Conference Paper, Published Version

**Coulet, Christophe; Mensencal, Yvon**

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Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/104287

Vorgeschlagene Zitierweise/Suggested citation:
Coulet, Christophe; Mensencal, Yvon (2012): Determination of marine risk by hydraulic coastal modelling – Application to Charente-Maritime coast. In: Bourban, Sébastien; Durand, Noémie; Hervouet, Jean-Michel (Hg.): Proceedings of the XIXth TELEMAC-MASCARET User
Conference 2012, 18 to 19 October 2012, St Hugh's College,
Oxford. Oxfordshire: HR Wallingford. S. 71-80.

# Determination of marine risk by hydraulic coastal modelling – Application to Charente-Maritime coast

Christophe COULET, Yvon MENSENCAL
Hydraulic Modelling and Software team
ARTELIA Water & Environment
Merignac, France
christophe.coulet@arteliagroup.com
yvon.mensencal@arteliagroup.com

*Abstract*— **In 2010, on February 28th, Storm Xynthia strikes Europe causing the death of 53 people in France and €1,4 billion damages mainly on the Atlantic coast. Charente-Maritime was highly impacted by this event, which covered 300 km of coasts. In this region alone, Xynthia caused 12 deaths, 4 800 flooded houses, 900 shellfish industries injured and 793 firms in trouble after the storm, 120 km of dikes damaged, 40 km of flooded roads and 232 km$^2$ of flooded area on the continent and on the islands of Oléron, Ré and Aix.**

**Despite, it has been demonstrate that the storm in itself was not a statistically exceptional event. The dramatic context is induced by the concomitant phenomenon of high spring tide and surge of sea level due to meteorological conditions.**

**In order to anticipate and assist stakeholders for the management of this kind of risk, including a potential increase due to climate change and sea level rise, we have built an efficient operational model of surge propagation on the Atlantic Ocean up to the coastal area and inland area. The exchanges at the coast are managed at the dikes scale and can take in account the breaches and the overtopping of waves. The methodology and the first results will be presented and discussed in regards of potential requirements for the needs in crisis preparedness and management of the Stakeholders.**

## I. INTRODUCTION

The events over the last decade (Martin in 1999, Klaus in 2000 and Xynthia in 2010) and the consequences of climate change on these phenomena lead decision makers to examine accurately the risk of marine submersion.

Marine or coastal flooding are generated by a combination of different factors linked for some and independent for others. Thus we could consider that these submersions are derived from the crossing of the statistical level to the coast, the swell at the coast and coastal protection system.

The water level at the coast consists of:

- The evolution of the astronomical tide.
- A chronicle of positive and negative surges off the coast, mainly generated by the anticyclones and depressions.
- The action of wind on the water.
- The action of the swell on tidal currents (set-up phenomenon).

The combination of all these parameters generates static water level at the coast. If this level is higher than the crest level of protections, a flooding by overflow protection is observed. This phenomenon is similar to the River overflow over the dikes of a river. The protections structures even not initially designed for this, are submitted to high stress, which often results in the appearance of breaches, or sometimes the complete destruction of an important linear of protection.

The swell at the coast is the result of the influence of:

- The swell offshore,
- The action of wind on the water.
- The influence of the water level (and associated water Heights) and tidal currents.

The swell at the Coast causes overflows above protections, without the static water level not necessarily above the crest level of the protection. This overflow by "packet of sea" is also called "overtopping".

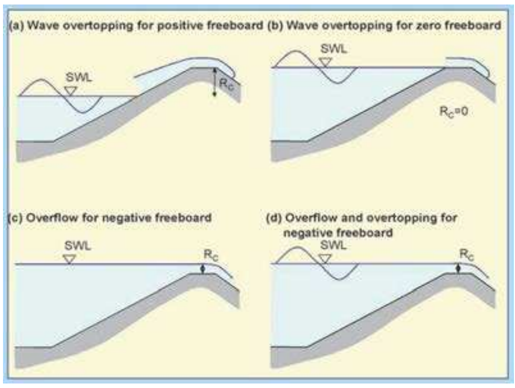

Figure 1. Visualization of the modes of crossing of a dike (sources [2]).

Fine representation of the phenomena of flooding using a modeling tool therefore requires the perfect representation of all of the factors described earlier to approach to the best of the physical reality of the phenomenon to study.

The extent of these territories and the complexity resulting from road networks and drainage networks as well as the protective devices make 2D models the best suited tools for the study these territories in the event of flooding.

TELEMAC-2D allows the calculation of free surface flows in such configurations [1] spread the flood initially dry areas corresponding to the terrestrial part of the study located behind the protection systems. In addition, the fact that it is based on a non-structured triangular mesh to represent all the structures (roads, ditches, dikes,...) by local refinement without forcing the size of mesh in the other sectors (in particular the marine area) and so therefore without increasing significantly the number of nodes. Finally, for some cases that require too great refinement of the mesh in relation to the problem posed (it is the case of dikes located in the interface of marine part and the terrestrial part), access to the sources allows the development of specific features such as:

- The computation of the flow in the drainage networks with the possibility to represent the valves and the sluice gates;
- The computation of the overflow on dikes (taken into account faithfully in the form of an exchange flow calculated at the scale of topographic survey);
- The wave overtopping on the dikes (with the same finesse of description).

Charente-Maritime coast located on the west coast of France, face to the Atlantic Ocean has largely been affected during the recent storms and Xynthia particularly in February 2010 (53 deaths and 1.4 billion € of damages in France). The consequences of this storm in this region (12 deaths, 4 800 flooded houses, 900 shellfish industries injured and 793 firm in trouble after the storm, 120 km of dikes damaged, 40 km of flooded roads and 232 km2 of flooded area) led the Greater La Rochelle (CDA) and the Territorial Collectivities of the Charente-Maritime (DDTM 17) to launch a study to determine the risk of marine submersion on a part of its territory.

## II. AREA MODELLED

The modelled area is defined by hydraulic criteria (topographic for the land part). All the territory of the CDA potentially flooded for the most pessimistic configuration to study is integrated in the model.

### A. *Marine area*

The outline is located about 80 km off the coast from the mouth of the Charente, beyond the bathymetric level - 50.0 m NGF IGN69.

The northern boundary is located at the level of the Sables D'olonne in Vendée and the southern boundary at the level of Vendays-Montalivet, along the Aquitaine coast, in Gironde.

All the ocean coast of the Poitou-Charentes region is thus covered by this model.

The main rivers are integrated in the model. It's the Lay, the Sèvre Niortaise, the Charente, the Seudre, the Garonne and the Dordogne which form the Gironde estuary just below Ambès.

This choice ensures that the various hydrodynamic phenomena are properly represented by the model and in particular the influence of fluctuating volumes of these rivers on the hydrodynamics of the Pertuis.

### B. *Land area*

This area is essentially based on the level 6.0 m NGF in order to integrate all the places under the maximum water level potentially reached by an event.

Taking into account this limit involves a mesh on very large areas, especially on the North and South of the territory of the CDA. These areas, bordering the Charente and Sèvre Niortaise estuaries are large marsh areas which were in the past the outlets of these rivers.

Fig. 2 illustrates the model area.

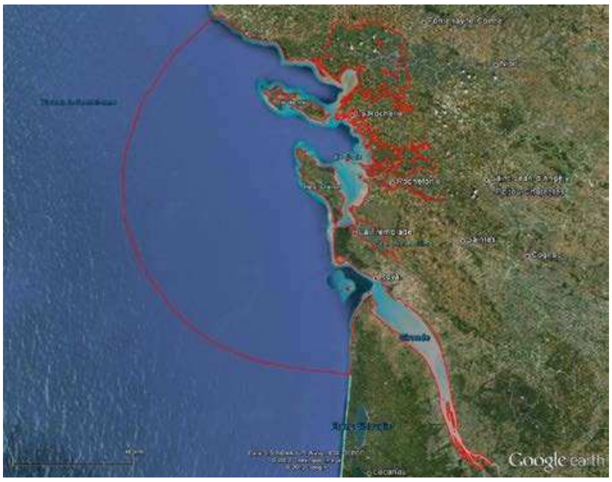

Figure 2. The modelled area.

### C. *The mesh: schematic representation of reality*

The mesh is a schematic representation of reality. Because of this mapping, its construction is an essential step in the realization of a hydraulic model study. It is essential that the mesh incorporates and represents the most accurately the reality of the land, and specifically at the level of structuring elements. These elements consist of particularities which have locally an influence on the behaviour of flows. On the area of study, structuring elements are many and various. Their treatment and how to represent them in the models are detailed in the following paragraphs.

*1) Embankments and dykes:* The representation of embankments and dykes requires good representation of the role of obstruction to the flow and their possibly submersible character. To do this, it is necessary to represent properly and jointly the altimetry of the foot of dikes and the top (crest).

Two principles are used to this, depending on the size of the obstacle and the vertical heterogeneity of its crest:

- The first is to integrate the obstacle in the mesh,
- The second is to represent the obstacle in the form of two boundaries of the model and to calculate the flow eventually overflowing on the obstacle with the "classics" hydraulics laws (weir law). For coastal levees, the calculation of those overflows also integrates the characteristics of wave to determine the flow generated by the phenomenon of overtopping.

This second method was chosen to represent the whole coastal dikes on the modelled area. It has the advantage to be able to integrate the vertical representation of the crest of the embankment at a small than the mesh size.

For example, topographic survey of the protections dikes has an average spacing between the points identified in 50 m approximately. It was fully taken into account in the model. This method allows representing the flow that passes on a low point of protection, whatever its width, without requiring the refinement of the mesh on this particular sector.

Note that the walls in the floodplain were not represented in the model; these elements have no vocation to protect against overflows.

*2) Buildings:* It was the choice for this study to not represent buildings existing in the study area.

It should however be noticed that buildings can play a role of barrier for the local progression of flows in dense urban areas. This detailed analysis is not compatible with the study area and thus with the resolution of the model scale implemented here.

*3) Lakes and gravel pits:* Large gravel pits and lakes were represented in the models. However, there is not always information on the bathymetry of these areas. Therefore, the bottom level in these sectors was assumed from our land investigations and our knowledge of the sector.

*4) Drying network and hydraulic works:* The main drying system (ditches, canals...) is integrated in the model.

The lack of bathymetric information on these sectors has led us to use standard hydraulic sections and to impose an assumed bottom level for this network. The bottom level has been selected based on our expertise combined with the survey available on the hydraulic works of this network.

An initial water level is imposed in the drying system, level which is lower than the overflow level of these rivers and which can be locally depending on reports made by people met during the on-site visit.

Main hydraulic works, and particularly works downstream of this network, have been incorporated in the model. The functioning of specific works (valves, sluice gate...) is also integrated in the computations.

The secondary network (ditches...) is not include in the model, but its outlets are however integrated. The outlet works is connected to the low point behind the protection, which means that the transfer of water from the low area to the sea is not represented by the model but the emptying of low points is achieved through those outlets.

The storm network is not represented in the model. The main existing outfalls on the urban area are however integrated to represent the drain from the low areas of the floodplain.

The model should determine the water hazards (levels and maximum heights of water). However, the methodology used to build the model allows the representation of the post-event period and the emptying of the flooded areas.

*5) Characteristics of the mesh:* The mesh of the model consists of 163 200 nodes and 315 500 triangular elements.

The maritime part is composed of approximately 23 600 nodes and 44 360 elements.

For the terrestrial part, the mesh sizes range from 25 m along the coast up to 100-250 m in the distant marshes. It can reach 800 m in the marshes of Vendée (North of the Sèvre Niortaise), areas that were simply modelled to dispose of the potential interactions over the dike of the “Canal des 5 Abbés”.

The maritime mesh size varies from 5 km off within 300 m between the Islands and the coast. At the level of the Pertuis Breton and Maumusson, the mesh size is around 100 m, Fig. 3.

The maritime mesh has been forced to properly represent the hydraulic sections of numerous channels and banks existing on this sector. This method allows the perfect representation of the effect of channel flows observed at the level of the Pertuis.

*6) Bathymetry and topography:* The bathymetry of the maritime part of the model is taken from SHOM maps available on the sector.

The topography of the land part of the model is the interpretation and the exploitation of a recent LIDAR survey of study. The topography of the crest of protection dikes comes from a topographic survey achieved after Storm Xynthia. These data have been changed during the calibration to best match to the altimetry of existing dikes during Storm Xynthia, which were for the most part lower than present because of the emergency work made after the event.

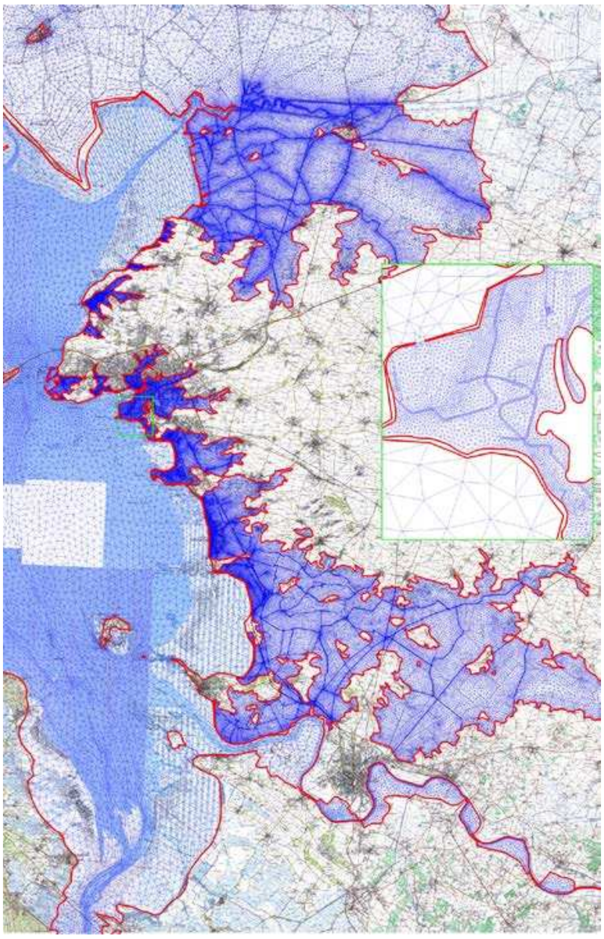

Figure 3. Mesh of the model.

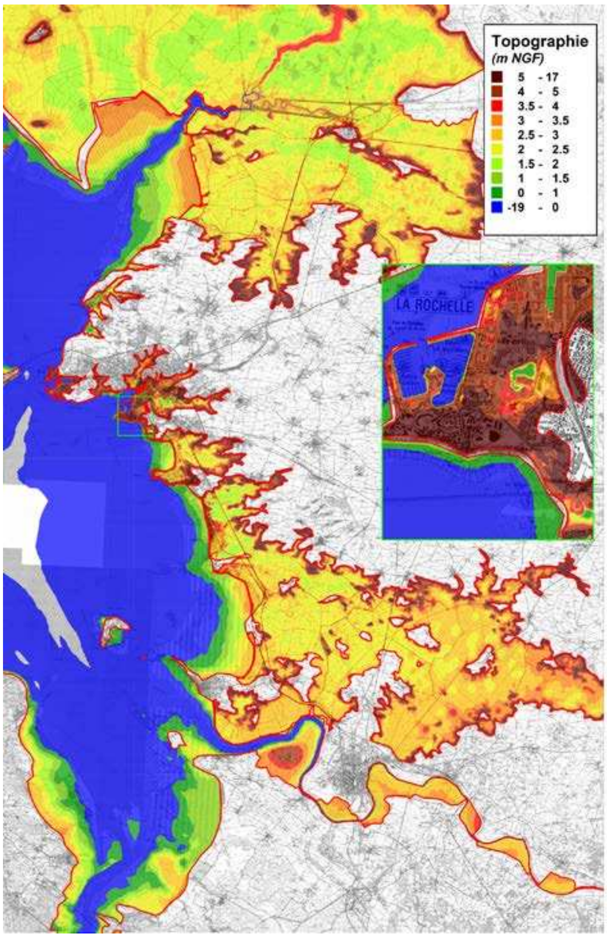

Figure 4. Bathymetry and topography of the model.

Fig. 4 shows the representation of the topography and bathymetry of the study.

## III. Implementation of the computation

Flooding taking into account swell but there is no interest to calculate it on the terrestrial part of the model, so we choice to separate TELEMAC 2D and TOMAWAC computations. We have therefore extracted the marine part of the model to calculate swell only on this area.

This quite light "submodel" in comparison with the global model allow us to calculate the swell conditions fairly quick. However, to take into account all of the phenomena a first hydrodynamic calculation taking into account the tide, the atmospheric set-up and the wind is made with TELEMAC-2D. The TOMAWAC computation uses this result to take into account the effects of currents. The results obtained (wave height, period, direction and the stress radiation) are projected on the global model. On the land area, the swell result is set to 0.

TELEMAC-2D "definitive" calculation can then be carried out. The result TOMAWAC (height, period and direction) is taken into account in the calculation of the overtopping of coastal protection dikes. Stress radiation allows taking in account the swell currents in the hydrodynamics.

## IV. Calibration of the model

### *A. Calibration of the oceanic part for normal tide conditions*

The hydrodynamic model is first calibrated using level and speed data on the maritime part for "normal" events, Fig. 5. That is to say with no specific hydro-meteorological conditions (storm surge, wind...).

This calibration is made by comparison between water level evolution provided by the hydrodynamic model for an astronomical tide cycle in the different gauges of the study area and predictions provided by SHOM for these same tide gauges.

This comparison is made on 19 days, from 20th February to 11th March 2010, in order to cover the whole tidal conditions that can be encountered within the study area.

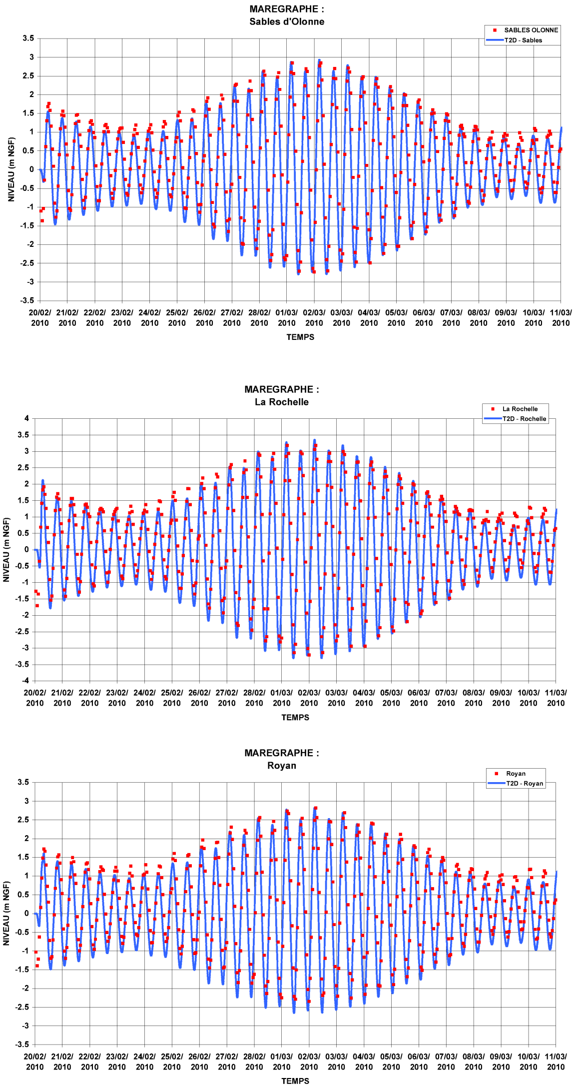

Figure 5. Comparison of the evolution of water levels given by the hydrodynamic model and those predicted by SHOM.

It is reminded here that simulated tides, as predictions of SHOM, correspond to the theoretical astronomical tides. The weather parameters that have an influence on observed actual tides (winds and atmospheric pressure which generate positive and negative surge at the large scale of the Bay of Biscay) are not represented by this simulation.

Indeed, the timing period incorporates the dates of occurrence of Storm Xynthia. Predicted level of tide on tide gauges and reproduced in the model are well below the levels found during the storm due to storm surge. However this does not change the validity of the model for the good representation of current in the area.

The evolution of the theoretical water level provided by the model is very close to that predicted by SHOM in amplitude and levels of high and low tide but also on the phasing of the tidal wave.

Velocities data (direction and intensity) for the characteristic tides (high and neap) which are available on SHOM maps on the area of study, Fig. 6, are also compared to the results provided by the model for the velocity of tidal currents.

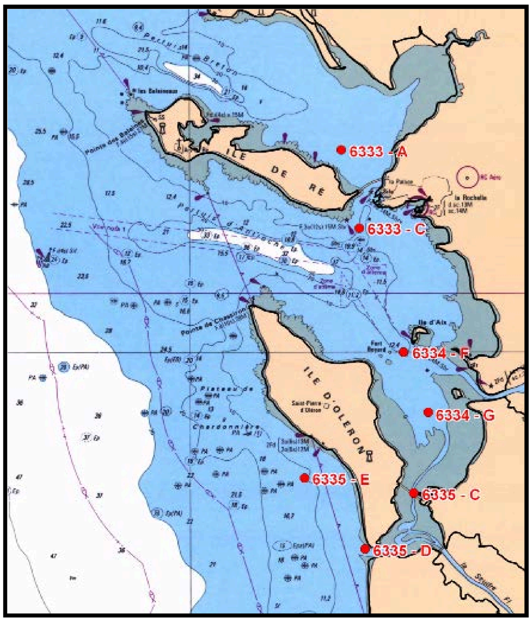

Figure 6. Location of SHOM points with velocities informations.

These comparisons are presented in Fig. 7. The lines correspond to the results of computation and points to the data provided by SHOM.

Note that SHOM provides velocities values in knots (integer values). These data correspond to velocities near the surface (problem of navigation). This generates some difficulties to compare that information with modelling (The velocities are integrated on the water column). Surface velocities are generally higher than the mean velocities.

This comparison shows that the model calculates tidal velocities similar to those provided by SHOM, in order of velocity magnitude as well as in direction.

The hydrodynamic model for its maritime part is able to reproduce the hydrodynamic phenomena associated with the tides for the "common" maritime events.

### B. *Calibration for events which generate significant levels of water*

*1) Storm Martin:* It was firstly achieved a calibration of the model in comparison to the information available for Storm Martin (December 27th 1999). The collected data are only for the maritime part of the study area.

For this comparison, the influence of the chronicles of winds and also the positive surge due to atmospheric low pressure (37 cm maximum) was imposed in addition to the representation of the astronomical tide.

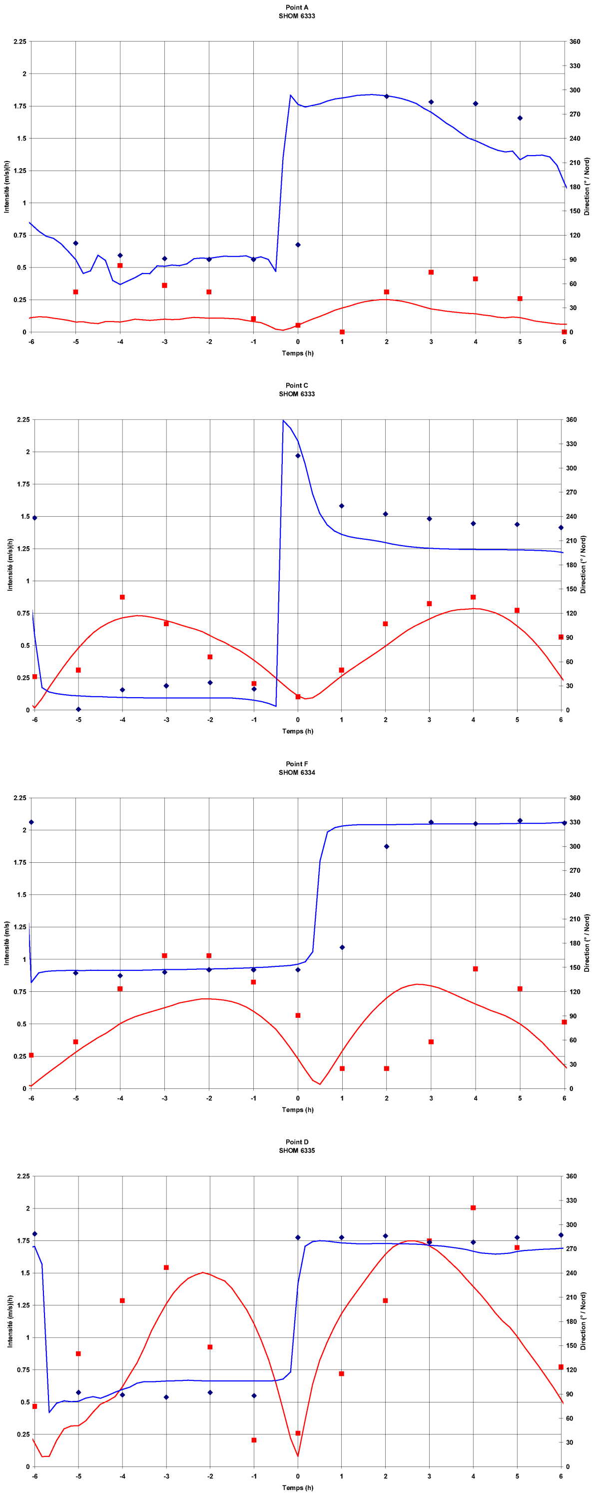

Figure 7. Comparison of calculated velocities and values provided by SHOM.

The swell was not considered for this computation due to the lack of information.

Fig. 8 shows the comparison of the observed and calculated water levels for Storm Martin. The maximum observed level was also drawn to counterbalance the lack of measurement at the peak of tide (December 27$^{th}$).

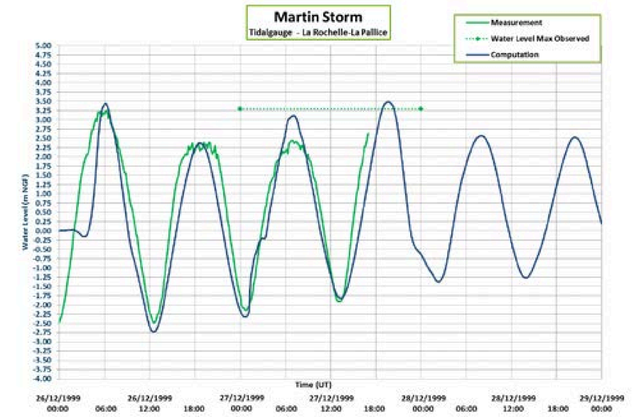

Figure 8. Storm Martin– Comparison at La Rochelle.

Without more information about this event, it is difficult to determine the representativeness of the model. Nevertheless, calculated water levels are consistent with estimation of maximum levels on the sector of La Rochelle.

2) *Storm Xynthia:*

a) *Astronomical tide:* February 2$^{nd}$ 2010 was a high spring tide. The theoretical high tide level at La Rochelle - La Pallice, was 2.99 m NGF (against about 4.50 m NGF reached during Storm Xynthia).

For this tide, hydrodynamic 2D model implemented in this study allows to represent the evolution of the theoretical tide, on magnitude and phase. This comparison between theoretical tide provided by SHOM and computed by the model is presented in Fig. 9:

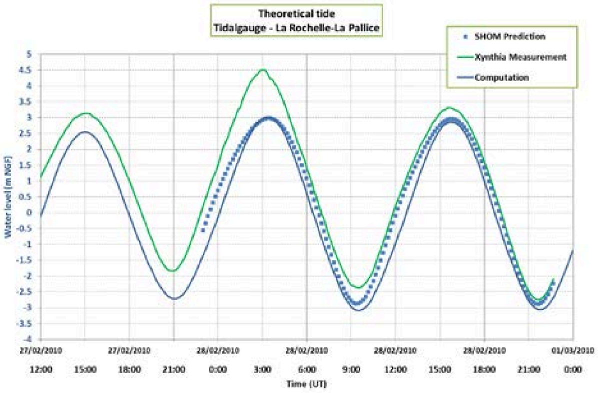

Figure 9. Storm Xynthia - Astronomical tide – Comparison at La Rochelle.

The following graph shows the comparison between the evolution of the theoretical tidal provided by SHOM and those calculated by the 2D model at Rochefort. The evolution of the water level recorded by the tide gauge for Storm Xynthia is also on this chart. The tide gauge is located in the Charente estuary, which explains the characteristic shape of the tidal wave which is observed. For this sector, the 2D model is less accurate, particularly on the phasing of the tidal wave. High levels are however correctly approached.

This is explained by:

- Schematic representation of the channel of the Charente, which leads to an error on the representation of the oscillating volume at this level. This error generates a delay between the moments of high and low tide in comparison to the predictions.
- The imposition of a constant discharge of the Charente. This discharge is higher than the discharge considered for the calculation of the predictions of SHOM. This explains the low tide levels calculated higher than those predicted.

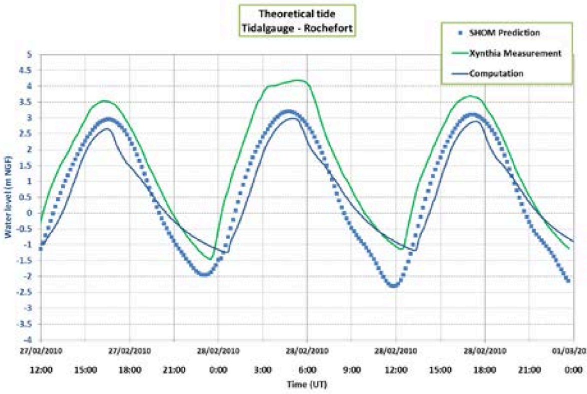

Figure 10. Storm Xynthia - Astronomical tide – Comparison at Rochefort.

The following graph shows the comparison of the evolution of water levels predicted by SHOM and calculated by the 2D model for the astronomical tide at the tide gauge of Le Verdon, at the mouth of the Gironde estuary. For this tide gauge, the model perfectly represents the evolution of the theoretical tide.

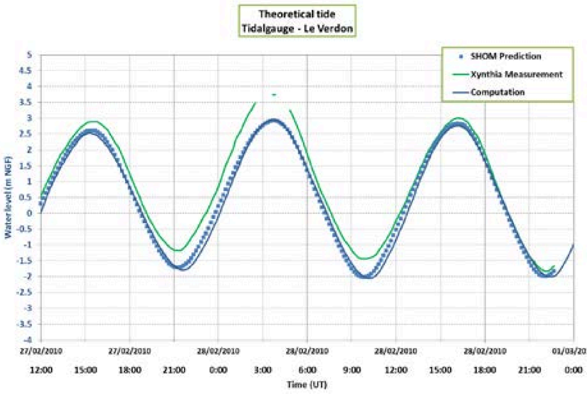

Figure 11. Storm Xynthia - Astronomical tide – Comparison at Le Verdon.

This analysis allows us to validate the representation by the model of astronomical tide on Charente-Maritime coast. We notice that the model represents less accurately the evolution of the tide in the estuary of the Charente, on an area which is outside of the main area of this study.

*b) Atmospheric surge:* To represent the real event as it has been observed, some hydro-meteorological parameters have been incorporated into the model. The first of them is the representation of the time evolution of the surge offshore. This positive (or negative according to the moments) surge, is characterized by the evolution in time of the mean sea level around which the astronomical tide oscillates. This variation of the mean level is mainly generated by the succession of low and high pressure area.

The chronicle of the imposed surge is determined by the method of inverse barometer: considering a rise in the average level of 1 cm for a decrease of 1hPa of the pressure at sea level. The evolution of the atmospheric pressure at La Rochelle during the passage Xynthia is used for this. A shift of 2 h is imposed to take in account the distance between the ocean limit of the model and La Rochelle (the propagation time of the storm). This method involves the imposition of a maximum surge around 50 cm offshore. This is illustrated in the following chart where the surge calculated at the level of the tide gauge of La Rochelle is also represented. There is no phenomenon of amplification of the surge offshore as a consequence of the bathymetry near the coast.

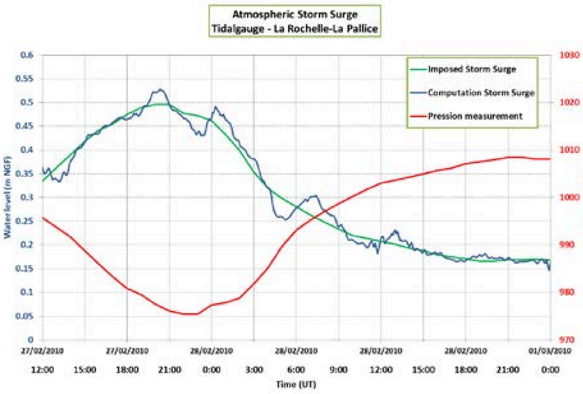

Figure 12. Storm Xynthia – Atmospheric surge.

*c) Winds:* The second parameter for the representation of the real event is the influence of wind on water. In this study, we impose a wind variable in time (intensity and direction) and uniform in space.

The influence of the wind is only considered on the maritime part of the model.

The chronicle of wind imposed has been defined by analysis of records available at the stations of Chassiron (Oléron Island).

The imposition of this wind chronicle on the maritime part gives a maximum positive surge around 1 m at La Rochelle - La Pallice.

*d) Swells:* The third parameter integrated in the model of Storm Xynthia is the influence of the swell on:

- The currents in the maritime part,

- The overtopping of the protections that flood the land areas.

The model built for this study takes into consideration in a couple ways, the influence of the swell on tidal currents that generate the set - up and the influence of tidal currents on the swell propagation.

The swell computed by TOMAWAC and imposed in the TELEMAC-2D (direction, period, and significant wave height) was calibrated to properly represent the data from SHOM swell buoy located offshore of Oléron island. This is illustrated in Fig. 13.

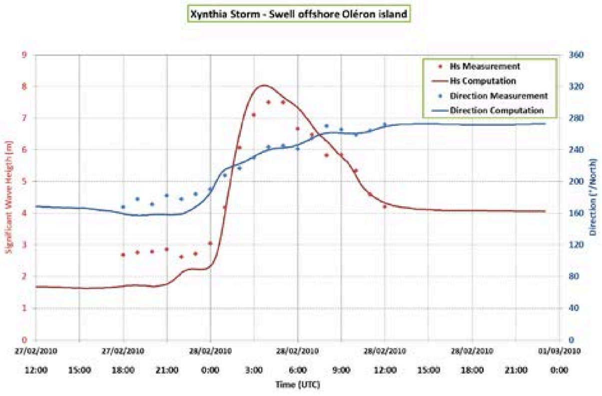

Figure 13. Storm Xynthia – Swell.

The maximum positive surge due to the consideration of the swell in hydrodynamic calculations is around 22 cm at La Rochelle - La Pallice. This maximum surge is observed 4 hours after the peak of the event, during the ebb. We could note that the swell then generates a negative surge of 15 cm up to 8 hours after the peak of Xynthia.

*e) Maximum water levels at the tige gauges:* The following figures present comparison at the tide gauges of La Rochelle - La Pallice, Rochefort, Le Verdon, La Cotinière and Royan, between the records during this storm and the results of model integrating the astronomical tide and the influences of the surge offshore, the wind and the swell. The theoretical tidal obtained with the 2D on the same period model is also draw to illustrate the importance of surges generated at the coast for the hydro meteorological parameters associated with this storm.

It appears from the analysis of these charts the following remarks:

- The evolution of water observed in tide of La Rochelle - La Pallice is very well represented by the model. There is a slight shift in the flow before the peak of the event,
- The model underestimated the level of the peak to the tide of Rochefort. The phase observed for the tide is similar to that observed for the astronomical tide.
- The tide gauge of Le Verdon is not exploitable for the peak of the Xynthia event. The exploitable period of the registration shows the good representation of the evolution of the water for the model
- For the tide of La Cotinière model underestimated about 25 cm the maximum water level observed in Storm Xynthia. A temporal shift is also observed for this tide,
- Data of Royan tide gauge is not consistent with data of Le Verdon, despite a near location on banks of the Gironde estuary.

Despite the low number of exploitable data, the model allows to precisely represent the maximum water level measured at the tide of La Rochelle - La Pallice. Outside the main study area, the model correctly represents the evolution of the water level, without offering such high level of precision.

On the study area, the model represents accurately the influence of the hydro meteorological parameters on the evolution of the water level (on maritime side).

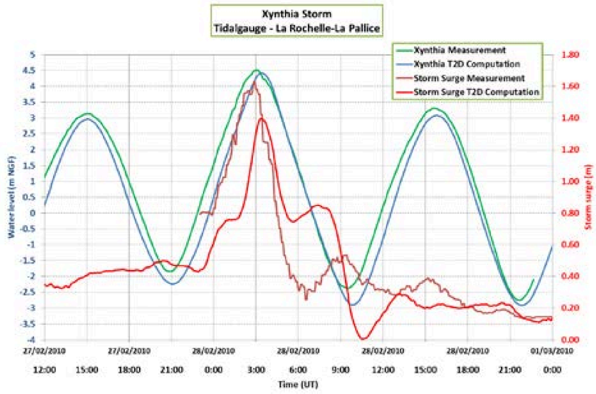

Figure 14. Storm Xynthia – Comparison at La Rochelle.

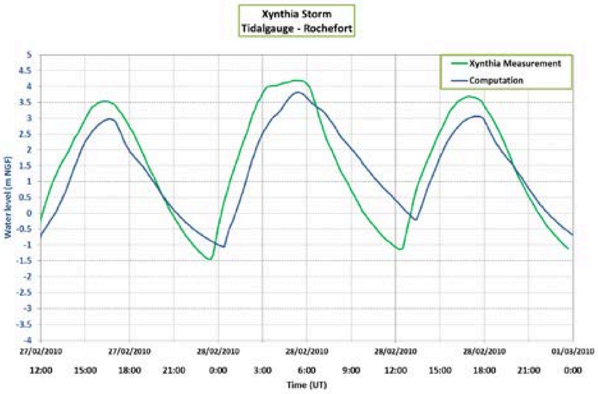

Figure 15. Storm Xynthia – Comparison at Rochefort.

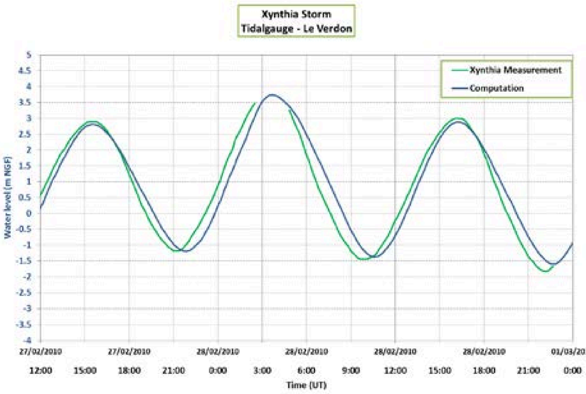

Figure 16. Storm Xynthia – Comparison at Le Verdon.

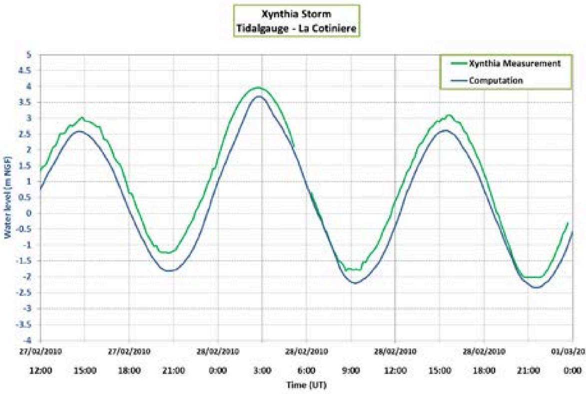

Figure 17. Storm Xynthia – Comparison at La Cotinière.

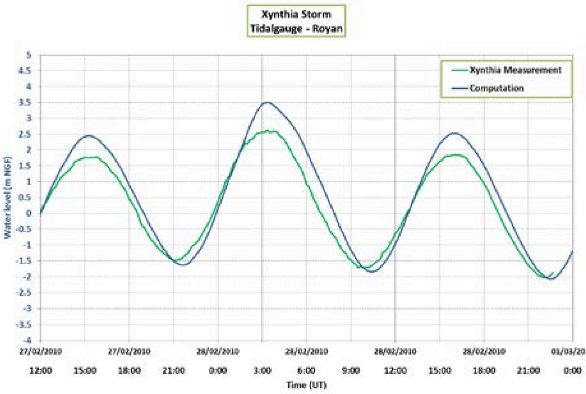

Figure 18. Storm Xynthia – Comparison at Royan.

*f) Maximum water levels in the land:* The calibration of the model in the land behind the dikes, for Storm Xynthia, is made by spatial comparison between the results of computation and:

- The limit of the area inundated or submerged determined in [3].
- The water marks identified in [3],

For this analysis of the representation, by the model, of flows on the land part, the configuration of protection has been modified from that currently observed. The level of protections has been puts at their level before Xynthia, on Charon and Yves sectors. Indeed, on these sectors, protections have been reconstructed with a higher level after the storm.

To properly represent the water volumes on the land part, ruptures and destruction of protection works have also been integrated in the model. These failures have been defined on the basis of the study [3]

The outline of the flooded areas is well represented by the model as it could be seen on Figs. 19 and 20.

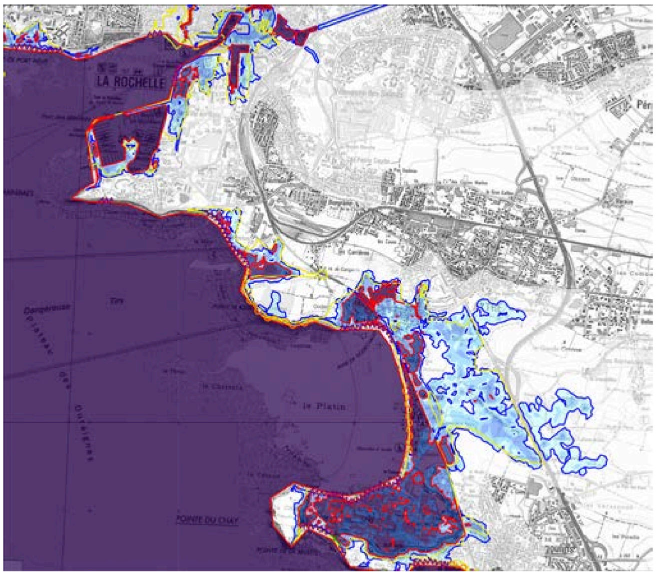

Figure 19. Storm Xynthia – Flooded area around La Rochelle.

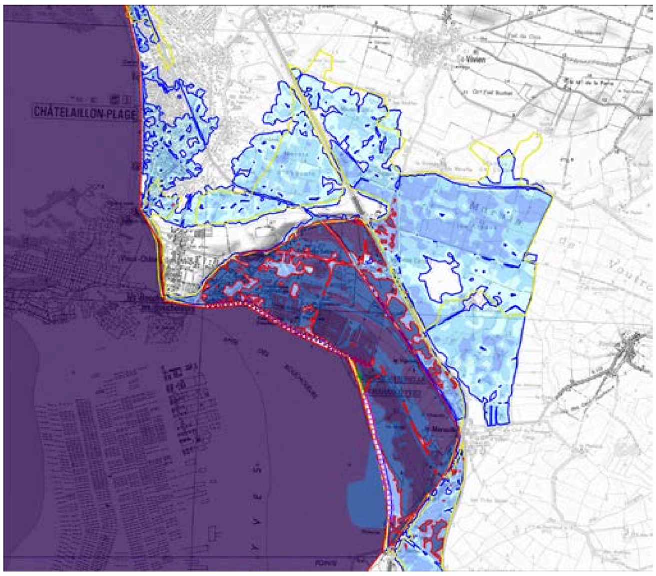

Figure 20. Storm Xynthia – Flooded area around Chatelaillon.

Table I presents, by communal territory, a summary of the differences between the observations and the results of the modelling.

At the end, more than 400 water marks were able to face the results of the model on the study area. Despite the great disparity of information, the model provides a mean absolute deviation about 25 cm from the observations on this area.

The model correctly represents the maximum water levels on all the study area.

We could note that on the low areas behind the protections, the time of failure is an important control for the dynamic of filling and by consequence for the maximum water level observed.

TABLE I. SUMMARY OF DIFFERENCES BETWEEN OBSERVATIONS AND MODEL PREDICTIONS

| **Cities** | **Water marks** | | | | |
|---|---|---|---|---|---|
| | ***Total number*** | ***Number used*** | ***%*** | ***Mean deviation*** | ***Absolute mean deviation*** |
| Andilly | 2 | 2 | 100 | -0.03 | 0.24 |
| Angoulins | 33 | 32 | 97 | 0.09 | 0.13 |
| Aytré | 44 | 43 | 98 | 0.04 | 0.20 |
| Charron | 35 | 35 | 100 | -0.01 | 0.22 |
| Châtelaillon | 64 | 54 | 84 | -0.17 | 0.23 |
| Esnandes | 26 | 26 | 100 | 0.15 | 0.21 |
| La Rochelle | 111 | 86 | 77 | -0.43 | 0.52 |
| L'houmeau | 18 | 17 | 94 | -0.14 | 0.16 |
| Marans | 7 | 6 | 86 | -0.02 | 0.17 |
| Marsilly | 18 | 17 | 94 | -0.06 | 0.22 |
| Nieul | 37 | 35 | 95 | 0.03 | 0.16 |
| Saint Ouen d'aunis | 1 | 1 | 100 | 0.00 | 0.00 |
| Villedoux | 2 | 2 | 100 | -0.04 | 0.04 |
| Yves | 53 | 53 | 100 | -0.03 | 0.16 |
| **Total** | **451** | **409** | **91** | **-0.11** | **0.26** |

## V. CONCLUSIONS

With the inaccuracies on the initial data which have a direct influence on overflow volumes entering on the land part of the model:

- Precise topography of the crest of the existing protections before the event,
- Chronology of the failures in the works of protection during the storm,
- And if we taking in account:
- The fact that the model cannot represent very local hydraulic effects in the disturbed areas (walls, water level in buildings ...).
- Inaccuracies (reliability) on some water marks,

All of the analyses conducted and detailed in the preceding paragraphs are sufficient to consider the model calibrate and valid for the representation of hydro meteorological events generating very high water levels in the Pertuis as well as the representation of the dynamic submersions on land side.

This model could be now used to test some reference events based on Storm Xynthia but also with a rise of sea level due to climate change.

## REFERENCES

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[3] Eléments de mémoire sur la tempête Xynthia du 27 et 28 Février 2010 en Charente Maritime, Rapport d'étude Artelia pour la Direction Départementale de Territoires et de la Mer de la Charente-Maritime, Aout 2010, unpublished