Use of TELEMAC software system as a technical modelling tool for coastal zone development studies

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Abstract

This article consists at the presentation of the various modules included in the TELEMAC system dedicated to free-surface flows and the associated processes of transport/dispersion of dissolved substances and sediment movements.

These modules are thus of very great interest for studies dealing with coastal development and may be considered as aids for decision-making and coastal zone management. They can be used to fine-tune knowledge of the physical conditions observed in the study area, determine the impacts associated with development works, monitor and quantify the impact of ordinary or exceptional pollution, monitor changes in morphodynamics, salinity or any other physicochemical parameter.

Contents

1 Generalities

The various simulation modules of the TELEMAC system use powerful algorithms based on the finite-element or finite-volume methods.

Space is discretised into an unstructured 2D grid of triangular elements, so that the calculation grid can be refined locally in areas of interest.

All the algorithms are gathered into a single library that is common to all the calculation codes, which makes it easier to use the various modules (it is easy to pass from one to another) and, in particular, allows them to be coupled internally and externally.

The pre- and post-processing tools are identical for each calculation code.

TELEMAC offers the user a set of sub-routines that are specific to each calculation code. These are all written in FORTRAN-90 and can easily be modified in order to meet users' specific requirements: prescription of initial conditions or complex boundary conditions, introduction of new functions, coupling with other modelling systems.

A parallel version is available for use on multi-processor computers or clusters of workstations for certain modules (use of the MPI library, automatic domain breakdown operations).

As a complement to the TELEMAC chain, the FUDAA-PREPRO software (developed from the FUDAA platform by the Research, Computing and Modelling Department of CETMEF) covers all the pre-processing tasks involved in completing a digital hydraulic study.

2 Developers

TELEMAC-2D was developed by the National Hydraulics and Environment Laboratory (Laboratoire National d'Hydraulique et Environnement - LNHE) of the Research and Development Directorate of the French Electricity Board (EDF-DRD), in collaboration with other research institutes.

The software complies with EDF-DRD's Quality Assurance procedures for scientific and technical programs. These set out rules for developing and checking product quality at all stages. In particular, a program covered by Quality Assurance procedures is accompanied by a Formulation Document that describes the theoretical aspects of the software, and a Validation Document that describes the field of use of the software and a set of test cases.

3 Open-source : free software

All the modules of the TELEMAC system have been open source since July 2010 and can be downloaded on the internet site (www.telemacsystem.com).

Difficulties related to installation, bugs as well as suggestions for future development are welcome and need to be submitted through the forum to the development team.

4 System structure

The TELEMAC system comprises the following modules:

Pre-processing

• The MATISSE software designed to generate a mesh consisting of triangular elements, using bathymetric and/or topographic data.

• FUDAA-PREPRO.

• STBTEL (adaptation to commercially available meshing programs).

Hydrodynamics

• The TELEMAC-2D software designed to perform a hydrodynamic simulation in two horizontal space dimensions. In addition, TELEMAC-2D can simulate the transport of dissolved tracers.

• The TELEMAC-3D software itself, designed to carry out hydrodynamic simulations of flows in three space dimensions. In addition, TELEMAC-3D can simulate the transport of tracers. The SEDI-3D library contains the relevant subroutines for simulating non-cohesive sediment transport. This document is concerned with the implementation of the TELEMAC-3D software.

• The SPARTACUS-2D software designed to simulate two-dimensional laminar and turbulent flows using the SPH method.

Sedimentology

• The SISYPHE2D and SISYPHE 3D programs designed to simulate the transport of sediment through bed load traction and suspension.

Water quality

• SUBIEF-2D (2D suspended sediment transport – Tracer transport – 2D), not distributed.

• SEDI-3D (3D tracer transport – integrated in TELEMAC-3D).

• Interface to Delft Hydraulics' DELWAQ program.

Waves

• The ARTEMIS software designed to simulate changes in the features of wave agitation either in a coastal water body or a harbour.

• The TOMAWAC software designed to simulate sea state in permanent or transitory conditions using a spectral method.

Sub-surface flows

• ESTEL-2D (2D flows and pollutant transport in a subsurface medium).

• ESTEL-3D (3D flows and pollutant transport in a subsurface medium).

Post -processing

- *RUBENS, not distributed.*
- *FUDAA-PREPRO.*
- *POSTEL-3D.*

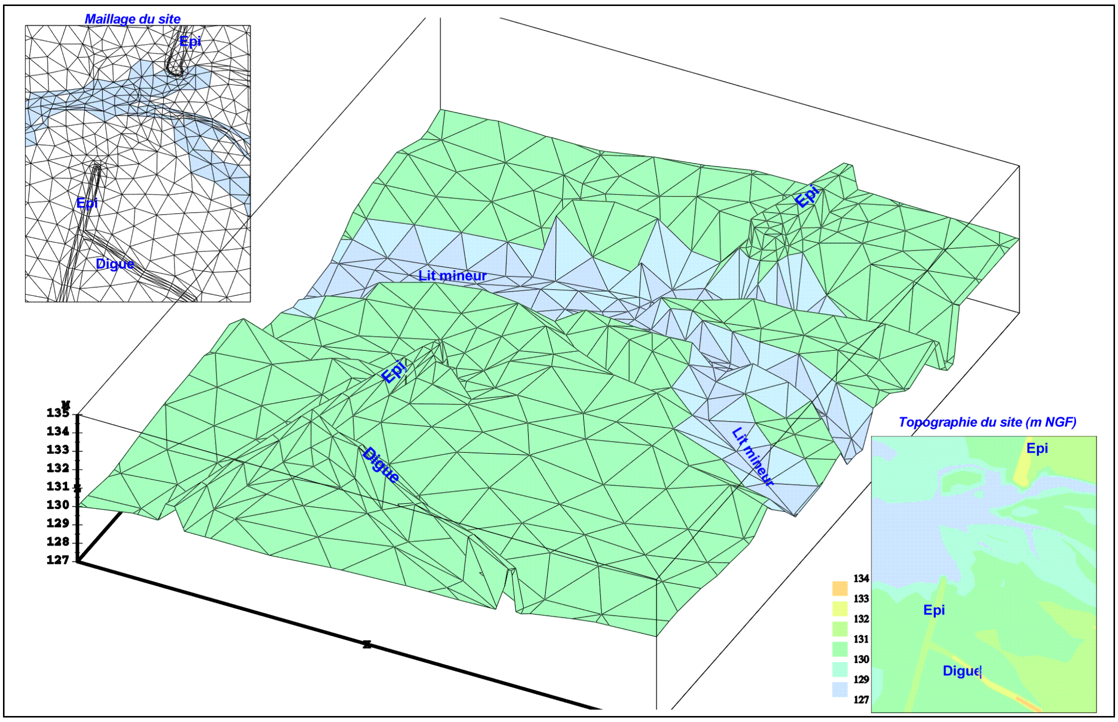
Main applications

The main applications of the TELEMAC system software are the following:

- *dam bursts,*
- *flood studies,*
- *harbour installation studies (structures, jetties, breakwaters, etc.),*
- *impact of hydraulic structures (bridges, embankments, etc.),*
- *estuary management and development,*
- *water quality (discharges from treatment plants, industrial discharges),*
- *thermal recirculation,*
- *dumping of dredged materials,*
- *hydrosedimentary studies,*
- *wave disturbance in a port or bay,*
- *river restoration studies,*
- *hydraulic studies for tourist development schemes,*
- *study of marine climates (generation by the wind and wave propagation).*

5 Specific feature of the TELEMAC system: finite elements

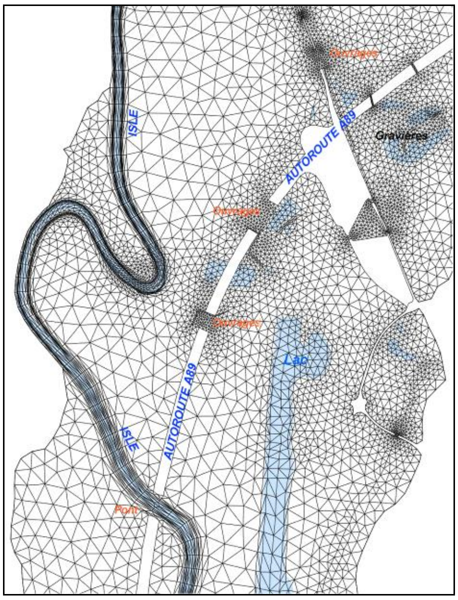
The strength of finite-element modelling lies in its complete characterisation of the major hydraulic magnitudes on the basis of a representation of the natural terrain that is faithful to the digital terrain model available. This type of modelling involves an unstructured grid consisting of 3D triangular facets of varying size and shape built like a virtual terrain model.



Example of a grid for a river and dikes (Sogreah)

The tip of each triangle is a calculation point characterised by its planimetric (X, Y) and altimetric (Z) references and by a roughness coefficient representing the surface state of the terrain.

The finite-element method on which TELEMAC is based, associated with a calculation grid consisting of triangular facets of various sizes and shapes, enables the topography to be broken down in a suitable manner and hence the complex geometries of the study area (embankments, low-water bed of meandering rivers, islands, structures, roads, streets, secondary tributaries, etc.) to be taken into account. The grid can be made denser (and hence the results produced by the model refined) in areas of special interest such as around discharge structures, bridge piers and sensitive areas.

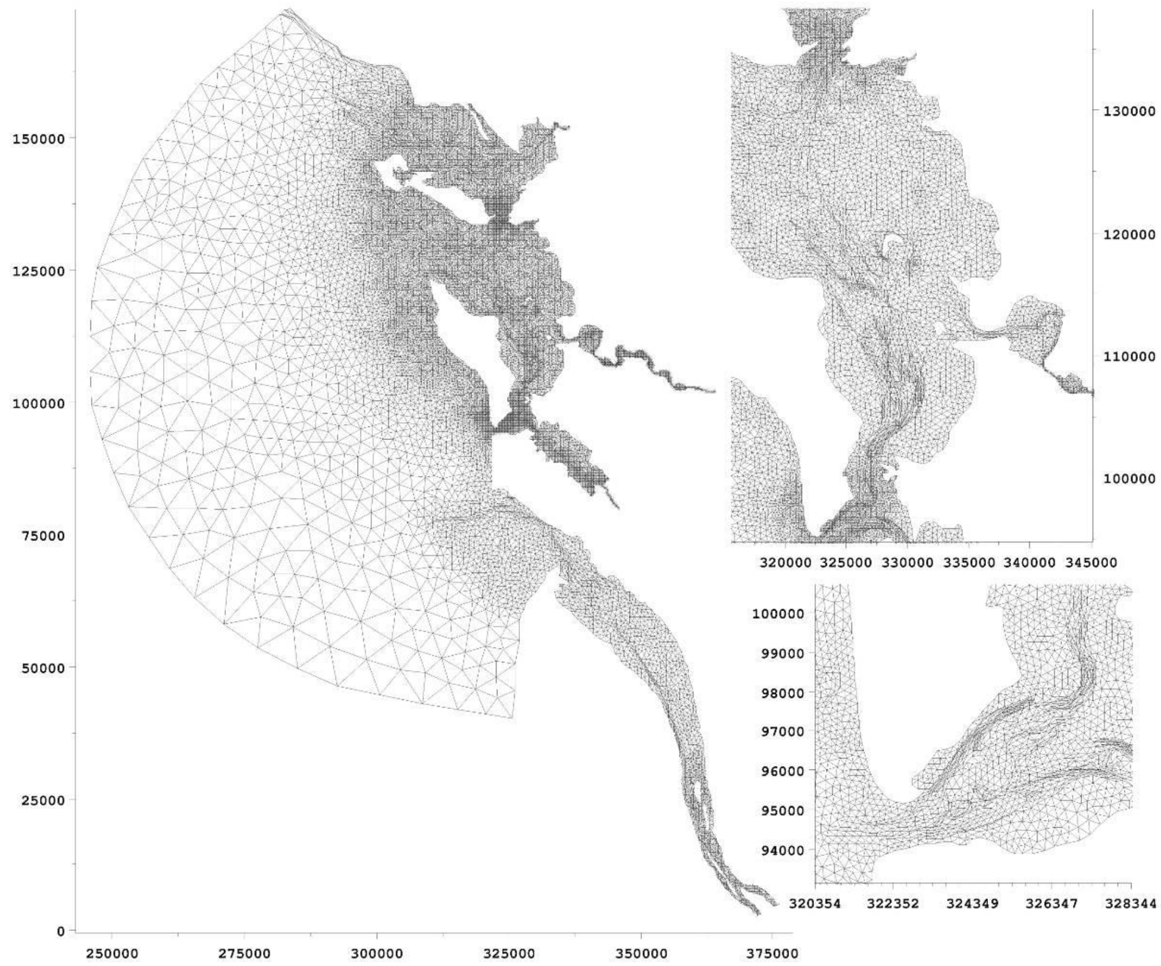


Mesh of the Isle river (SOGREAH)

In terms of actual exploitation, TELEMAC models have the advantages of numerical processing: using basic results, it is possible to calculate many other magnitudes, such as changes in water level at any point in the model or in the discharge flowing along a river, through a structure or in a flood plain, changes in the volumes stored in a high-water bed, or an evaluation of trajectories, etc.

In spite of its apparent complexity, this type of model produces a very high-quality support for hydraulic appraisals in terms of analysing results and understanding hydraulic phenomena in the presence of complex flow areas.

It also serves as a communication medium by virtue of its extremely clear rendering and the possibility of producing animated displays.



SSA Pertuis-Charentais mesh

6 TELEMAC-2D: 2D hydrodynamic software

General description

The TELEMAC-2D code solves depth-averaged free surface flow equations as derived first by Barré de Saint-Venant in 1871. The main results at each node of the computational mesh are the depth of water *and the depth-averaged velocity components. The main application of TELEMAC-2D is in free-surface maritime or river hydraulics and the program is able to take into account the following phenomena:*

- *Propagation of long waves, including non-linear effects*
- *Friction on the bed*
- *The effect of the Coriolis force*
- *The effects of meteorological phenomena such as atmospheric pressure and wind*
- *Turbulence*
- *Supercritical and subcritical flows*
- *Influence of horizontal temperature and salinity gradients on density*
- *Cartesian or spherical coordinates for large domains*
- *Dry areas in the computational field: tidal flats and flood-plains*
- *Entrainment and diffusion of a tracer by currents, including creation and decay and sink terms*
- *Particle tracking and computation of Lagrangian drifts*
- *Treatment of singularities: weirs, dikes, culverts, etc.*
- *Inclusion of the drag forces created by vertical structures*
- *Inclusion of porosity phenomena*
- *Inclusion of wave-induced currents (by link-ups with the ARTEMIS and TOMAWAC modules)*
- *Coupling with sediment transport*

Technical description

The TELEMAC-2D code solves the following four hydrodynamic equations simultaneously:

$$\frac{\partial h}{\partial t} + u \cdot \vec{\nabla}(h) + h div(\vec{u}) = S_h \qquad \textit{continuity}$$

$$\frac{\partial u}{\partial t} + \vec{u} \cdot \vec{\nabla}(u) = -g \frac{\partial Z}{\partial x} + S_x + \frac{1}{h} div(h \nu_t \vec{\nabla} u) \qquad \textit{momentum along x}$$

$$\frac{\partial v}{\partial t} + \vec{u} \cdot \vec{\nabla}(v) = -g \frac{\partial Z}{\partial y} + S_y + \frac{1}{h} div(h \nu_t \vec{\nabla} v) \qquad \textit{momentum along y}$$

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \vec{\nabla}(T) = S_T + \frac{1}{h} div(h \nu_T \vec{\nabla} T)$$ *tracer conservation*

in which:

h	*(m)*	*depth of water*
u,v	*(m/s)*	*velocity components*
T	*(g/l or °C)*	*non-buoyant tracer*
g	*(m/s²)*	*gravity acceleration*
υ_t, υ_T	*(m²/s)*	*momentum and tracer diffusion coefficients*
Z	*(m)*	*free surface elevation*
t	*(s)*	*time*
x,y	*(m)*	*horizontal space coordinates*
S_h	*(m/s)*	*source or sink of fluid*
S_x, S_y	*(m/s²)*	*source or sink terms in dynamic equations*
S_T	*(g/l/s)*	*source or sink of tracer*

h, u, v and T are the unknowns.

The equations are given here in Cartesian coordinates. They can also be processed using spherical coordinates.

S_X *and* S_Y *(m/s²) are source terms representing the wind, Coriolis force, bottom friction, a source or a sink of momentum within the domain. The different terms of these equations are processed in one or more steps (in the case of advection by the method of characteristics):*

1) *advection of h, u, v and T,*
2) *propagation, diffusion and source terms of the dynamic equations,*
3) *diffusion and source terms of the tracer transport equation.*

Any of these steps can be skipped, and in this case different equations are solved. In addition, each of the variables h, u, v and T may be advected separately. In this way it is possible, for example, to solve a tracer advection and diffusion equation using a fixed advecting velocity field.

Turbulent viscosity may be given by the user or determined by a model simulating the transport of turbulent quantities k (turbulent kinetic energy) and Epsilon (turbulent dissipation), for which the equations are the following:

$$\frac{\partial k}{\partial t} + \vec{u} \cdot \vec{\nabla}(k) = \frac{1}{h} div(h \frac{\nu_t}{\sigma_k} \vec{\nabla} k) + P - \varepsilon + P_{kv}$$

$$\frac{\partial \varepsilon}{\partial t} + \vec{u} \cdot \vec{\nabla}(\varepsilon) = \frac{1}{h} div(h \frac{\nu_t}{\sigma_\varepsilon} \vec{\nabla} \varepsilon) + \frac{\varepsilon}{k}(c_{1\varepsilon} P - c_{2\varepsilon} \varepsilon) + P_{\varepsilon v}$$

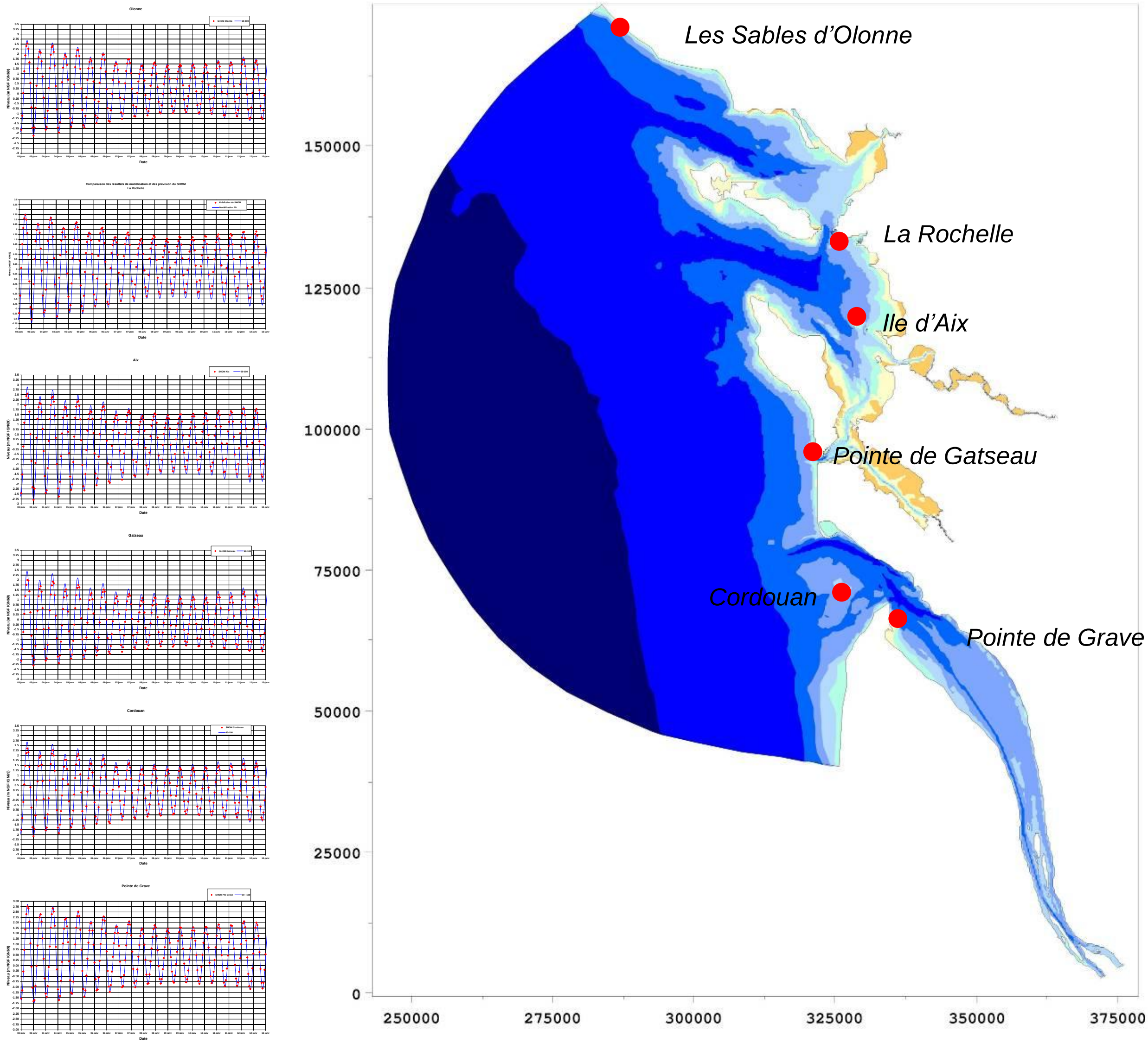
The right-hand side terms of these equations represent the production and destruction of turbulent quantities (energy and dissipation).

A complete description of the theory is given in the following book: "Hydrodynamics of free surface flows", by Jean-Michel Hervouet (Wiley, 2007).

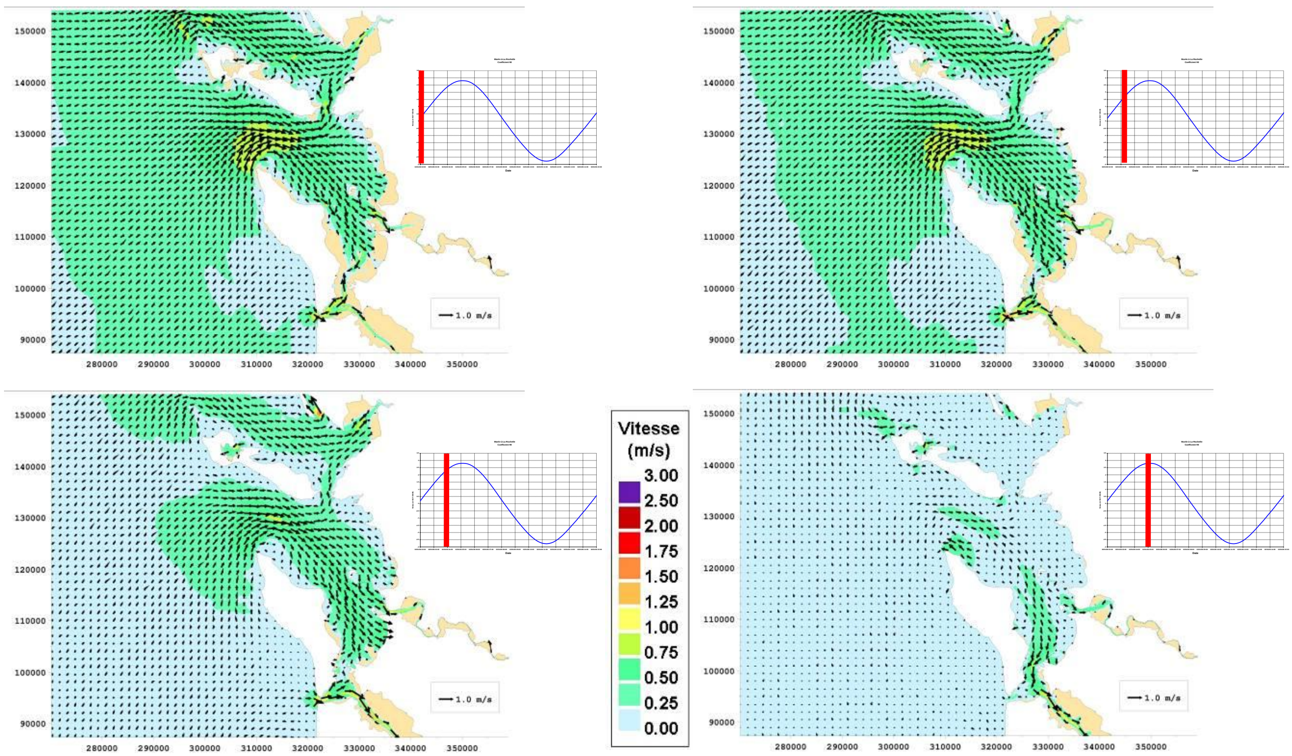
Applications

The software has many fields of application. In the maritime sphere, particular mention may be made of the sizing of port structures, the study of the effects of building submersible dikes or dredging, the impact of waste discharged from a coastal outfall or the study of thermal plumes. In river applications, mention may also be made of studies relating to the impact of construction works (bridges, weirs, groynes), dam breaks, flooding or the transport of decaying or non-decaying tracers.

TELEMAC-2D has also been used for a number of special applications, such as the bursting of industrial reservoirs, avalanches falling into a reservoir, etc.



Validation of the SSA Pertuis Charentais hydrodynamic model



Current fields for a spring tide issued from the SSA Pertuis Charentais hydrodynamic model

7 TELEMAC-3D: 3D hydrodynamics software

General description

The TELEMAC-3D code solves such three-dimensional equations as the free surface flow equations (with or without the hydrostatic pressure assumption) and the transport-diffusion equations of intrinsic quantities (temperature, salinity, concentration). Its main results, at each point in the resolution mesh, are the velocity in all three directions and the concentrations of transported quantities. Water depth is the major result as regards the surface mesh. TELEMAC-3D's prominent applications can be found in free surface flow, in both seas and rivers; the software can take the following processes into account:

- *Influence of temperature and/or salinity on density,*
- *Bottom friction,*
- *Influence of the Coriolis force,*
- *Influence of weather factors: air pressure and wind,*
- *Consideration of thermal exchanges with the atmosphere,*
- *Sources and sinks for fluid movement within the flow domain,*
- *Simple or complex turbulence models (K-Epsilon) taking the effects of the Archimedean force (buoyancy) into account,*
- *Dry areas in the computational domain: tidal flats,*
- *Current drift and diffusion of a tracer, with creation or decay terms.*

The code is applicable to many fields. The main ones are related to the marine environment through the investigations of currents induced either by tides or density gradients, with or without the influence of such an external force as the wind or air pressure. It can be applied either to large areas (a sea) or to smaller domains (coasts and estuaries) to study the impact of sewer effluents, thermal plumes or even sediment transport. As regards continental waters, the study of thermal plumes in rivers, and the hydrodynamic behaviour of natural or man-made lakes can be mentioned as well.

Technical description

TELEMAC-3D is a three-dimensional computational code describing the 3D velocity field (u, v, w) and the water depth h (and, from the bottom depth, the free surface S) at each time step. In addition, it solves the transport of several tracers which can be grouped into two categories, namely the so-called "active" tracers (primarily temperature and salinity), which change the water density and act on flow through gravity, and the so-called "passive" tracers, which do not affect the flow and are merely transported.

EQUATIONS

The reader will refer to J.M. Hervouet's book [1] for a detailed statement of the theoretical aspects on which TELEMAC-3D is based.

EQUATIONS WITH THE HYDROSTATIC ASSUMPTION

In its basic release, the code solves the three-dimensional hydrodynamic equations with the following assumptions:

- *three-dimensional Navier-Stokes equations with a free surface changing in time,*
- *negligible variation of density in the conservation of mass equation (incompressible fluid),*
- *pressure-hydrostatic assumption (according to which the pressure at a given depth is the sum of the air pressure at the fluid surface plus the weight of the overlying water body),*
- *Boussinesq approximation for the momentum (density variations are not taken into account in the gravity term).*

Due to these assumptions, the three-dimensional equations being solved are:

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z}=0$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+W\frac{\partial U}{\partial z}=-g\frac{\partial Z_S}{\partial x}+\upsilon\,\Delta(U)+F_x$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+W\frac{\partial V}{\partial z}=-g\frac{\partial Z_S}{\partial y}+\upsilon\,\Delta(V)+F_y$$

$$p=p_{atm}+\rho_0 g\,(Z_S-z)+\rho_0 g\int_z^{Z_S}\frac{\Delta\rho}{\rho_0}\,dz$$

$$\frac{\partial T}{\partial t}+U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}+W\frac{\partial T}{\partial z}=\upsilon\,\Delta(T)+Q$$

where:

h (m)	*water depth.*
S (m)	*free surface elevation.*
U, V, W (m/s)	*three-dimensional components of velocity.*
T (°C, g/l …)	*passive or active (acting on density) tracer.*

p (X)	pressure.
g (m/s^2)	gravity acceleration.
v (m^2/s)	velocity and tracer diffusion coefficients.
Z_f (m)	bottom depth.
ρ_0 (X)	reference density.
$\Delta\rho$ (X)	variation of density.
t (s)	time.
x, y (m)	horizontal space components.
z (m)	vertical space component.
F_x, F_y (m/s^2)	source terms.
Q (tracer unit)	tracer source or sink.

h, U, V, W and T are the unknown quantities, also known as computational variables

Fx and Fy are source terms denoting the wind, the Coriolis force and the bottom friction (or any other process being modelled by similar formulas). Several tracers can be taken into account simultaneously. They can be of two different kinds, either active, i.e. influencing the flow by changing the density, or passive, without any effect on density and then on flow.

The TELEMAC-3D basic algorithm can be split into three computational steps (three fractional steps).

The first step consists in finding the advected velocity components by solving only the advection terms in the momentum equations.

The second step computes the new velocity components from the advected velocities taking into account the diffusion terms and the source terms in the momentum equations. These two solutions enable an intermediate velocity field to be obtained.

The third step computes the water depth from the vertical integration of the continuity equation and the momentum equations including only the pressure-continuity terms (all the other terms have already been taken into account in the two earlier steps). The resulting two-dimensional equations (analogous to the Saint-Venant equations without diffusion, advection and source terms) are written as follows:

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0$$

$$\frac{\partial u}{\partial t} = -g \frac{\partial Z_S}{\partial x}$$

$$\frac{\partial v}{\partial t} = -g \frac{\partial Z_S}{\partial y}$$

u and v in lower case denote the two-dimensional variables of the vertically integrated velocity.

These two-dimensional equations are solved by the libraries in the TELEMAC-2D code and enable the vertically averaged velocity and the water depth to be obtained.

The water depth makes it possible to re-compute the elevations of the various mesh points and then those of the free surface.

Lastly, the U and V velocities are simply computed through a combination of the equations linking the velocities. Finally, the vertical velocity W is computed from the continuity equation.

NON-HYDROSTATIC NAVIER-STOKES EQUATIONS

The following system (with an equation for W *which is similar to those for* U *and* V *) is then to be solved:*

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0$$
$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + W\frac{\partial U}{\partial z} = -g\frac{\partial Z_S}{\partial x} + \upsilon\,\Delta(U) + F_x$$
$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + W\frac{\partial V}{\partial z} = -g\frac{\partial Z_S}{\partial y} + \upsilon\,\Delta(V) + F_y$$
$$\frac{\partial W}{\partial t} + U\frac{\partial W}{\partial x} + V\frac{\partial W}{\partial y} + W\frac{\partial W}{\partial z} = -g\frac{\partial Z_S}{\partial z} + g + \upsilon\,\Delta(W) + F_z$$

In order to share a common core as much as possible with the solution of the hydrostatic equations, the pressure is split up into a hydrostatic pressure and a "dynamic" pressure term.

$$p = p_{atm} + \rho_0 g (Z_S - z) + \rho_0 g \int_z^{Z_S} \frac{\Delta\rho}{\rho_0} dz + p_d$$

The TELEMAC-3D algorithm solves a hydrostatic step which is the same as in the previous section, the only differences lying in the continuity step ("projection" step in which the dynamic pressure gradient changes the velocity field in order to provide the required zero divergence of velocity) and the computation of the free surface.

THE LAW OF STATE

Two laws of state can be used by default through TELEMAC-3D

In most of the simulations, salinity and temperature make it possible to compute the variations in density. The first law expresses the variation in density from just these two parameters. The second law is more general and enables all the variations in density to be constructed with the active tracers being taken into account in the computation.

The ***first law*** *is written as follows:*

$$\rho = \rho_{ref}\left[1 - \left(7\left(T - T_{ref}\right)^2 - 750S\right)10^{-6}\right]$$

with T_{ref} *being a reference temperature of 4°C and* ρ_{ref} *a reference density at that temperature when the salinity is zero. Hence* $\rho_{ref} = 999{,}972 kg/m^3$. *This law remains valid for 0°C < T < 40°C and 0g / l < S < 42g / l .*

The ***second law*** *is written as follows:*

$$\rho = \rho_{ref}\left[1 - \sum_i \beta_i \left(T_i - T_i^0\right)\right]$$

ρ_{ref}*, the reference density can be modified by the user together with the volumetric expansion coefficients* β_i *related to the tracers* T_i *.*

K-EPSILON MODEL

The turbulent viscosity can be given by the user, as determined either from a mixing length model or from a k-ε model, the equations of which are:

$$\frac{\partial k}{\partial t} + U\frac{\partial k}{\partial x} + V\frac{\partial k}{\partial y} + W\frac{\partial k}{\partial z} = \frac{\partial}{\partial x}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial z}\right) + P - G - \varepsilon$$

$$\frac{\partial \varepsilon}{\partial t} + U\frac{\partial \varepsilon}{\partial x} + V\frac{\partial \varepsilon}{\partial y} + W\frac{\partial \varepsilon}{\partial z} = \frac{\partial}{\partial x}\left(\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial z}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}\left[P + \left(1 - C_{3\varepsilon}\right)G\right] - C_{2\varepsilon}\frac{\varepsilon^2}{k}$$

wherein:

$k = \frac{1}{2}\overline{u_i' u_i'}$ *denotes the turbulent kinetic energy of the fluid,*

$\varepsilon = \upsilon \overline{\frac{\partial u_i^{'}}{\partial x_j} \frac{\partial u_i^{'}}{\partial x_j}}$ *the dissipation of turbulent kinetic energy,*

P is a turbulent energy production term,

G is a source term due to the gravitational forces

$$P = \nu_t \left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i} \right) \frac{\partial \overline{U_i}}{\partial x_j} \qquad G = -\frac{\nu_t}{\Pr_t} \frac{g}{\rho} \frac{\partial \rho}{\partial z}$$

and ν *verifies the equality:* $\nu_t = C_\mu \frac{k^2}{\varepsilon}$

$C_\mu, \Pr_t, C_{1\varepsilon}, C_{2\varepsilon}, C_{3\varepsilon}, \sigma_k, \sigma_\varepsilon$ *are constants in the K-Epsilon model.*

TRACER EQUATIONS

The tracer can be either active (it affects hydrodynamics) or passive in TELEMAC-3D. Temperature, salinity and in some cases a sediment are active tracers. The tracer evolution equation is formulated as:

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} + V \frac{\partial T}{\partial y} + W \frac{\partial T}{\partial z} = \frac{\partial}{\partial x}\left(\nu_T \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(\nu_T \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z}\left(\nu_T \frac{\partial T}{\partial z} \right) + Q$$

with:

- *T (tracer unit)* *tracer either passive or affecting the density.*
- ν_T *(m^2/s)* *tracer diffusion coefficients.*
- *t (s)* *time.*
- *x, y, z (m)* *space components.*
- *Q (tracer unit(s)* *tracer source or sink.*

Applications

The main applications of TELEMAC-3D concern configurations in which the three-dimensional aspect is preponderant:

- *monitoring water temperature or salinity, owing to their preponderant role in density effects,*

- *sedimentary issues, in which there are considerable vertical disparities (maximum turbidity zones, etc.),*
- *vertically heterogeneous flows,*
- *need for more detailed knowledge of flows at a given level (water intakes, outfalls, etc.).*

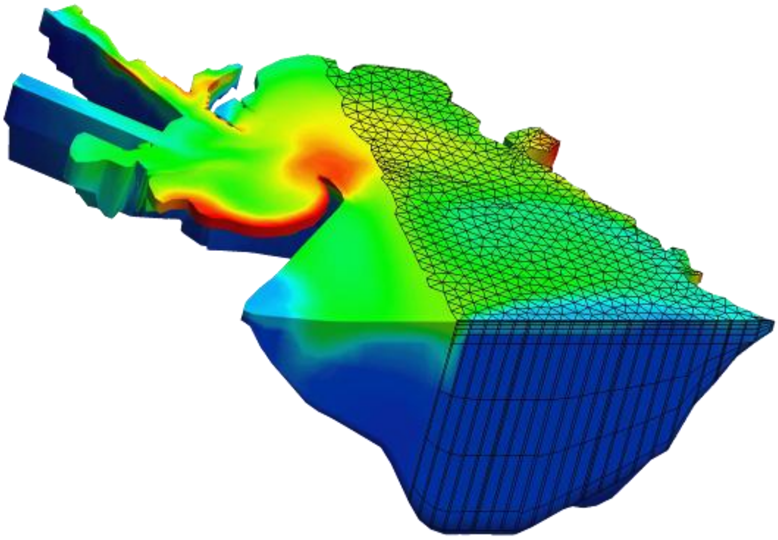
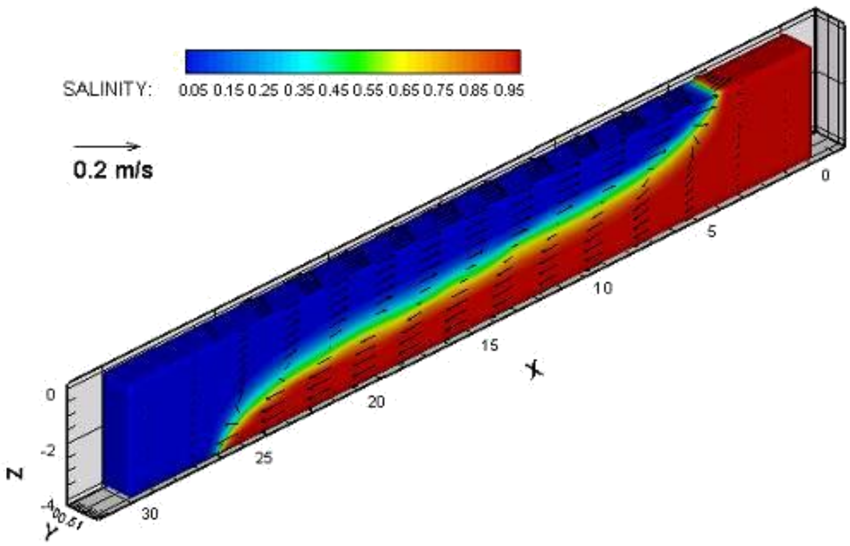


Illustration of a 3D mesh (SOGREAH)



3D salinity front representation with TELEMAC-3D (SOGREAH)

8 TOMAWAC: Software for sea state modelling on unstructured grids over oceans and coastal seas

General description

TOMAWAC models sea states by solving the balance equation for the action density directional spectrum. To do so the model should reproduce the change in the action density directional spectrum at each node of a spatial computational grid.

In TOMAWAC the wave directional spectrum is split into a finite number of propagation frequencies f_i *and directions* $_i$*. The balance equation of wave action density is solved for each component (*f_i, $_i$*). The model is said to be a third generation model (e.g. like the WAM model [WAMDI, 1988] [Komen et al., 1994]), since it does not require any parameterization on the spectral or directional distribution of power (or action density). Each component of the action density spectrum changes in time under the effects of the software-modelled processes.*

TOMAWAC general purposes

TOMAWAC can be used for three types of applications:

*1. **Wave climate forecasting** a few days ahead, from wind field forecasts. This real time type of application is directed mainly at weather-forecasting institutes such as Météo-France, whose one role involves predicting the weather development on a continuous basis and, as the case may be, publishing storm warnings.*

*2. **Hindcasting** of exceptional events that have severely damaged maritime structures and for which field records are either incomplete or unavailable.*

*3. **Studying wave climatology and maritime or coastal site features,** through the application of various medium or extreme weather conditions in order to obtain the conditions necessary to carry out projects and studies (harbour construction, morphodynamic coastal changes, etc.).*

During the development of the TOMAWAC model, the LNHE concentrated mainly on the last two types of application. It also considered the possibility of carrying out research activities focused on the following topics:

- *wave-current and wave-surge interactions, especially in places where tide plays a significant role,*
- *coastal morphodynamics,*
- *probability of floods in coastal zones,*
- *coastal structure stability and coastal protection,*
- *assimilation of wind or wave satellite data during computations, etc.*

Technical description
Application domain of the TOMAWAC model

TOMAWAC is designed to be applied from the ocean domain up to the coastal zone. The limits of the application's range can be determined by the value of the relative depth d/L, wherein d denotes the water height (in metres) and L denotes the wave length (in metres) corresponding to the peak spectral frequency for irregular waves.

The application domain of TOMAWAC includes:

- *the oceanic domain, characterized by large water depths, i.e. by relative water depths of over 0.5. The dominant physical processes are: wind-driven wave generation, whitecapping dissipation and non-linear quadruplet interactions;*

- *the continental seas and medium depths, characterized by a relative water depth ranging from 0.05 to 0.5. In addition to the above processes, bottom friction, shoaling (wave growth due to a bottom rise) and the effects of refraction due to bathymetry and/or to currents are to be taken into account;*

- *the coastal domain, including shoals or nearshore areas (relative water depth lower than 0.05). For these shallow water areas, such physical processes as bottom friction, bathymetric breaking and non-linear triad interactions between waves should be included.*

Furthermore, it could be useful to take into account effects related to unsteady sea level and currents due to tide and/or to weather-dependent surges.

Through a so-called finite element spatial discretization, one computational grid may include mesh cells among which the ratio of the largest sizes to the smallest ones may reach or even exceed 100.

That is why TOMAWAC can be applied to a sea domain that is characterised by highly variable relative water depths; in particular, the coastal areas can be finely represented.

The application domain of TOMAWAC does not include harbour areas and, more generally, all those cases in which the effects of reflection on structures and/or diffraction may not be ignored.

Wave interactions with other physical factors

Several factors are involved in the wave physics and interact to various extents with the waves, changing their characteristics. The following main factors should be mentioned:

- *bathymetry and sea bottom geometry (bottom friction, refraction, surf-breaking, nonlinear effects of interactions with the bottom, sand rippling, etc.);*

- *atmospheric circulation (wind and pressure effects);*

- *tide pattern (variation of currents and water heights);*

- *three-dimensional oceanic circulation currents;*

- *over/underelevations caused by exceptional weather events, resulting in sea level variations up to several metres (storm surges).*

Fine modelling of the interactions between these various physical factors and waves is generally rather complex and several research projects are currently focused on it. Within the application domain as defined in the previous section, TOMAWAC models the following interactions:

- *wave-bathymetry interaction: the submarine relief data entered into TOMAWAC are constant in time, but the sea level can change in time. In addition to the effects of sea level variations in time, TOMAWAC can take into account refraction, shoaling, bottom friction and bathymetric breaking;*

- *wave-atmosphere interaction: this interaction is the driving phenomenon in wave generation, takes part in energy dissipation processes (whitecapping, wave propagation against the wind, etc.) and is involved in energy transfers. To represent the unsteady behaviour of this interaction, TOMAWAC requires 10 m wind fields (specification of the pair of horizontal velocity components) with a time step matched to the weather conditions being modelled. These wind fields can be provided either by a meteorological model or from satellite measurements;*

- *wave-current interaction: sea currents (generated either by the tide or by oceanic circulations) may significantly affect waves depending on their intensity.*

They modify the refractive wave propagation direction, they reduce or increase the wave height according to their propagation direction in relation to the waves and may influence the wave periods if they exhibit a marked unsteady behaviour. In TOMAWAC, the current field is provided by the pair of horizontal components of its average (or depth-integrated) velocity at the nodes of the computational grid. TOMAWAC models frequency changes caused either by the Doppler effect or by unsteady currents, as well as by a non-homogeneous current field.

The physical processes modelled in TOMAWAC

The interactions taken into account by TOMAWAC have been reviewed and a number of physical events or processes have been mentioned in the previous section. These processes modify the total wave energy as well as the directional spectrum distribution of that energy (i.e. the shape of the directional spectrum of energy). Numerical modelling of these various processes is not yet mature, even though some of them are now very well known, and many subjects are still being investigated. Considering the brief review of physical interactions given in the previous section, the following physical processes are taken into account and modelled numerically in TOMAWAC:

—> Energy source/dissipation processes:

• wind-driven interactions with the atmosphere. These interactions involve modelling wind energy input into the waves. This is the prevailing source term for the wave energy directional spectrum. The way the spectrum changes depends primarily on wind velocity, direction, time of action and fetch (distance over which the wind is active). It should be pointed out that the energy that is dissipated when the wind blocks the waves is not taken into account in TOMAWAC;

• whitecapping dissipation or wave breaking, due to excessive wave steepness during wave generation and propagation;

• bottom friction-induced dissipation, occurring mainly in shallow water (bottom grain size distribution, ripples, percolation, etc.);

• dissipation through bathymetric breaking. As waves come near the coast, they swell due to shoaling until they break when they become too steep;

• dissipation through wave blocking due to strong opposing currents.

—> Non-linear energy transfer conservative processes:

• non-linear resonant quadruplet interactions; this is the exchange process prevailing at great depths;

• non-linear triad interactions, which become the prevailing process at small depths.

-—> Wave propagation-related processes:

• wave propagation due to wave group velocity and, on occasions, to the velocity of the medium in which it propagates (sea currents);

• depth-induced refraction which, at small depths, modifies the directions of the wave-ray and then involves energy transfer over the propagation directions;

• shoaling: wave height variation process as the water depth decreases, due to the reduced wavelength and variation in energy propagation velocity;

• current-induced refraction, which also causes a deviation of the wave-ray and energy transfer over the propagation directions;

• interactions with unsteady currents, inducing frequency transfers (e.g. as regards tidal seas);

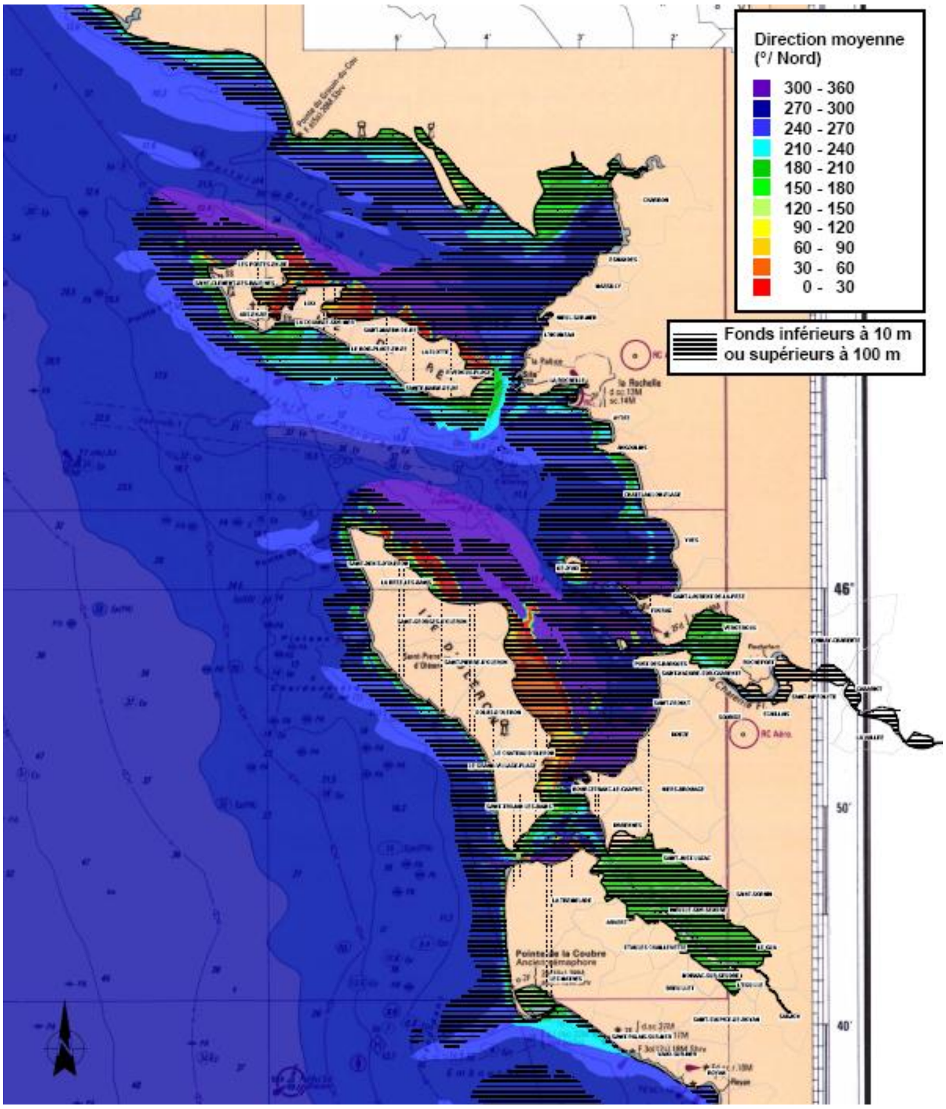
• diffraction by a coastal structure (breakwater, pier, etc.) or a shoal, resulting in energy transfer towards the shadow areas beyond the obstacles blocking the wave propagation.

• reflection (partial or total) from a structure or a pronounced depth irregularity.

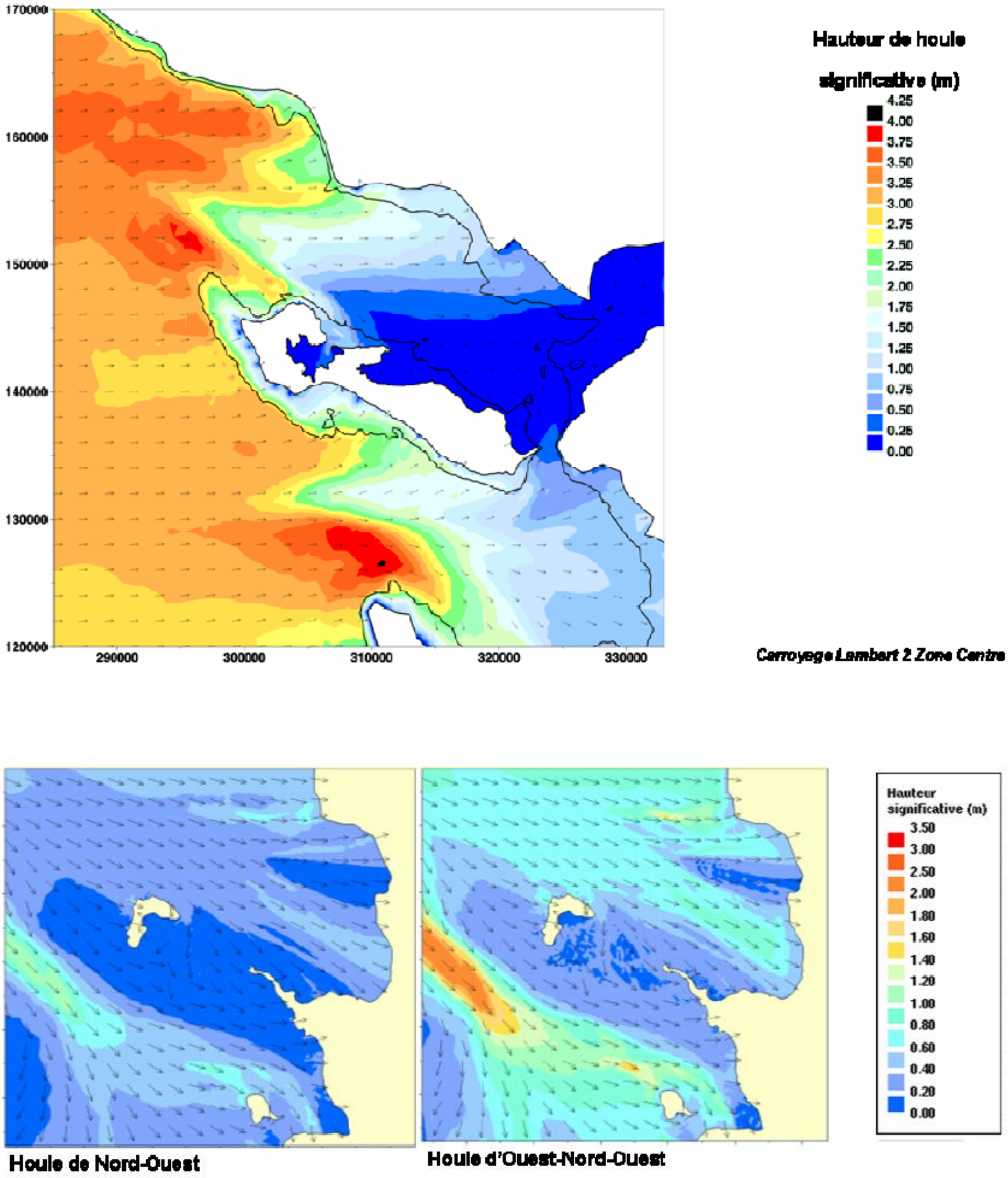
Applications

The applications of this software are connected with the definition of observed wave conditions:

- *definition of the impact of a coastal development scheme (on wave conditions and therefore its implications for the associated sediment behaviour using appropriate software),*
- *definition of constraints on structures,*
- *definition of energy potential linked with waves,*
- *definition of marine submersion risks connected with waves as they approach the coast, etc.*



Annual mean wave directions in the SSA Pertuis Charentais



Wave propagation on the SSA Pertuis Charentais coast

9 SYSIPHE

General description

SISYPHE is a process-based model: sediment transport rates, decomposed into bed-load and suspended load, are calculated as a function of the time-varying flow field and sediment properties at each node of the triangular grid. The resulting bed changes are determined by solving the Exner equation using either finite-element or finite-volume techniques.

SISYPHE is applicable to sand (uniform or not) as well as to cohesive sediments or sand-mud mixtures. The sediment composition is represented by a finite number of classes, each characterized by its mean diameter, grain density and settling velocity. Sediment transport processes also include the effect of bottom slope, rigid beds, secondary currents, sliding beds, etc. In the case of cohesive or mixed sediments, the effect of bed consolidation can be accounted for.

SISYPHE can be applied to a wide variety of hydrodynamic conditions from rivers and estuaries to coastal applications, where the effects of waves superimposed on a tidal current can be included. The bed shear stress, decomposed into skin friction and form drag, can be calculated either by imposing a friction coefficient (Strickler, Nikuradse or Chézy) or predicted by a bed-roughness predictor.

SISYPHE can be either chained or internally coupled to the hydrodynamic models (TELEMAC-2D, -3D) or to the wave propagation model (TOMAWAC).

Coupling with hydrodynamics

SISYPHE does not calculate the flow field: the relevant hydrodynamic variables can be either imposed in the model or calculated by a hydrodynamic computation ('chaining method' or 'internal coupling'). It is more convenient to use one of the hydrodynamic modules of the TELEMAC system (namely TELEMAC-2D, -3D and TOMAWAC for waves) for compatibility reasons (same grid, same pre- and post-processor, etc.), but the user can also choose a different hydrodynamic model.

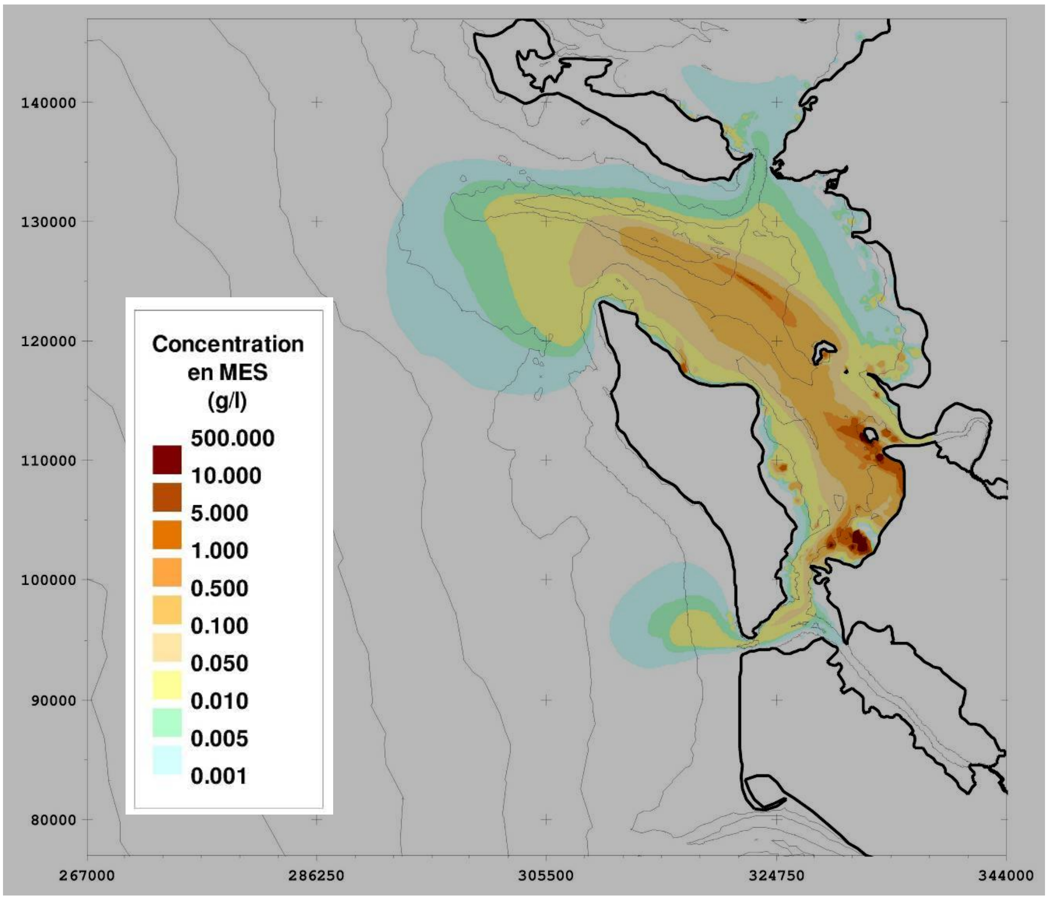
As with any morphodynamics model, the end-user should have a sufficient knowledge of the sedimentary issues, both for selecting the input data (e.g. the transport formulae) and for assessing the results produced.

Applications

This type of model can be used to define sediment behaviour in a given configuration and thus anticipate where erosion or accretion problems are liable to occur.

It can thus be used to define, for example, maintenance dredging programmes and the associated costs for harbour areas in a given configuration. The extra maintenance costs for a harbour development scheme can thus be defined.

It can also be used to determine the environmental impact of such works and of possible discharges at sea (by monitoring discharged material, defining deposition areas, etc.), or to determine seasonal changes in turbidity in estuarine areas and thus anticipate suspended sediment levels that are incompatible with local uses (water intakes, etc.).



Maximum concentration of suspended matter resulting from oceanic dispersal of dredged material in the SSA Pertuis Charentais

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