

**EXPERIENCES DE MODELISATION NUMERIQUE DANS  
L'ESTUAIRE DE LA GIRONDE. ETUDE D'UNE  
CIRCULATION TIDALE ET COMPARAISON DES METHODES  
NUMERIQUES EMPLOYEES.**

**A.S. UNNIKRISHNAN\***

*NUMERICAL MODELLING EXPERIMENTS IN THE GIRONDE  
ESTUARY. STUDY OF TIDAL CIRCULATION AND A  
COMPARISON OF THE NUMERICAL METHODS USED.*

*Mots-Clés :* Marée,  
Circulation,  
Mailles irrégulières,  
Courants résiduels.

*Key-Words :* Tides,  
Circulation,  
Irregular grid,  
Residual currents.

**RESUME :**

L'article présente une étude de la propagation de la marée et des courants dans la Gironde, en utilisant des méthodes numériques :

Deux modèles bidimensionnels horizontaux ont été employés :

- un modèle aux différences finies avec maillage régulier et procédure d'intégration implicite en directions alternées,
- un modèle à maille triangulaire et méthode explicite.

Pour faciliter la comparaison des deux modèles on a utilisé le même fichier bathymétrique et les mêmes conditions aux limites ouvertes. Les résultats des deux simulations sont comparés avec des mesures in situ et les résultats d'un modèle réduit construit au Laboratoire National d'Hydraulique. On a observé que les deux modèles décrivaient correctement la marée ; le modèle implicite s'avérant meilleur pour la simulation des variations transversales de la marée et des courants résiduels.

**ABSTRACT :**

The present paper deals with the study of tidal propagation and horizontal circulation in the Gironde estuary using numerical methods. A classical two dimensional model using an ADI scheme is applied. In addition, a new model is developed using triangular meshes by making use of a scheme called irregular grid finite difference.

rence method. In the application to the Gironde, the two models have the same topography and open boundary conditions. The results of the two models are compared with the results of hydraulic model simulations of Laboratoire National d'Hydraulique and in situ measurements. It is found that the two models reproduce well the transient eddies during slack and the hour of the tide at which they occur. The results of the classical model are used for studying lateral variations of tidal propagation in the estuary, residual currents etc.

## INTRODUCTION.

The present paper has two objectives. Firstly, to study the tidal propagation and horizontal circulation in the Gironde estuary by numerical methods. Secondly, the paper aims at comparing the merits and demerits of the two numerical methods used for this purpose.

The Gironde is situated (figure 1) along the southwestern part of France, near Bordeaux. The estuary is characterised by the presence of a number of channels, bars and islands. Historically, there had been deposition of sediments in certain regions and erosion in other regions in the Gironde, where as certain regions have suffered alternate erosion and deposition. In order to study sedimentation problems, various workers have studied the circulation patterns based on observed data on tides, currents, and hydrology (Allen, 1973 ; Castaing, 1981). In addition, hydraulic models and a few mathematical models were also developed by Laboratoire National d'Hydraulique (L.N.H., Rapports 1971, 1975 etc.). In 1979, De Grandpré developed a numerical model in the x-z plane in order to study the vertical circulation in the Gironde. Most of earlier studies were limited to the study of tidal propagation in the principal channel, as all the tide gauges are installed along the southern bank side. In the present work, a depth averaged 2D model is applied to study the lateral variations of tidal propagation and horizontal circulation in the estuary.

The present work also aims at developing a numerical model using an alternate scheme. The purpose is to adopt a technique which can give a good representation of the coastline and the islands. This becomes particularly relevant in the case of the Gironde because of its geomorphological peculiarities. In the present work, we have adopted a scheme called irregular grid finite difference scheme (IGFD) for developing a model for estuarine applications. This scheme employs triangular meshes and it is similar to the finite element method, as far as the grid network is concerned. However, the equations are treated in finite difference form. The scheme was introduced for oceanic problems by Thacker (1977). For the sake of notation, the first model using a classical finite difference scheme is called stair step boundary model and the model developed during the present work is called IGFD model. Essentially, we discuss various aspects of tidal flow in the Gironde and a comparison of the two techniques used.

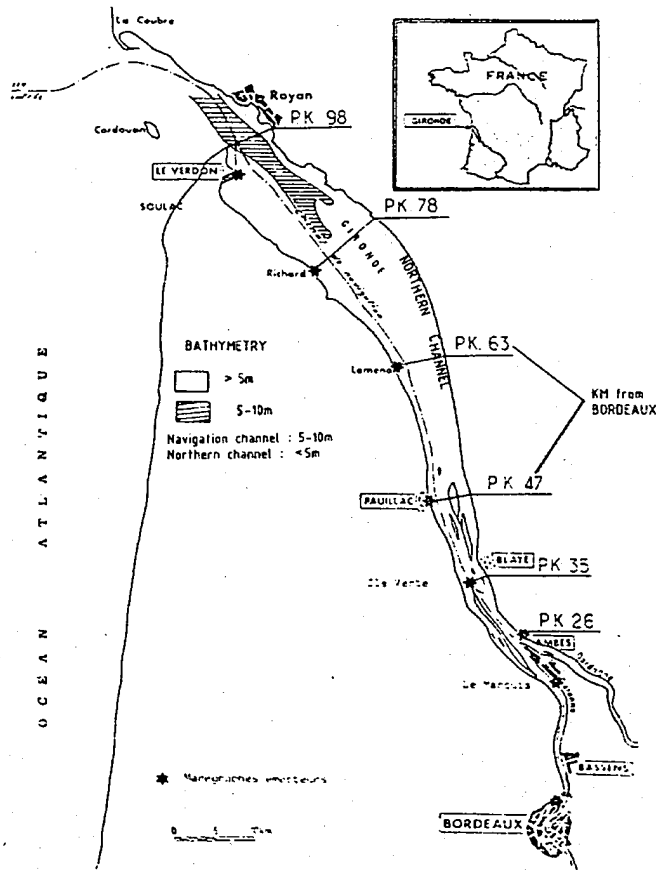


Fig. 1 - La Gironde.  
The Gironde estuary.

## METHODS.

The numerical model used in the present study is the one developed for French estuaries by Salomon and Le Hir (1980). The model uses an implicit in alternate direction scheme applied by Leendertse and Gritton (1971) for computation of tides in estuaries. Salomon and Le Hir (1980) modified the scheme for the application to the French estuaries. This involves the introduction of a psuedo viscosity term and a modification in the calculation of friction term. The details are elaborated by Salomon and Le Hir (1980). Only a brief description is given below. The following are the equations of momentum in the x and y directions and the equation continuity. The equations are integrated in a vertical plane.

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV + g \frac{\partial \zeta}{\partial x} + \frac{gU(U^2 + V^2)}{C^2 H} + \frac{1}{2} \frac{\tau_{sx}}{\rho H} + \epsilon \Delta U = 0 \quad (1)$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + fU + g \frac{\partial \zeta}{\partial y} + \frac{gV(U^2 + V^2)}{C^2 H} + \frac{1}{2} \frac{\tau_{sy}}{\rho H} + \epsilon \Delta V = 0 \quad (2)$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (HU)}{\partial x} + \frac{\partial (HV)}{\partial y} = 0 \quad (3)$$

Where U and V are the depth averaged velocity components,  $\phi$  is the surface elevations ; f is the Coriolis parameter, g is the acceleration due to gravity, C is the coefficient of Chezy,  $\tau_{sx}$  and  $\tau_{sy}$  are the wind stress components in the x and y directions ;  $\epsilon$  is the coefficient of psuedo viscosity,  $\Delta U$  and  $\Delta V$  are the Laplacians of U and V respectively. The integration is carried out over  $H = -h + \phi$ , where h is the still water depth.

Bottom friction is parameterised in terms of the coefficient of Chezy based on the hypothesis of Prandtl by the following relation.

$$C = 7.83 \log (0.37 H/z_0) \quad (4)$$

where  $z_0$  is the thickness of rugosity of the bottom. Wind stress components are computed as follows.

$$\tau_{sx} = \rho_a C_D (u_x - U) \sqrt{(u_x - U)^2 + (u_y - V)^2} \quad (5)$$

$$\tau_{sy} = \rho_a C_D (u_y - V) \sqrt{(u_x - U)^2 + (u_y - V)^2} \quad (6)$$

where :

- $\rho$  : density of air
- $C_D$  : drag coefficient
- $u_x, u_y$  : wind velocities in the x and y directions.

### Numerical resolution.

An implicit in alternate direction scheme is used for the resolution. In the computational grid,  $U$ ,  $V$  and  $\phi$  are calculated on a staggered grid as shown in fig. 2. The scheme is centred in space. For the first half time interval, the equation of momentum in the  $x$  direction and the equation of continuity are solved for each row of the matrix. The variables situated at the row concerned are treated implicitly and the variables situated at the adjacent rows are solved explicitly. For the next half time interval, the momentum equation in the  $y$  direction and the equation of continuity are solved for each column of the matrix in a similar manner. The equations (1) to (3) can be written as tridiagonal matrices. Finally, the solution is made by an inversion of the matrix.

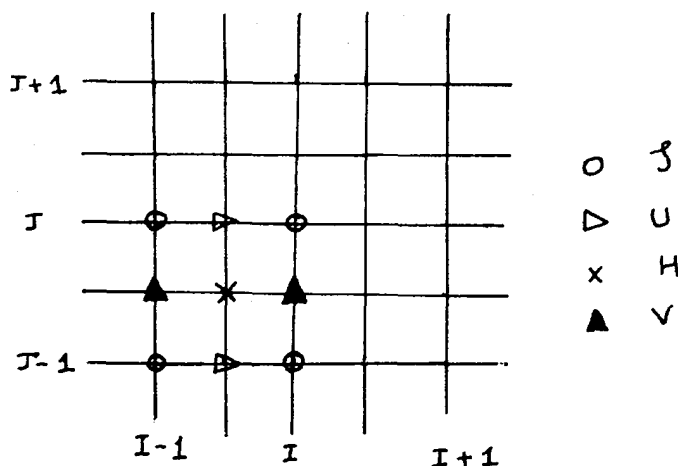


Fig. 2 - Les points du calcul sur la grille.  
Calculation points on the staggered grid.

### Stability.

Leendertse and Gritton (1971) showed that the above system is unconditionally stable, when the equations are linearised. When non linear terms are included, the stability is governed by the following relation.

$$\Delta t < \frac{2g (\Delta x)^2}{C^2 HU} \quad (7)$$

where  $\Delta x$  is the grid spacing and  $\Delta t$  is the time step.

### Conservation.

The system is conservative for a constant topography. In the case of variations in depths, oscillations of small wave length was reported by Salomon and Le Hir (1980) in the case of the Seine estuary. This is overcome by the introduction of the pseudo viscosity term.

### Application to the Gironde.

In the application to the Gironde, the estuarine region is represented by a 2D model and the rivers by a 1D model each. The two dimensional domain consists of 93 20 points. The one dimensional models for the Dordogne and the Garonne consist of 94 and 74 grid points respectively. In the 1D models,  $\Delta x$  is the same as in the 2D model, while the grid spacing in the  $y$  direction varies according to the breadth of the section concerned. The time step used is 180 seconds.

### Open boundary conditions.

The seaward boundary conditions are given in terms of water surface elevations. A cotidal line approximately passing through the open boundary is taken for specifying the conditions. The amplitude is defined as a sinusoidal function of time and the phase being determined based on the distance from the centre of the arc, which approximates the cotidal line. It is true that this method of defining the boundary conditions needs more precision. At the river sides, the open boundary conditions are defined in terms of discharge rates.

### Irregular grid model.

Thacker (1977) used the IGFD scheme for the simulation of shallow water oscillations, in which the equations were linearised. Later, in 1979, he developed a full fledged model including non linear terms for the forecast of storm surges.

The principle of the IGFD scheme may be briefly described as follows. The slope of a curved surface may be approximated by the slope of the plane passing through the three points of the curve (figure 3). The partial derivatives of the curved surface can be approximated by the slope of the plane passing through the surface.

The domain of interest can be divided into a number of triangles. Inside the domain, each vertex of a triangle is surrounded by six triangles, whereas at the boundary by two, three, four or five. The vertices of triangles are taken as grid points. Partial derivatives at a grid point are calculated by a weighted average of the values obtained from surrounding triangles. The formulas used are as follows (Thacker, 1979) :

$$\frac{\partial f}{\partial x} = \frac{\sum_{i=1}^N f_i (Y_{i+1} - Y_{i-1}) / \delta}{\sum_{i=1}^N (Y_{i+1} - Y_{i-1})} \quad (8)$$

$$\frac{\partial f}{\partial y} = - \frac{\sum_{i=1}^N f_i (X_{i+1} - X_{i-1}) / \delta}{\sum_{i=1}^N (X_{i+1} - X_{i-1})} \quad (9)$$

where :  $f$  is any veritable  $U$ ,  $V$  or

$$\text{and :} \quad \delta = \sum_{i=1}^N x_i (Y_{i+1} - Y_{i-1})$$

$i$  is the index of the grid point and  $N$  varies from 3 to 6.

### Model description.

The above mentioned principle of approximating partial derivatives is used in developing a non linear tidal model in the present study. The following are the equations of momentum in  $x$  and  $y$  directions and the equation of continuity. The equations are in the vertically integrated form. The symbols used below have the same meaning as in the previous model.

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV + \frac{\partial \zeta}{\partial x} + \frac{gU (U^2 + V^2)^{\frac{1}{2}}}{C^2 H} = 0 \quad (10)$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + fU + \frac{\partial \zeta}{\partial y} + \frac{gV (U^2 + V^2)^{\frac{1}{2}}}{C^2 H} = 0 \quad (11)$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (HU)}{\partial x} + \frac{\partial (HV)}{\partial y} = 0 \quad (12)$$

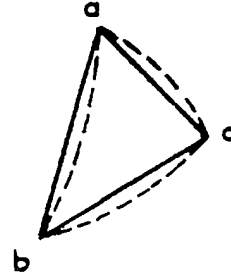


Fig. 3 - L'approximation d'une courbe par un triangle.  
Approximation of a curve by a triangle.

### Numerical resolution.

An explicit scheme in time is used in the model. The Coriolis terms are evaluated at the advanced time steps to guarantee numerical stability.

$$\begin{aligned} \frac{U_i^{n+\frac{1}{2}} - U_i^{n-\frac{1}{2}}}{\Delta t} + U_i^{n+\frac{1}{2}} \left( \frac{\partial U}{\partial x} \right)_i^{n-\frac{1}{2}} + V_i^{n-\frac{1}{2}} \left( \frac{\partial U}{\partial y} \right)_i^{n-\frac{1}{2}} - fV_i^{n+\frac{1}{2}} + g \left( \frac{\partial \zeta}{\partial x} \right)_i^n \\ + \frac{gU_i^n \left( U_i^{n-\frac{1}{2}} \right)^2 + V_i^{n-\frac{1}{2}} \left( V_i^{n-\frac{1}{2}} \right)^2}{C^2 H_i} = 0 \end{aligned} \quad (13)$$

$$\begin{aligned} \frac{V_i^{n+\frac{1}{2}} - V_i^{n-\frac{1}{2}}}{\Delta t} + U_i^{n-\frac{1}{2}} \left( \frac{\partial V}{\partial x} \right)_i^{n+\frac{1}{2}} + V_i^{n+\frac{1}{2}} \left( \frac{\partial V}{\partial y} \right)_i^{n-\frac{1}{2}} + fU_i^{n+\frac{1}{2}} + g \left( \frac{\partial \zeta}{\partial y} \right)_i^n \\ + \frac{gV_i^{n+\frac{1}{2}} \left( U_i^{n-\frac{1}{2}} \right)^2 + V_i^{n-\frac{1}{2}} \left( V_i^{n-\frac{1}{2}} \right)^2}{C^2 H_i} = 0 \end{aligned} \quad (14)$$

$$\frac{\zeta_i^{n+1} - \zeta_i^n}{\Delta t} + \frac{\partial}{\partial x} (HU)_i^n + \frac{\partial}{\partial y} (HV)_i^n = 0 \quad (15)$$

where  $i$  is the index of the triangle and  $n$  corresponds to the time step.

### Stability and convergence.

Thacker (1978) determined the stability and convergence conditions of the scheme as follows.

$$\gamma = \frac{(gh)^{1/2} \cdot \Delta t}{\Delta x} \quad (16)$$

The condition for stability is  $\gamma < 1$

By the application of Green's theorem on an irregular grid, it is shown that the numerical scheme is convergent as long as there is no flow across the boundaries. Further, by using Taylor's series it can be shown that accuracy of the scheme is of the order one.

It is to be noted that in the present scheme, there is no direct method for approximating the second derivatives. Since the viscosity terms appear in the second derivatives, they are not included in the momentum equations. Sunderman (1966) introduced a factor called numerical viscosity, which is given as follows.

$$f(x) = \alpha f + \frac{1-\alpha}{N} \sum_{i=1}^N f_i \quad (17)$$

where  $0 < \alpha < 1$  and  $f$  is any variable  $U$ ,  $V$  or  $\phi$ . The summation is done over the values of the variables at the surrounding grid points.

### Application to the Gironde.

The grid network used is as shown in figure 4. The whole domain consists of 1330 triangles. In the estuarine region, isosceles triangles of equal dimensions are used with the grid spacing equal to 960 metres. Inside the rivers,  $\Delta x$  is the same as in estuarine region, while the grid spacing in the  $y$  direction varies according to the breadth of the section concerned. In fact, it would have been ideal to use bigger triangles near the seaward side, where the depths are high. This will help in increasing the time step. In the present application, the grid spacing is taken constant, which is the same as in the previous model. This will help in comparing the results of the models closely. However, in the IGF model, the triangles near the coast in the upper estuary are oriented in such a way as to represent the coastline and the islands in a better way. In the lower estuary, such a procedure is not necessary because of the regular geometry of the region. The time step used is 30 seconds. This corresponds to about one third of the maximum allowed value. In the present application, a time step much less than the maximum allowed value is found to give a better solution.



Fig. 4 - La grille irrégulière utilisée pour l'application à la Gironde.  
*Irregular grid used for the application to the Gironde.*

### RESULTS.

The stair step boundary model is calibrated based on the observed tide gauge curves. The coefficients of Chezy used are between 50 to 60 in the lower estuary and 30 to 45 in the upper estuary. In the upper estuary, lower values are given because of higher friction in the region due to the presence of islands. The value of the coefficient of viscosity chosen is 850 and it is constant through the domain.

The irregular grid model is also calibrated and the coefficients of Chezy used are more or less similar to the stair step boundary model. The computed water surface elevations are shown in figure 5. The precision achieved in amplitudes is  $\pm 5$  cm. The phase difference between the observed and the computed water surface elevations increases towards the head of the estuary practically absent at Verdon and maximum found at Pauillac. The model is not used for the comparison of water surface elevations between the two bank sides of the estuary due to the smoothing procedure employed.

The simulation results obtained the stair step boundary model are used to study the lateral variations of tidal propagation in the Gironde estuary. Lateral variations occur due to topographical changes, effects of meandering of the geometry etc ... Fig. 6a representing the cotidal lines shows that the tidal wave moves faster in the northern channel than along the southern bank side in the lower estuary. Previous workers have explained this due to the curvature of the estuary near the mouth, which directs the tidal wave towards the northern side while entering into the estuary. From PK 74 onwards, the phase difference between the two bank sides are absent, as the geometry of the estuary becomes regular. Upstream, there is no data regarding the tidal variations along the north bank side.

The computed water surface elevations are presented in figure 6b to 7. It can be seen that at Richard, Valeyrac and St. Christoly the phase difference between the two bank sides is more along the southern side than along the northern bank side and these differences increase gradually towards the head. It means that in the model, the tidal wave accelerates in the deeper region, i.e., along the principal channel which is situated near the southern bank side. At Pauillac, the simulated curve of surface elevations indicates that the tidal wave is in advance along the northern bank side. In fact, along the lateral section considered for comparison at this point, the distance travelled by the tidal wave is less along the north bank side than at the southern side. At Pauillac, observations show that the tidal wave moves faster in the principal channel than in the northern channel. In the region of curvature, centrifugal forces are important. The slight curvature of the geometry of the estuary near Pauillac makes the radius of curvature more along the southern bank side than the northern side. So water particles near northern bank side get accelerated more due to the centrifugal forces than the southern side. Upstream, at Ile Verte, lateral differences in phase speed between the two bank sides are absent, as the width of the estuary reduces considerably towards the head.





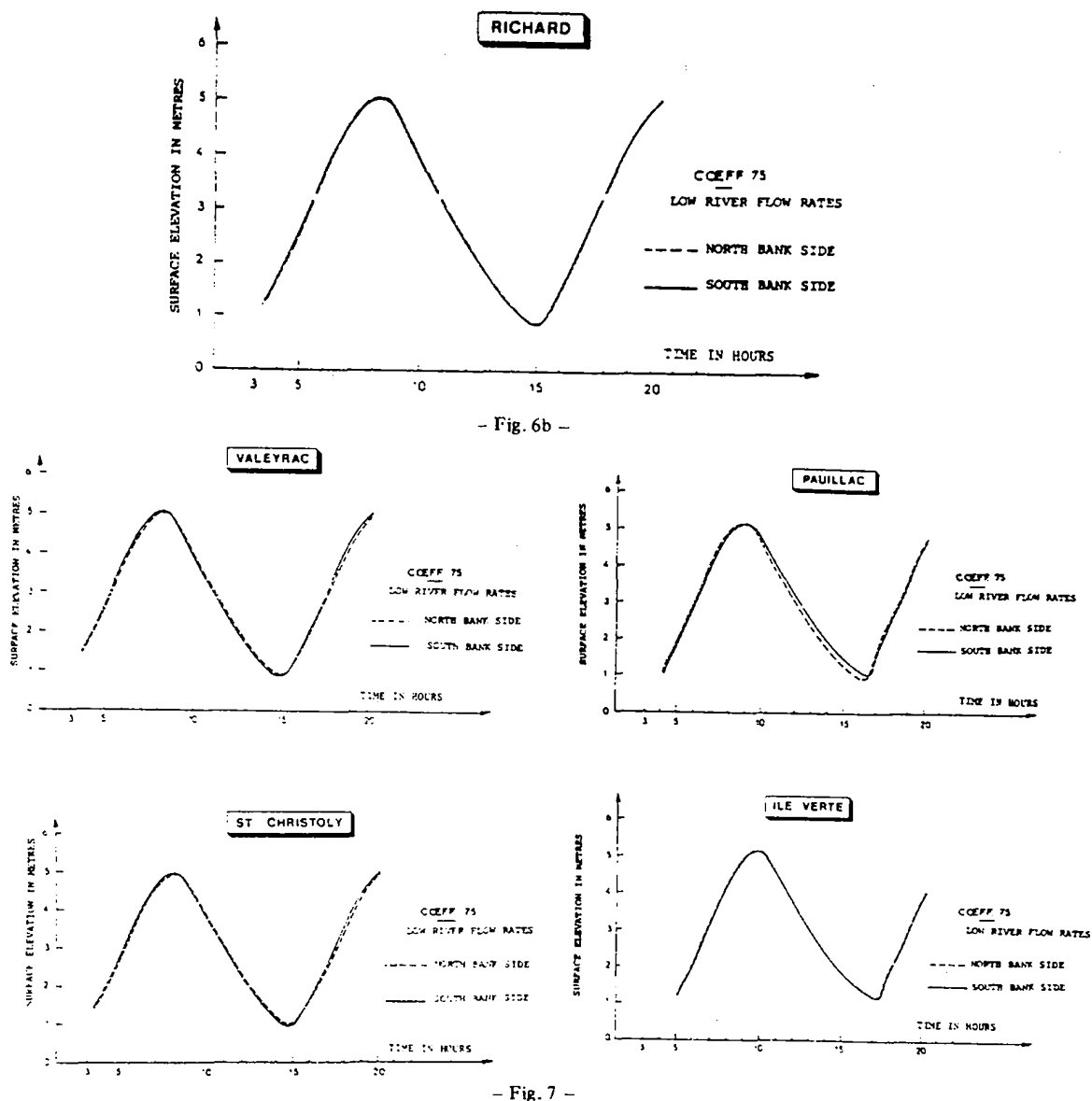


Fig. 6b et 7 - Comparaison des hauteurs d'eau des deux rives de l'estuaire (modèle en marche d'escalier).  
Comparison of surface elevations between the two bank sides of the estuary.

### Circulation in the Gironde.

A lot of observed data on currents in the Gironde is available. Based on this data, various workers (Allen, 1972 ; Reports of Laboratoire National d'Hydraulique (L.N.H. Rapports 1971, 1975 etc ..) ; Castaing, 1981) have described the circulation patterns in the estuary. Circulation studies also include hydraulic model simulations made by L.N.H.

### Stair step boundary model results.

A numerical experiment is done for an average tidal coefficient 75 (note : coefficient 120 corresponds to the highest spring tide and 20 to the lowest neap tide) and for low river flow rates ( $187 \text{ m}^3/\text{sec}$ ). The instantaneous vector diagrams are shown every hour for one tidal period (figures 8 to 10).

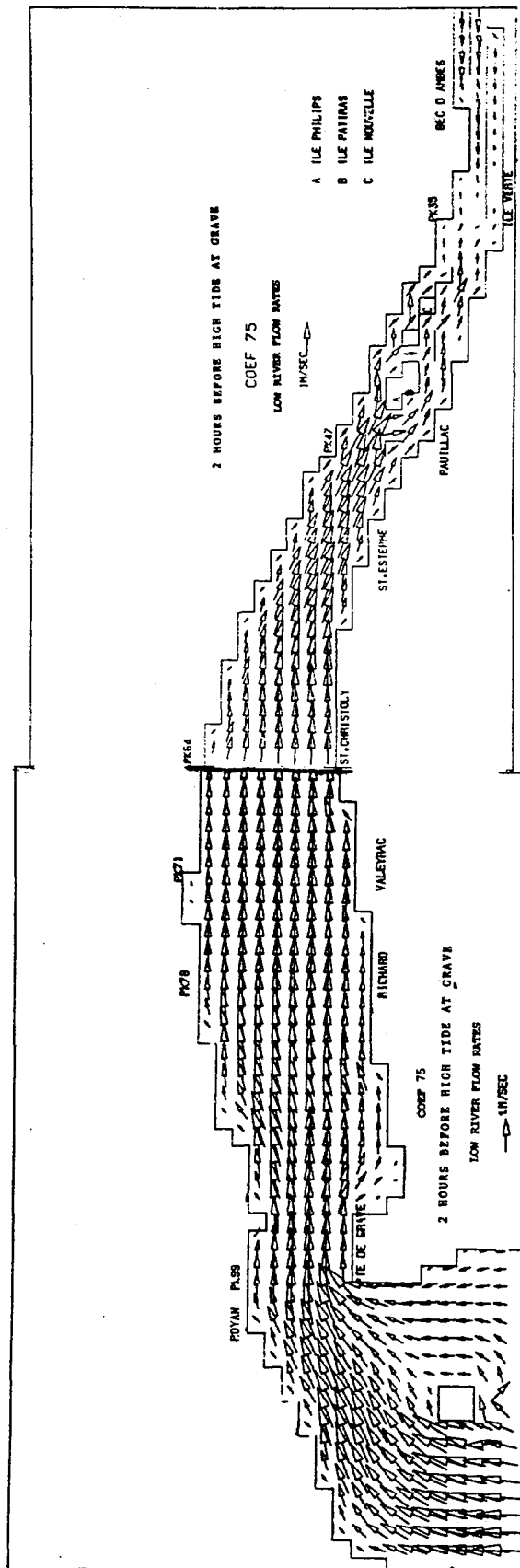
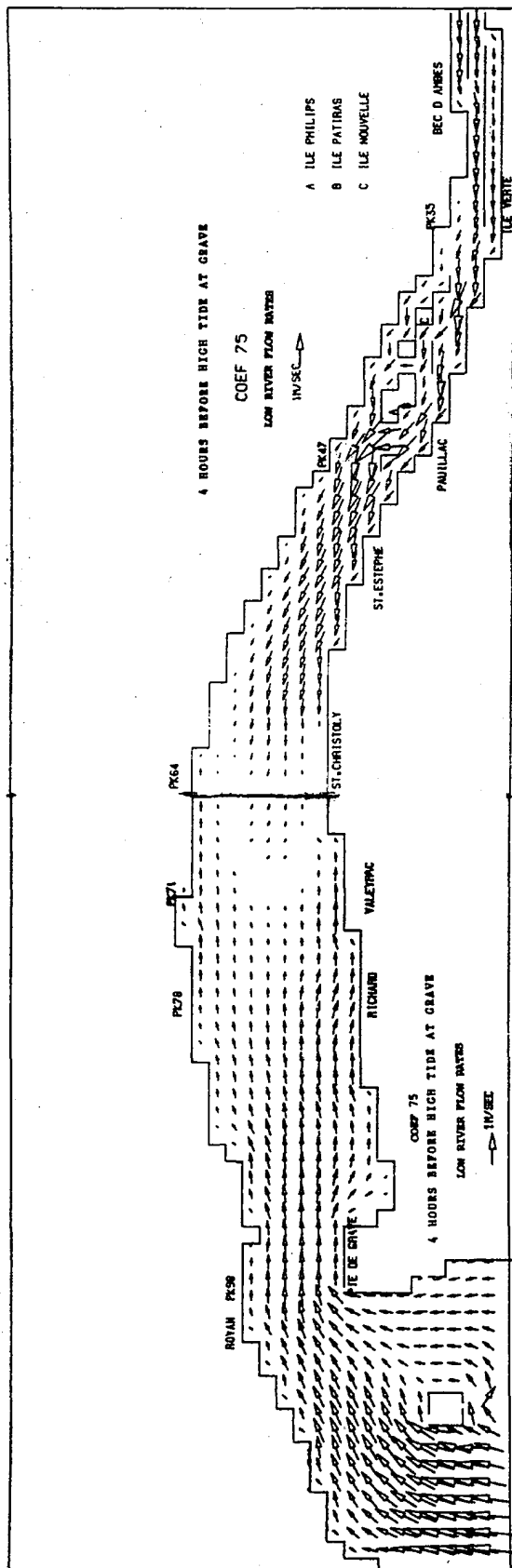
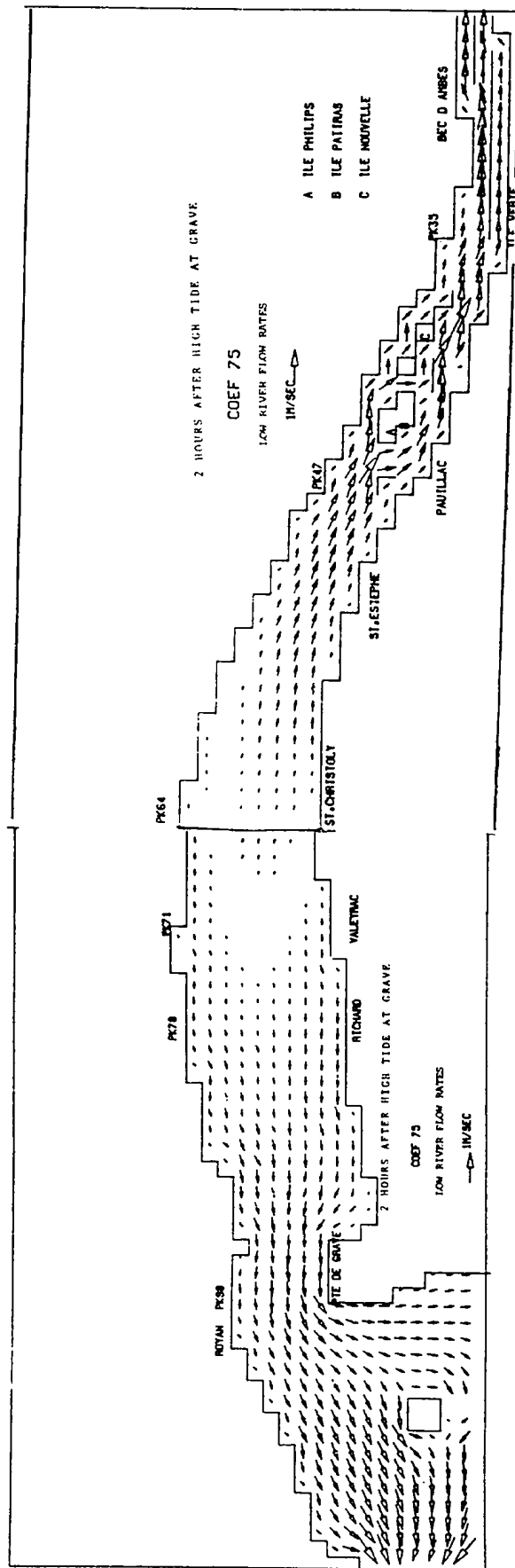
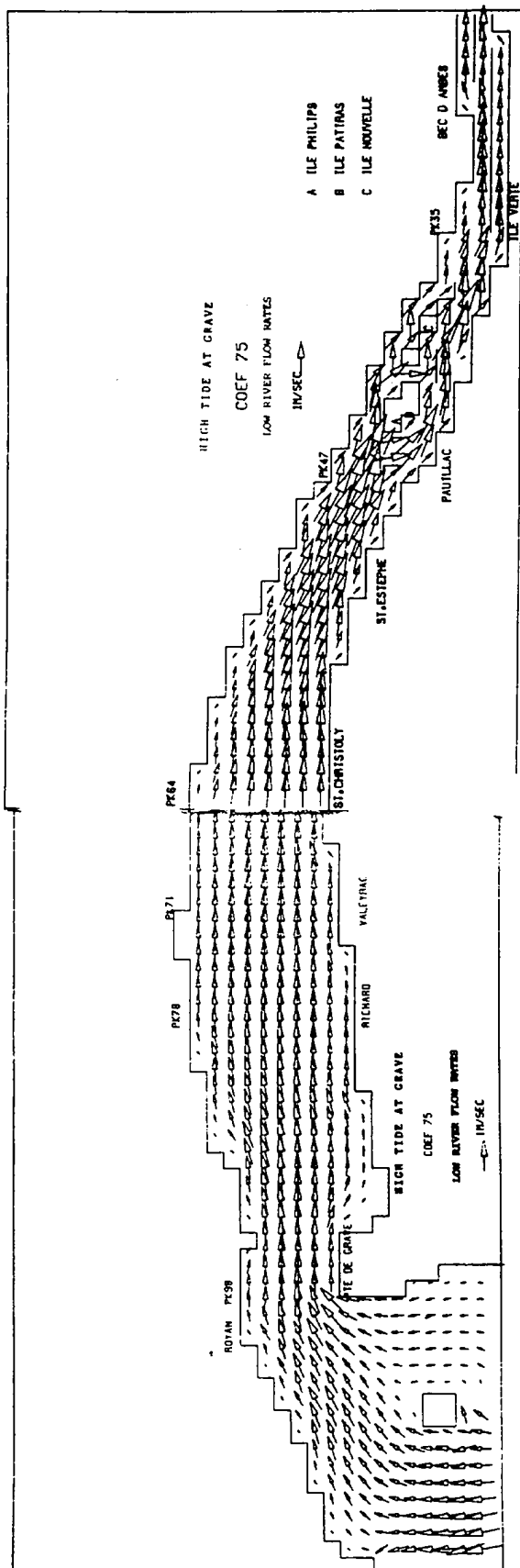


Fig. 8, 9 et 10 - Le champ des courants calculés (modèle en marche d'escalier).  
 Computed currents (stair step boundary model).



- Figure 9 -

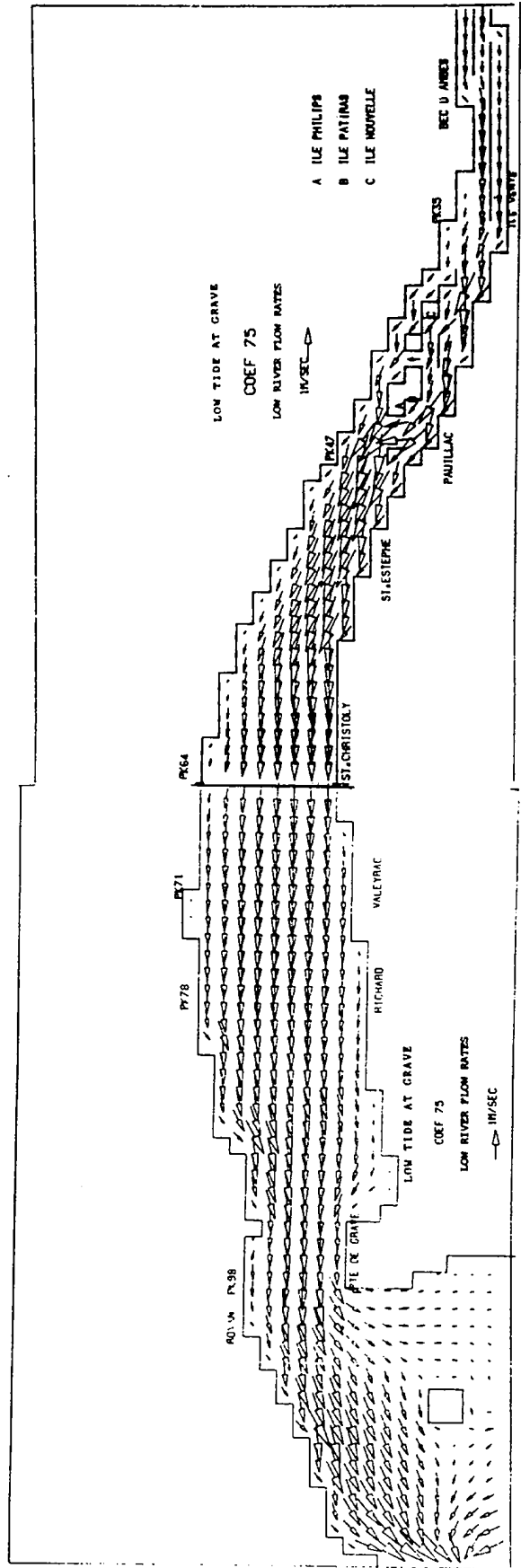
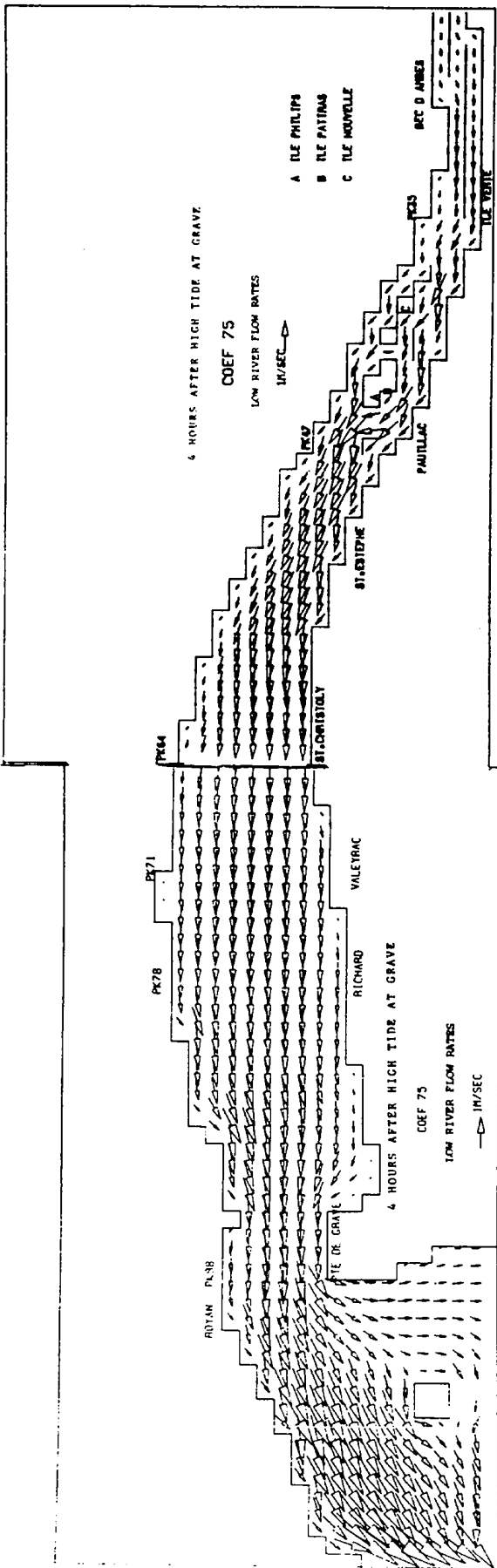


Figure 10

A few salient features of the current field may be noted as follows. In the lower estuary, currents flow parallel to the coast with intensities decreasing towards either coast. Lateral gradients of velocities are determined by the choice of the coefficient of viscosity in the model. A constant value is taken for the whole domain. A minimum value of the coefficient is chosen so that the solution is free from oscillations.

A few transient eddies are present during slack. These are located near the seaward boundary, between PK 70 and 65, near PK 47 and near PK 35. Their lifetime is about one hour. During the transition from flood to ebb, the eddies are clockwise and vice versa. Towards the head of the estuary, the size of transient eddies decreases. The location of these transient eddies and the hour of tide at which they occur correspond to those obtained in the hydraulic models of L.N.H. However, in the hydraulic model, the transient eddy during slack at PK 66 is located in the principal channel (fig. 11), whereas in the numerical model the width of the estuary determines the size of the eddy.

Between PK 50 and PK 40, flood currents are very small in intensities near both the bank sides, though the principal channel has high depths in this region. This is probably due to the fact that the main channel is situated very near the coast in this region and any possible poor representation of the coast by a stair step boundary has affected the computed values of the currents.

In the region of islands, a few notable features are as follows. Near Pauillac, during flood, currents are found to be more intense along the north bank side. Upstream, flood currents are stronger in the principal channel, which is situated towards the northern bank side. During ebb, all along the upper estuary, maximum intensities of currents in different lateral sections are found in the principal channel.

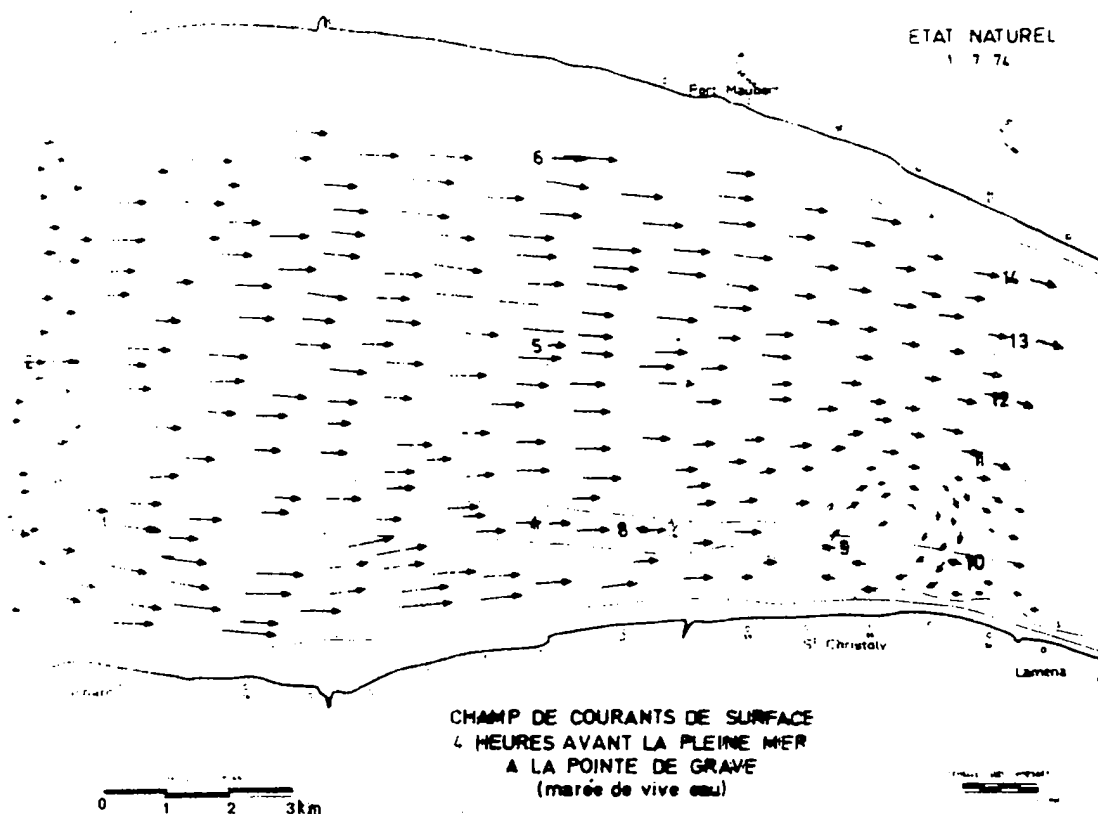


Fig. 11 - Le champ des courants obtenus par une simulation hydraulique du L.N.H.  
Current field obtained from hydraulic simulations (L.N.H.).

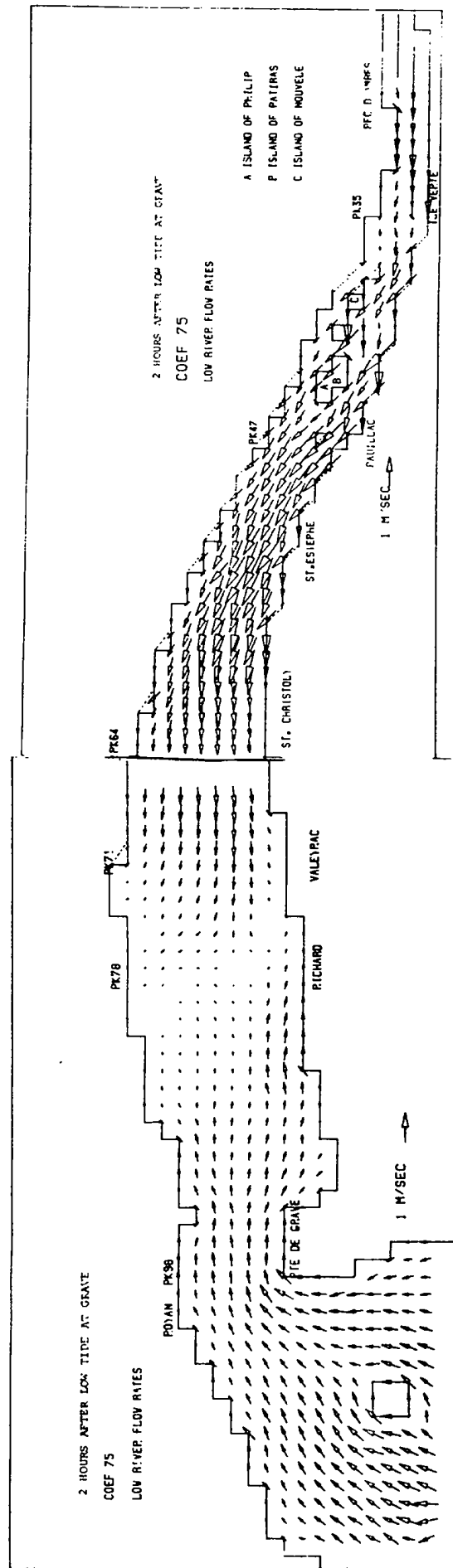
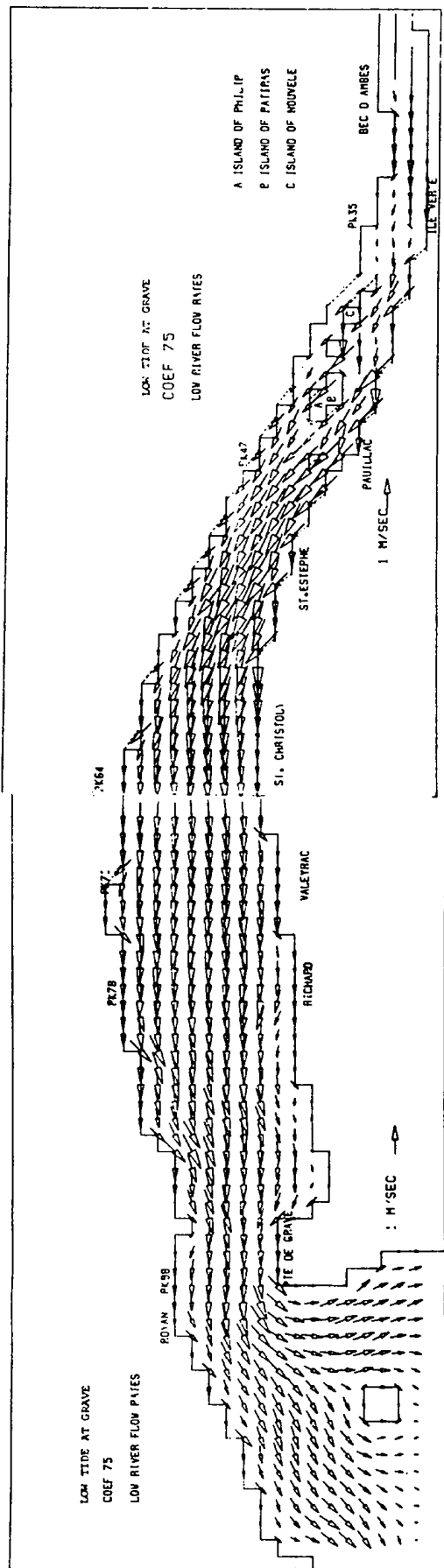


Fig. 12 & 13 - Le champ des courants calculés par le modèle des mailles irrégulières.  
*Computed currents (irregular grid model).*

### Irregular grid model results.

Figures 12 and 13 show a few examples of instantaneous currents. In general, the computed current pattern is similar to that of the stair boundary model. However, lateral and longitudinal gradients of velocities are less marked than the stair step boundary model. This may be attributed to the effect of smoothing. For the present simulations, a small value of the order of 0.01 (corresponds to  $\alpha = 0.99$  in the equation 17) is found to be necessary to avoid oscillations in the curves of velocities plotted against time. This procedure does not have much physical significance and it is found to be necessary because of the difficulties in introducing viscosity term in the momentum equations.

A few transient eddies are found in the current field during slack. They are located near the seaward boundary, near Richard, near St. Estephe and near Ile Verte. The location of these transient eddies and the hour of the tide at which they occur corresponds to that of the stair step boundary model. However, the transient eddy during slack in the lower estuary is found to be located downstream of the location found in the stair step boundary model. This is due to a difference in phase of tidal propagation between the models.

In the upper estuary, between St. Christoly and Pauillac, high intensities of currents are found towards the southern bank side. It is found that computed currents in this region are very small in intensities in the stair step boundary model, in spite of the presence of the main channel very near the coast. In the irregular grid model, an improvement in the computed currents is achieved by virtue of a better grid configuration near the coast.

Upstream of Pauillac, the computed currents along the north bank side are found to have smaller values in magnitudes compared to the hydraulic model results. In the region of islands, it may be necessary to use smaller meshes to have a better description of circulation in this region.

### Comparison between the models.

Computed currents obtained from the two models are compared with observed currents at mid depth, data available under the same coefficients of tide and river discharge rates. It can be noted from figure 12 that the stair step boundary model is more accurate in both magnitude and phase than the IGFD model. At station VI, near PK 63, there is very less phase difference between the observed and the stair step model, where as the IGFD model shows a high phase difference with the observed. In the case of current vector diagram also (fig. 8 and 11), this is observed in the location of transient eddy during slack. At station V, near Pauillac, both the models have a large phase difference with the observed currents during low tide (fig. 14). The computed elevation curve also showed a significant phase difference with that observed at Pauillac (fig. 5).

In the present application, the irregular grid model is found to take approximately two and half times more computer time than the stair step boundary model. This is due to the fact a better solution was obtained by taking a much small value of the time step (1/3 of the maximum allowed). However, by using bigger meshes near the seaward side of the domain, time step can be increased.

### Residual circulation in the Gironde.

Residual circulation in the Gironde is studied based on two parametres, namely depth averaged residual currents and the lagrangian residual displacements. The former is calculated as follows.

$$u_r = \frac{1}{T} \int_0^T u \, dt ; v_r = \frac{1}{T} \int_0^T v \, dt \quad (18)$$

where  $u_r$  and  $v_r$  are the residual currents in  $x$  and  $y$  directions.

Mathematical entities and their physical significance is not very clear. However, these results along with the lagrangian residual displacements may be useful in estuarine applications such as to study the effect of river discharges on currents etc ..

The latter parameter is computed in the following manner.

$$x(t) = \int_0^t U(x, t) \, dt + x_0$$

where  $x_0$  is the starting point and  $x$  is the point of arrival.

The stair step boundary model is used for the calculation of residual parameters. The irregular grid model is not used for this purpose mainly due to the fact the scheme having an accuracy of first order may not be accurate enough for the computation of residual currents. The computed residual currents are shown in fig. 16. The residual currents obtained from observations during high river discharge rates is shown in fig. 15 (Allen, 1973). In the lower estuary, high magnitudes of residual currents are found in the southern channel upto PK 78 and in the northern channel downstream further. Near PK 85, a residual eddy is present. In this region, the presence of a sand bank near the southern bank side and the deep channel near the north bank side make sharp depth gradients in different lateral sections. This depth gradient is mainly responsible for the formation of the residual eddy.

The residual current field in the upper estuary is characterised by a high intensity in the southern channel. Along the north bank side, currents are very small compared to those observed. It means that the depth averaged residual currents show more lateral variations than in nature. In the model, the residual flux of water is concentrated in the regions which favour the ebb flow.

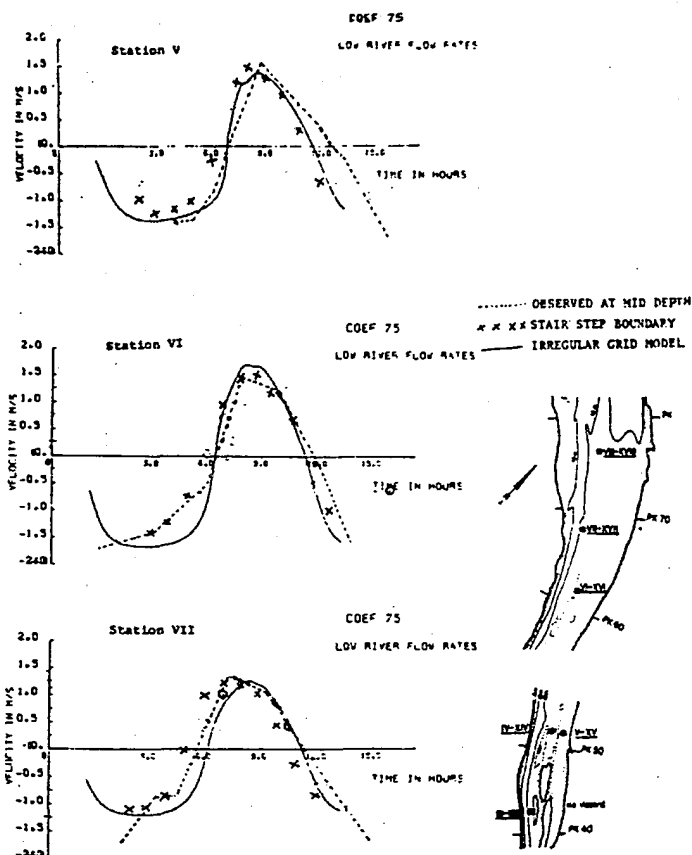


Fig. 14 - Comparaison entre les courants calculés et les courants observés à mi-profondeur.

Comparison of computed and observed currents at mid depth.

In the model, the residual flux of water is concentrated in the regions which favour the ebb flow.

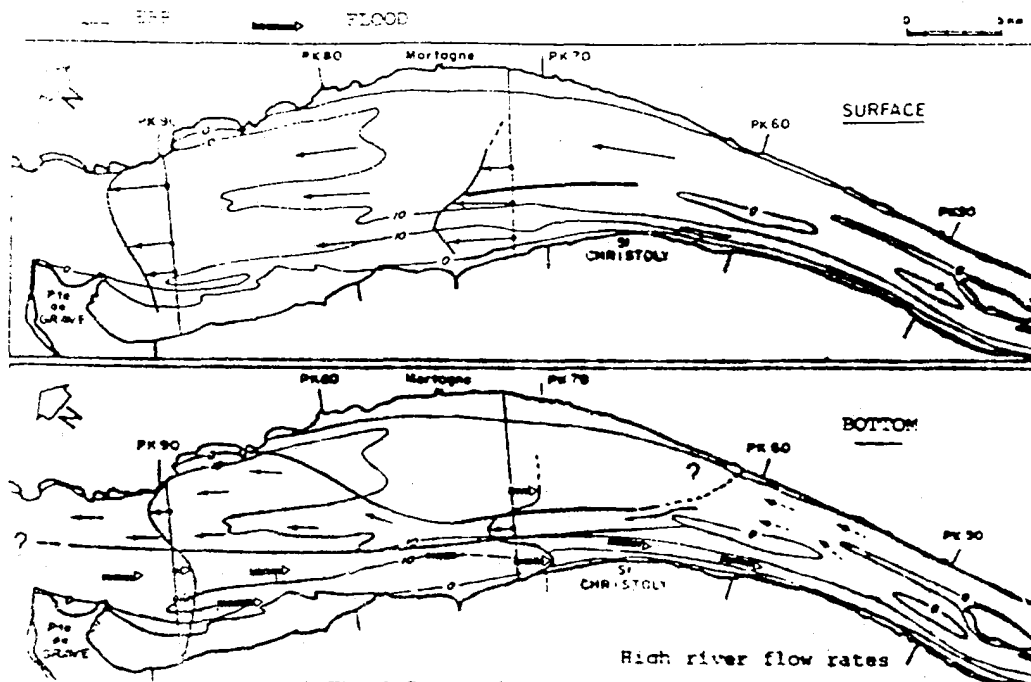


Fig. 15 - Courants résiduels.  
Observed residual currents.



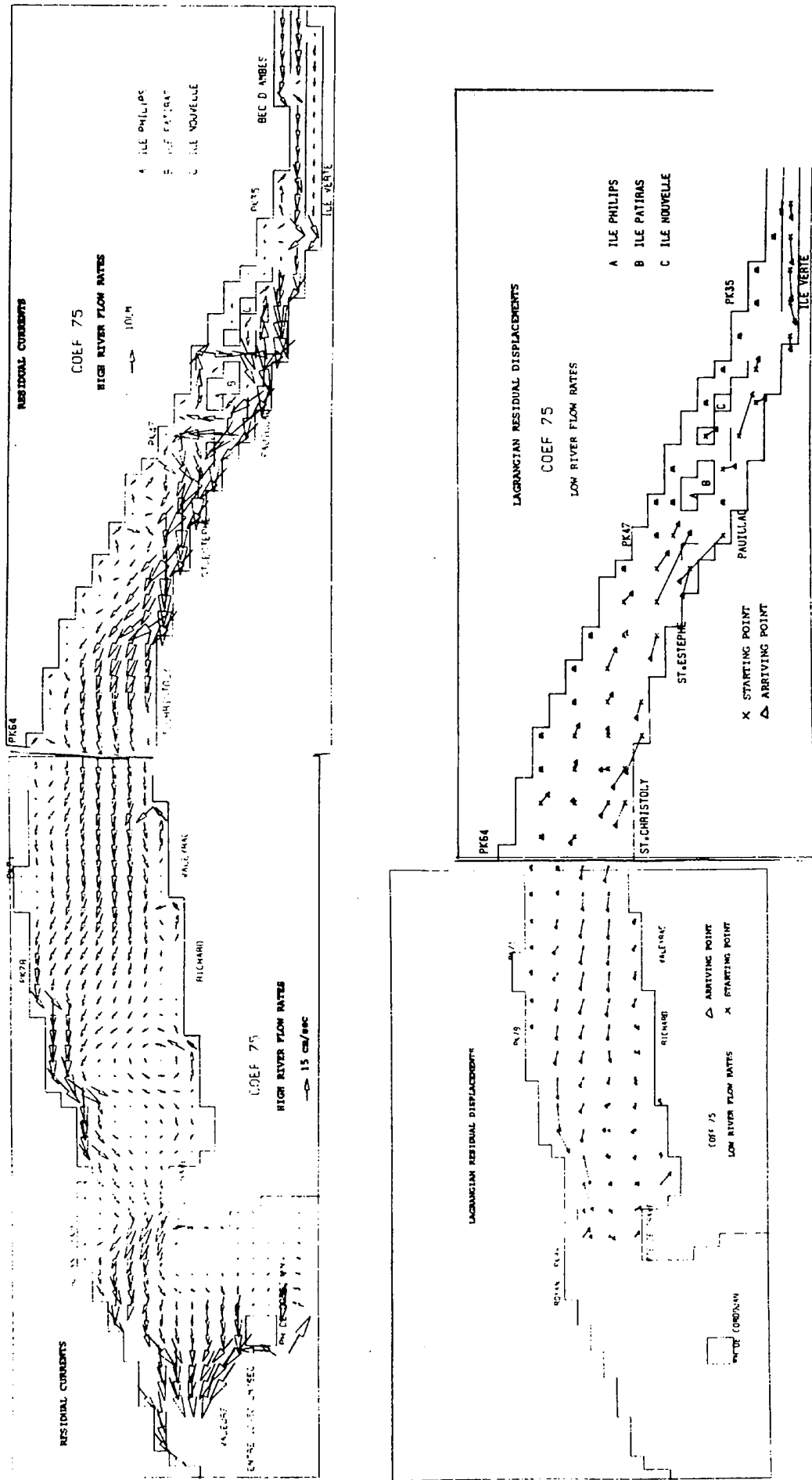


Fig. 16 - a) Courants résiduels calculés (modèle en marche d'escalier) - b) Les déplacements résiduels lagrangien (modèle en marche d'escalier).  
 a) Computed residual currents (stair step boundary model) - b) Computed lagrangian residual displacements (stair step boundary model).

In the case of residual lagrangian displacements (fig. 16), in the lower estuary, the phenomena observed are similar to those of Eulerian field. However, near the mouth, the results indicate a higher residual flux along the northern side than the southern side. This agrees to the observed results better than the Eulerian results. In the upper estuary, the pattern is similar to the Eulerian residual current field.

The above results show that the principal channel is an ebb channel in the upper and lower estuaries. Near the mouth, the northern channel favours the ebb flow. Similar inferences have also been made by previous workers from the observed residual currents.

## CONCLUSION.

The stair step boundary results are found to be better than those of the IGFD model. This is an apriori conclusion, because the former employs a scheme having an accuracy of second order, where as the IGFD scheme has an accuracy of order one.

Results obtained from the stair step boundary model show a systematic acceleration of the tidal wave before Pauillac. At Pauillac, the tidal wave advances faster in the northern channel. For a better knowledge of lateral variations of tidal propagation, some more tidal data near the north bank side is desirable.

The stair step boundary model reproduces well the transient eddies of slack. The residual current pattern shows clearly the existence of the ebb channels in the Gironde, namely the principal channel in the upper and lower estuaries and the northern channel towards the mouth.

The IGFD model is also equally good enough as far as the precision in tidal elevations and currents, description of the current patterns etc. One of the handicaps is the smoothing procedure employed. This was found necessary because of the difficulties in introducing viscosity terms in the momentum equations, since the scheme does not show any direct method for evaluating second derivatives.

Since the IGFD method has an accuracy of only order one, the model may not be sufficiently accurate for the calculation of residual currents and it is not used for that purpose.

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