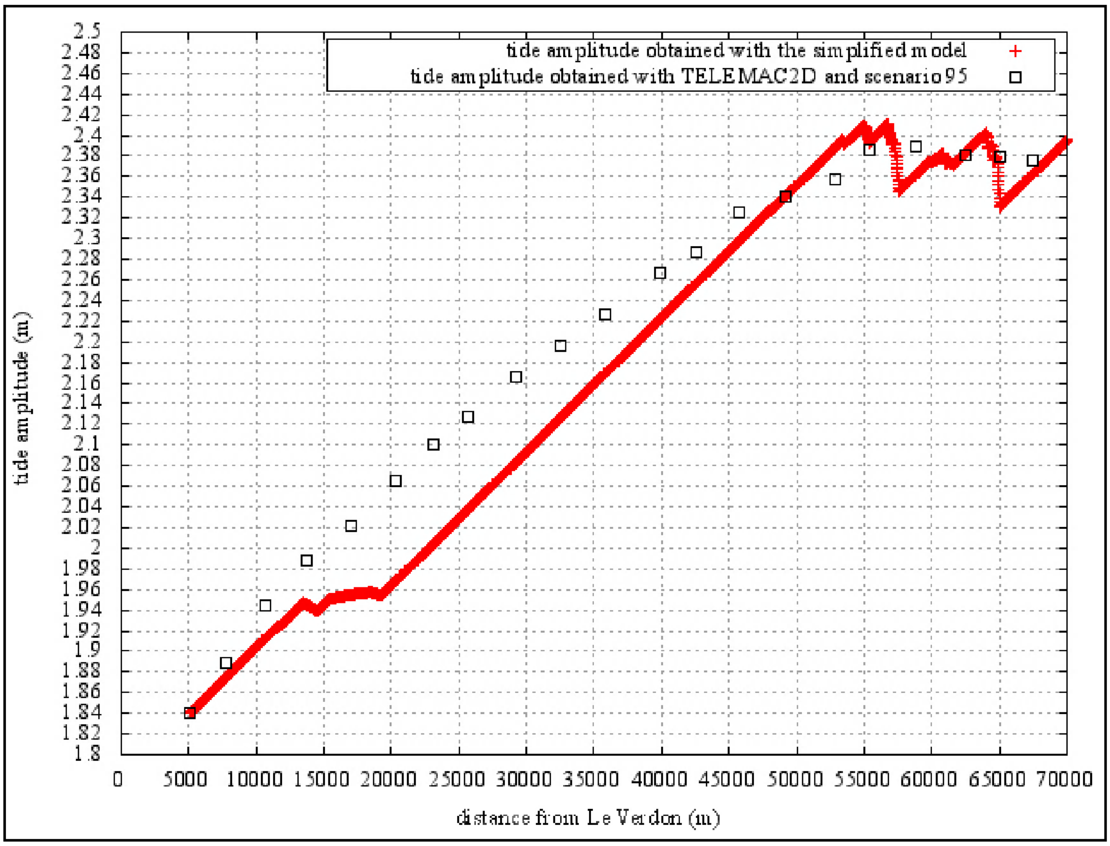

Figure 6. Tide amplitude obtained with the simplified model of Gironde Estuary (in red) and with TELEMAC-2D (black points) for scenario 95

VI. Conclusions and Perspectives

A simplified numerical model to calculate the propagation of water levels and tide amplitudes along Gironde Estuary has been developed and compared with a database provided by a 2D numerical model based on TELEMAC2D.

Concerning mean water levels along Gironde Estuary, differences are between 0 and -0.30 m at Ambès with a mean absolute error of 0.15 m. Therefore, results have to be improved not to propagate such a high error to Bordeaux. At Bordeaux, considering the TELEMAC-2D value at Ambès, differences between the simplified model and the database are less than 15 cm, which is quite acceptable, in light of the many assumptions that were made.

For several hydrometeorological scenarios, the simplified tide amplitude model well represent tide amplitudes along the estuary as overflows occur. The results and the methodology have to be applied to all scenarios.

Acknowledgement

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