CHAPTER 201

NUMERICAL MODELLING OF SUSPENDED SEDIMENT TRANSPORT IN THE LOIRE ESTUARY

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ABSTRACT

In order to evaluate silt displacements and deposits in the outer part of the Loire Estuary over one year, a two-dimensional depth-integrated model of suspended sediment transport has been carried out. It takes into account transport and dispersion of suspended sediment by tidal currents, and processes of erosion, deposition and bed consolidation. Erosion laws and consolidation laws are specific of the Loire Estuary and come from laboratory experiments.

Representative tidal conditions and river Loire flowrates have been identified : results of the model for these typical cases will be tentatively extrapolated to a one year evolution.

1. INTRODUCTION

As part of environmental studies involved in a future nuclear power plant near the mouth of the Loire Estuary, the Laboratoire National d'Hydraulique has been commissionned to look into hydraulic and sediment problems and to focus on silt displacement in the outer part of this estuary, located on the west coast of France (fig. 1).

The main feature of this estuary is a turbidity maximum which lies most of the time in the inner part ; but every year, during flood discharge, about one million tons of suspended sediments are partially expulsed seawards (fig. 1).

It is therefore of great interest to know if a silt particle, coming from the inner part of the estuary and possibly polluted with radionucleide, will be either quickly ejected seawards or trapped off the mouth of the estuary in one of the sensitive bays devoted to tourism or oyster farming.

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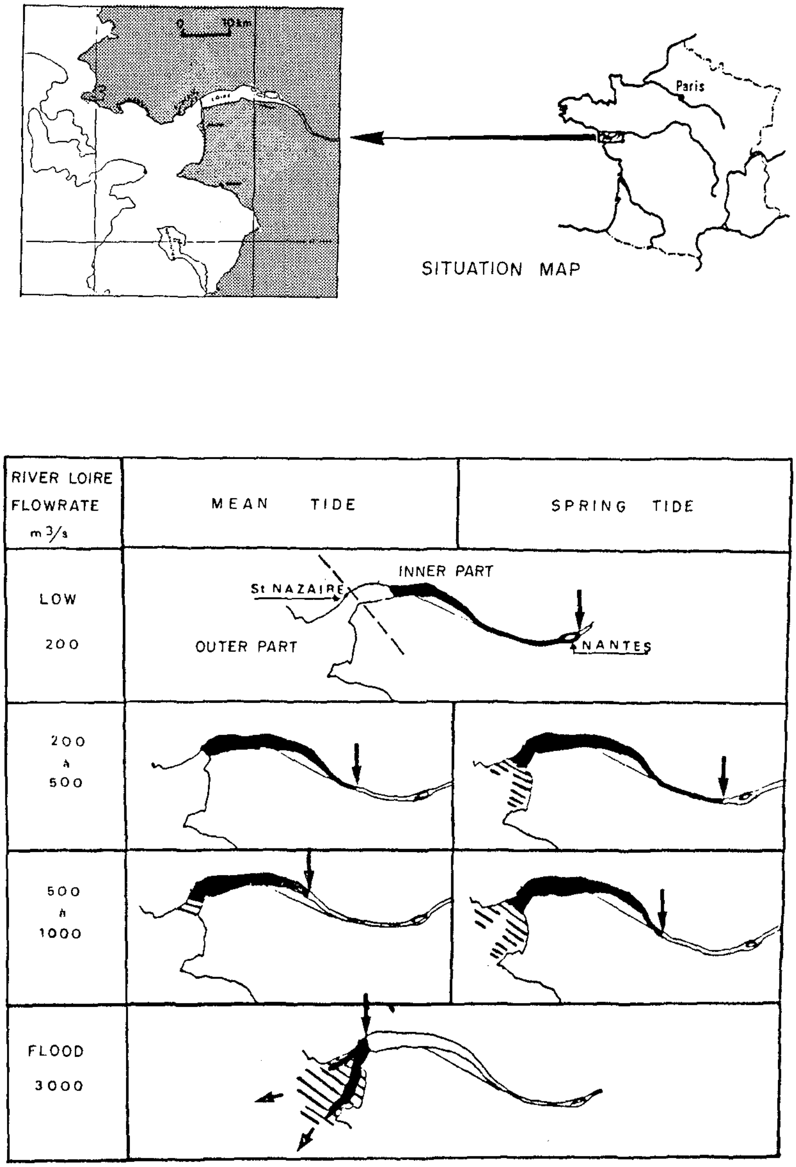


Figure 1 _ OSCILLATIONS OF THE TURBIDITY MAXIMUM IN THE LOIRE ESTUARY, ACCORDING TO RIVER FLOWRATES AND TIDAL RANGE (after GALLENNE 1974) _

After a presentation of the sediment model and processes of mud involved, hydrodynamic results, turbid plume extent, bed evolution are shown and lead to a better understanding of sediment dynamic.

2. SEDIMENT MODEL

2.1 The depth-averaged equation and its hypothesis

Flow structure and sediment circulations in coastal waters and estuaries are complex phenomena and need often a three- dimensional model in order to simulate really accurately their motions and patterns. In fact, in case of morphological computations as maintenance of navigation facilities, a prediction over a period of several months or years is asked and a three-dimensional model is not well adapted due to prohibitive computational work.

Fortunately, it is not always necessary to model the complete structure of the flow. Provided the transport quantity is well mixed throughout the water depth, it can be sufficient to consider depth-averaged equations : this approximation is particularly appropriate for a wash-load which consists of fine cohesive particles with very low settling velocities, and when sediment concentration remains moderate. Such depth-integrated models have been extensively developped in the past years (ARIATHURAI and al, 1977 ; HAYTER, 1983 ; THOMAS and MC ANALLY, 1985).

In this way the use of a monodimensional vertical model of suspended sediment transport developped at LNH has enabled to outline first criteria concerning the vertical homogeneity allowing depth integration : advection time scale (linked to the fall velocity) has to be at least twice the diffusion time scale, and furthermore must be much larger than the slack duration (TEISSON, 1984).

The bidimensional depth-averaged equation for transport of suspended sediment is then the following :

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = \frac{1}{h} \frac{\partial}{\partial x}\left[hK_x \frac{\partial C}{\partial x}\right] + \frac{1}{h} \frac{\partial}{\partial y}\left[hK_y \frac{\partial C}{\partial y}\right] + \frac{S}{h} \qquad (1)$$

in which :

C = depth-integrated concentration of the suspended sediment

u, v = depth-integrated components of velocity

Kx, Ky = dispersion coefficients

h = water depth

S = source - sink term accounting for erosion or deposition

The main hypothesis of the numerical modelling of suspended sediment transport is the decoupling between hydrodynamic and sedimentology. In the equation for transport of suspended sediment, hydrodynamic conditions - i.e. velocity and water depth fields (U, V, h) - are known, being previously computed by a numerical model solving the equations of tide propagation. It is assumed that sediment transport does not affect the hydrodynamic behaviour of the flow ; a new computation of velocity components occurs only if bottom evolution is relevant, due to erosion or deposition.

2.2 Mud processes

2.2.1) Settling velocity

For very low concentration, the settling velocity W_c is assumed constant. For higher concentration the settling velocity can depend on the concentration, in the range C = 1 - 10 g/l, as for example :

$$W_c = K\, C^{4/3} \tag{2}$$

where K is a constant about 10^{-5} (S.I. units), depending on sediment characteristics (from measurements in the Loire Estuary made in 1969).

2.2.2) Deposition rate

The deposition rate can be given by the KRONE's formulation (1962).

$$Q_d = P_d \; W_c \; C \tag{3}$$

in which P_d is the probability of particles sticking to the bed and not being reentrained by the flow, given by :

$$P_d = 1 - \left[\frac{u_*}{u_{*d}}\right]^2 \qquad \text{for } u_* < u_{*d} \tag{4}$$

where u_* is the shear velocity and u_{*d} the critical shear velocity under which deposition occurs.

2.2.3) Erosion rate

Erosion rate is represented by an experimental formulation obtained for the Gironde Estuary (CORMAULT, 1971) :

$$Q_e = M\left[\left(\frac{u_*}{u_{*e}}\right)^2 - 1\right] \qquad \text{for } u_* > u_{*e} \tag{5}$$

where u_{*e} is the critical shear velocity above which erosion occurs and M is determined experimentally :

$$M = 0.55\left(\frac{C_s}{1000}\right)^3 \qquad \begin{array}{ll} C_s & \text{in g/l} \\ M & \text{in kg/m}^2\text{/s} \end{array} \tag{6}$$

where C_s is the concentration of the outcropping deposit.

Other formula of erosion rate depending of soil consolidation (MEHTA et al, 1982) may also be tested.

2.2.4) Bed profile

Consolidation of the bed is simulated at each node in the numerical model by a pile of ten layers of increasing concentration, each layer of various thickness being characterized by a maximum residence duration (after which mud of the layer goes into the underlocated more concentrated layer) and a critical shear stress for erosion related to the layer density.

The duration stay accounts for consolidation and is based upon experiences of MIGNIOT (1980) (fig. 2).

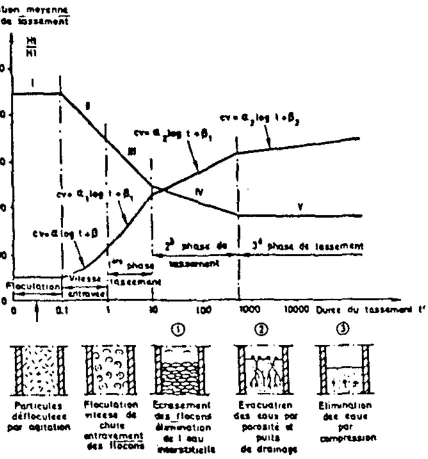


Fig. 2 - Graphical representation of bedding-down phases

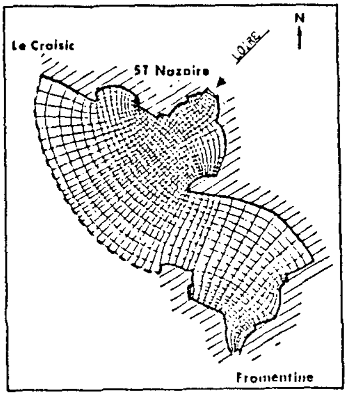
For instance, for the Loire Estuary, the mean concentration of settled sediment in g/l is given by :

$$C\ (t) = 136.2 \log_{10} (t + 5.42) \quad 0<t<24h \quad t \text{ in hours}$$
$$C\ (t) = 200 + 70 \log_{10} (t) \quad t>1 \text{ day} \quad t \text{ in days} \tag{7}$$

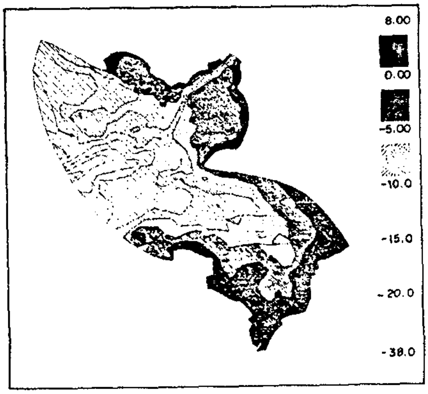
Furthermore MIGNIOT (1981) has related the critical shear for erosion to the concentrations of deposit. For the Loire Estuary :

for partially consolidated deposits
$$(C_s<240g/l) : u_{*e} = 3.2\ 10^{-5}\ (C_s)^{1.175}$$

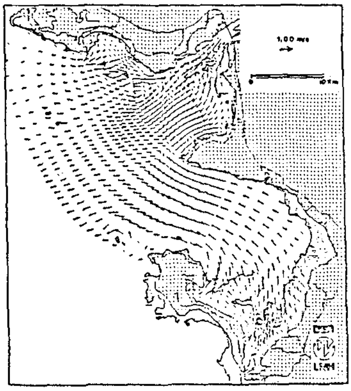
for consolidated deposits
$$(C_s>240\ g/l) : u_{*e} = 5.06\ 10^{-8}\ (C_s)^{2.35} \tag{8}$$



a) Curvilinear Grid _



b) Bathymetry _



c) Current Field (Ebb)

Figure 3 _ MODEL OF THE RIVER LOIRE ESTUARY.SPRING TIDE .
LOIRE FLOWRATE : 1000 m^3/s .

With these data, and for a type of mud corresponding to the one of the Loire Estuary, the bed has been modelled as shown in table 1 :

n° Layers	Concentration (g/l)	Duration stay (h)	u_{*e} (cm/s)
1	100	2	0.72
2	118.6	2	0.88
3	132.7	2	1.00
4	144.1	4	1.10
5	161.8	6	1.26
6	181.3	8	1.44
7	200	16	1.62
8	215.5	32	1.77
9	233.4	54	1.94
10	250.4	infinite	2.19

Table 1 : Layer characteristics for bed modelling

When deposition occurs, the deposit always goes into the first layer, the thickness of which increases consequently. After 2 hours, if no erosion occurs, the content of the first layer goes into the underlocated more consolidated layer and is added to the existing content (the same operation is repeated for other layers).

When bed shear exceeds critical shear velocity of the top layer, then erosion occurs ; each successive layer is similarly tested for potential erosion.

Finally at each time step, the source - sink term is computed :

$$S = Q_d + Q_e$$

from the formulations (3) and (5) above.

2.3 Numerical solution

Given the hydrodynamic data, the numerical model of suspended sediment transport computes horizontal advection and dispersion by the current by means of a time splitting method.

The first intermediary step solves the advection terms on the left hand of equation (1), with a characteristics method.

The second and third intermediary steps solve dispersion in the x and y direction by means of an implicit scheme which takes into account the source term S (TEISSON, 1985).

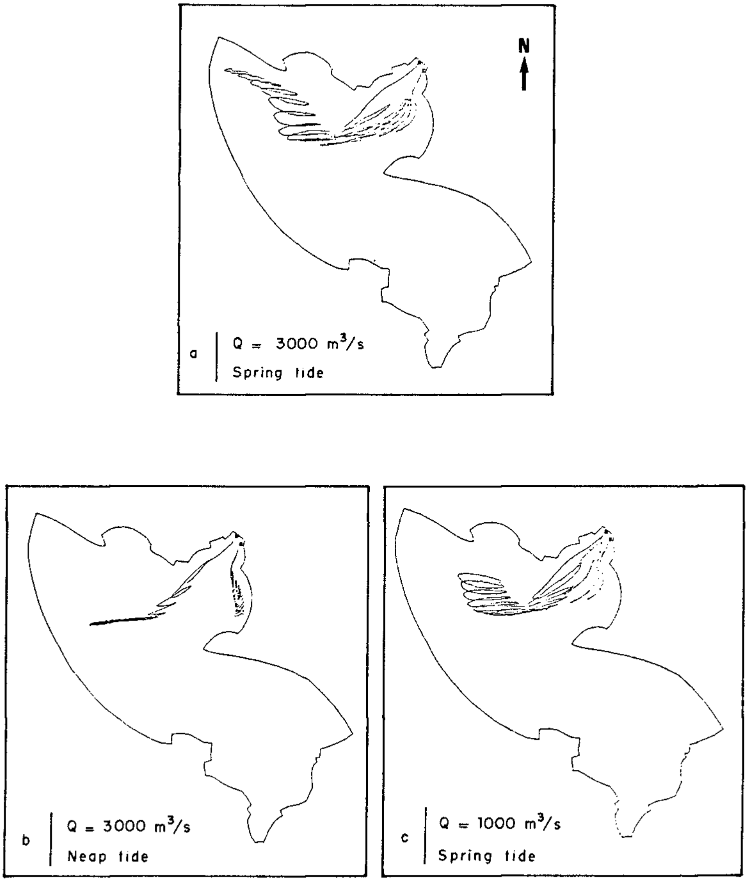


Figure 4 _ INFLUENCE OF THE TIDAL RANGE (a - b) AND OF THE LOIRE FLOWRATE (a-c) ON LAGRANGIAN DRIFTS _

Every 2 hours the residence times of deposits are compared to the duration stay of the corresponding layers : when this duration stay is reached, the contents of the layer go into the underlocated more consolidated layer and the total thickness of deposit is reduced consequently.

Both hydrodynamic and sediment depth-integrated models use rectangular or curvilinear orthogonal grid, finite difference scheme, time - splitting method.

3. APPLICATION TO THE LOIRE ESTUARY

Running of the hydrodynamic and sediment models have been performed for various tidal conditions and discharge flows of the Loire river. Assuming that the most interesting phenomena for suspended sediment occur for strong discharge flows (see fig. 1), two flow rates have been chosen - 1000 m^3/s and 3000 m^3/s - associated to three different tidal range - spring tide, neap tide and mean tide - in order to obtain six representative environmental conditions.

The curvilinear grid comprises 1146 nodes ; the size of the mesh varies from less than 300 meters in refined areas (navigation fairway) to 2500 m for the largest (fig. 3). Bathymetry has been very accurately represented, taking into account navigation fairway, intertidal flat, isolated islands. Time step is 240 s, both for hydrodynamic and sediment model.

3.1 Results of the hydrodynamic model

The hydrodynamic modelling is performed using the two-dimensional, depth-integrated flow model CYTHERE ES1 (BENQUE and al., 1982). This model solves the classical St-Venant equation for tide propagation and incorporates intertidal flats.

The corresponding fields of current and water depth (u, v, h) have been calculated for the six environmental conditions, and calibrated against natural measurements (TEISSON and al., 87). The results are good and do account with the complex problem of intertidal flats : these flats take up 10% of the area at low water.

As an example figure 3 presents current field during the ebb of a spring tide for a Loire flowrate of 1000 m^3/s.

Lagrangian calculations have also been made and keeping tracks of floats during 10 tides from hydrodynamic result displays an offshore drift, magnified in flood, which saves the bays (fig. 4).

3.2 Input data for the sediment model

In addition to velocity and water depth fields at each time step, the model requires values for sediment parameters derived from consolidation, deposition and erosion laws already presented in Section 2.2, as also boundaries and initial conditions.

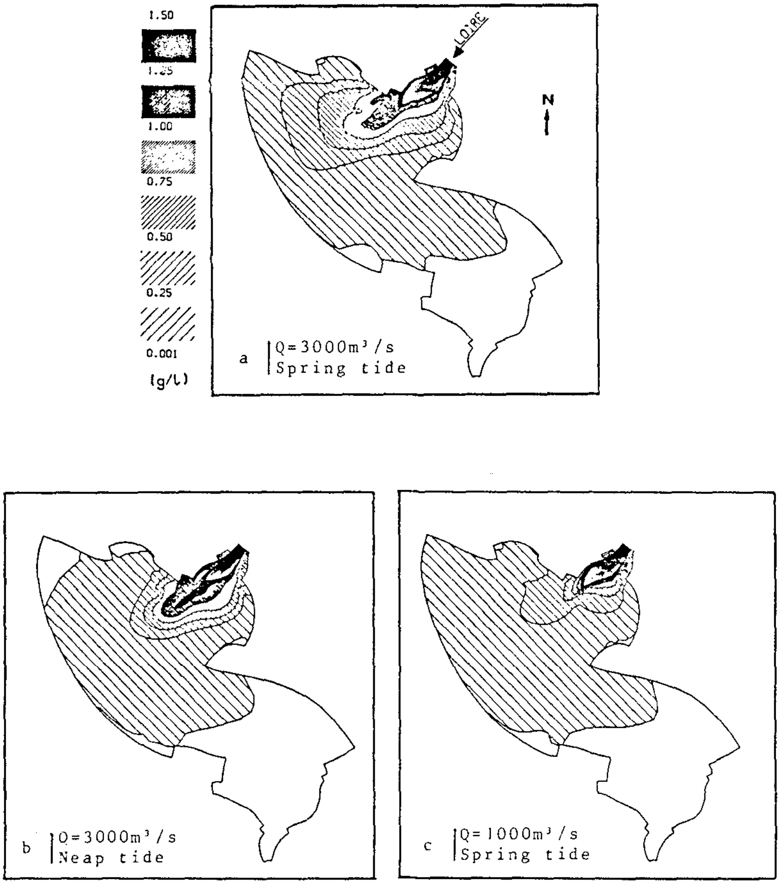


Figure 5 - INFLUENCE OF THE TIDAL RANGE (a-b) AND OF THE LOIRE FLOWRATE (a-c) ON THE PLUME EXTENT (Low Water)

At the upstream boundary, extensive fields surveys have been made in four stations in the narrowest section, and provide suspended sediment concentrations throughout the tide period for various tidal range and river flowrate : these concentrations can reach up to several grams per liter. At the seaward boundary, suspended sediment concentration varies from 0 to 5 mg/l from scarce measurements.

Initial conditions are the following : there is no sediment in suspension or at the bottom, as the aim is to investigate silt displacement coming from the inner part of the estuary.

3.3 Results of the sediment model

Numerous model runs, constituting a sensitivity analysis, have been conducted in order to evaluate the influence of various parameters as horizontal dispersion coefficient, critical shear stress for deposition, dependance of fall velocity upon suspended sediment concentration. For each typical case, representative of one tidal range and one river flowrate, computations were performed over a period of ten identical tides in order to load the model and reach an equilibrium state.

The fig. 5 presents the influence of the tidal amplitude (compare a - b) and of the Loire flowrate (a - c) on the suspended concentration : the flowrate appears to be the main parameter for plume extent. The plume extent is canalized by the navigation fairway where the highest concentrations of suspended sediment are found : this is a feature common to the prototype.

Although suspended sediment concentration is governed by the river flowrate, sediment deposition appears to be controlled by tidal range : thicknessess of deposit are 8 times greater in neap conditions than in spring conditions (compare a-c on fig. 6). Bed evolutions throughout the tide can be followed : deposit that occurs in the fairway during slack at high water is swept out by strong currents during ebb conditions (a-b, fig. 6). Beside the navigation fairway, the first results show good qualitative results ; the difficulty is the lack of reliable and evenly distributed in situ measurements to accurately assess the results for deposit.

3.4 Modelling of a typical year evolution

As it would be computer time consuming to represent the whole year (705 tides), modelling of a typical year evolution is attempted by use of the six typical environmental conditions of the hydrodynamic model. A fortnightly tidal cycle is schematized by a succession of the three basic tidal ranges, for a constant Loire flowrate (either 1000 or 3000 m^3/s). The typical year evolution is approached by the combination and extrapolation of various fortnightly tidal cycles results, with or without mud injection at the upstream boundary depending on season (winter-summer).

This stage of the experimentation is going on at the present time : results after fortnightly tidal cycles are available but it remains to combine and extrapolate these results to one year.

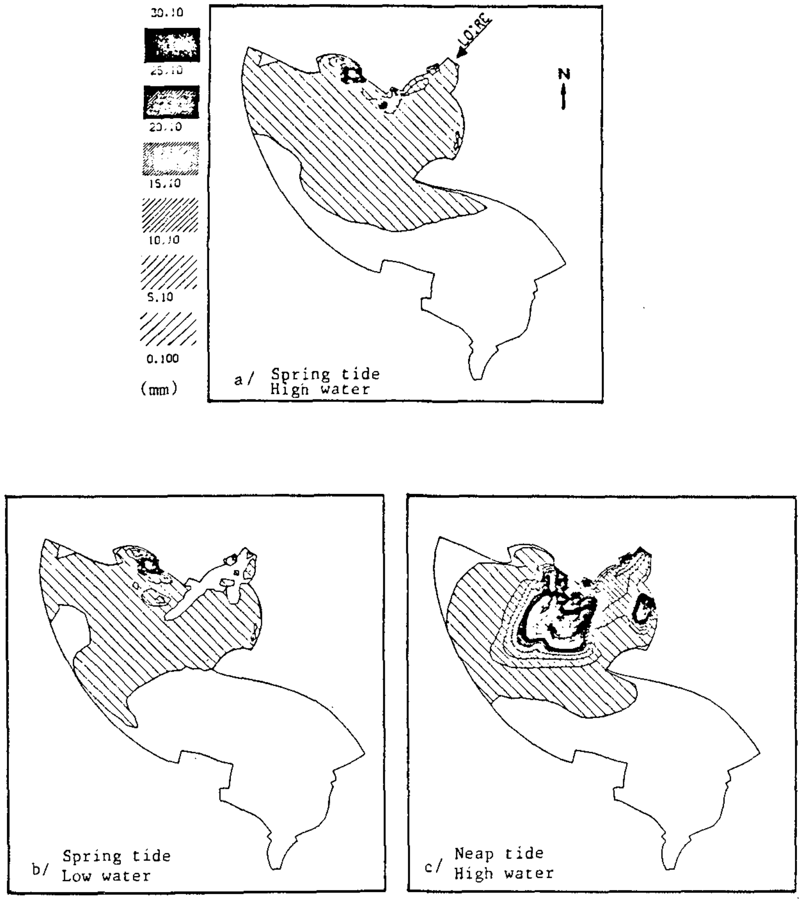


Figure 6 - TOTAL THICKNESS OF DEPOSIT

$Q = 3\ 000\ m^3/s$

CONCLUSION

The objective of the study was to evaluate silt displacement and deposit in the outer part of Loire estuary in an attempt to represent typical year's evolution.

The hydrodynamic model CYTHERE ES1 has enabled to compute very satisfactorily six typical current and water depth fields related to different tides and flowrates of the Loire River.

For each of these six typical cases, the 2D numerical model of suspended sediment transport has led to a better understanding of the processes which govern sediment dynamic. Suspended sediment concentration is under the influence of river Loire flowrate, while deposit is controlled by tidal range. Importance of spring-neap tidal cycle has been pointed out, and this fortnightly cycle has been chosen as an intermediary step before the extrapolation to one year's evolution which is currently under progress.

REFERENCES

ARIATHURAI R., MAC ARTHUR R.C, KRONE R.B. (1977 : Mathematical model of estuarial sediment transport. T.R. D77.12 - U.S. Army Engineer - Waterways Exp. Station P.O. Box 63 Vicksburg, Miss 39180.

BENQUE J.P., CUNGE J.A., FEUILLET J., HAUGUEL A., HOLLY F.M. Jr. (1982) : "New Method for Tidal Current Computation", Journal of the Waterway, Port, Coastal and Ocean Div., ASCE, vol 108, No. WW3, Aug. 1982.

CORMAULT P. (1971) : "Détermination expérimentale du débit solide d'érosion des sédiments fins cohésifs", 14e Congrès de l'A.I.R.H., Paris.

GALLENNE B. (1974) : "Les accumulations turbides de l'estuaire de la Loire. Etude de la crème de vase. Thèse de 3ème cycle. Université de Nantes.

HAYTER E.J. (1983) : Prediction of cohesive sediment movement in esturial waters PHD Thesis UFL/COEL-83/010 Coastal and Oceanographic Engineering Department. University of Florida, Gainesville, Florida 32611.

KRONE R.B. (1962) : "Flume studies of the Transport Sediment in Estuarial Shoaling Process", Tech. Resp., Hydr. Eng. Lab., University of California at Berkeley.

MEHTA A.J., PARCHURE T.M., DIXIT J.G., ARIATHURAI R. (1982) : Resuspension potential of deposited cohesive sediment beds Estuarine comparison, U.S. Kennedy, Ed, Acad. Press. New York pp. 591-609.

MIGNIOT Cl. (1980) : "Dynamique sédimentaire estuairienne - Matériaux cohésifs et non cohésifs", Oceanis, vol. 6, Fasc. 4, pp. 359-432.

MIGNIOT Cl. (1981) : "Erosion et sédimentation en mer et en rivière" in "La Pratique des Sols et des Fondations", Edition Moniteur 1981, 103 p.

TEISSON Ch. (1984) : "Transport en suspension en mer ouverte. Modélisation bidimensionnelle verticale", LNH HE/42/84.30.

TEISSON Ch. (1985) : "Transport en suspension en mer ouverte - Modélisation bidimensionnelle horizontale", LNH HE/42/85.57.

TEISSON Ch., GRAFF M., FRITSCH D. (1987) : "Etudes hydrosédimentaires de l'estuaire externe de la Loire liées au projet de Centrale du Carnet - 1ère partie : Modèle hydrodynamique", LNH HE/42/87.15.

THOMAS, W.A., and W.H. Mc ANALLY (1985) : A generalized numerical modeling system for open channel flow and sedimentation, TABS-2, "IR HL-85-1, U.S.A. WES, Vicksburg, Miss.