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NUMERICAL MODELING OF TIDAL PROPAGATION IN THE ST. LAWRENCE ESTUARY

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ABSTRACT

A two-dimensional numerical model is developed to study the tidal propagation in the St. Lawrence Estuary. Linearized vertically integrated equations of motion and continuity are used. Central finite difference scheme is used both in space and time (forward differences for the dissipative term) and conjugate Richardson lattice scheme is used to ensure computational stability. In this model, the independent tides as well as water level variations due to meteorological causes are omitted. Hence the direct tidal forcing term is set to zero, and the observed tidal constituent is specified at the mouth of the estuary. Separate runs are made for each of the five important tidal constituents in the estuary, namely M_2, S_2, N_2, K_1 and O_1 and also for the total tide. Co-amplitude, co-phase lines and tidal current ellipses are constructed for each of the five tidal harmonics. Comparison of the model results with previous work and shore based gauge observations shows that the model gives good agreement and can be used to interpret tidal propagation in the St. Lawrence Estuary.

INTRODUCTION

The St. Lawrence Estuary in eastern Canada (fig. 1A) forms a link between the Great Lakes and the Atlantic Ocean by connecting the St. Lawrence River with the Gulf of St. Lawrence. It is the principal navigational route from the Atlantic Ocean to Eastern U.S.A. and Canada. A knowledge of the tides in the estuary is necessary not only for navigational purposes but also for understanding the mixing processes in the estuary, noting that many industries are located along its shores.

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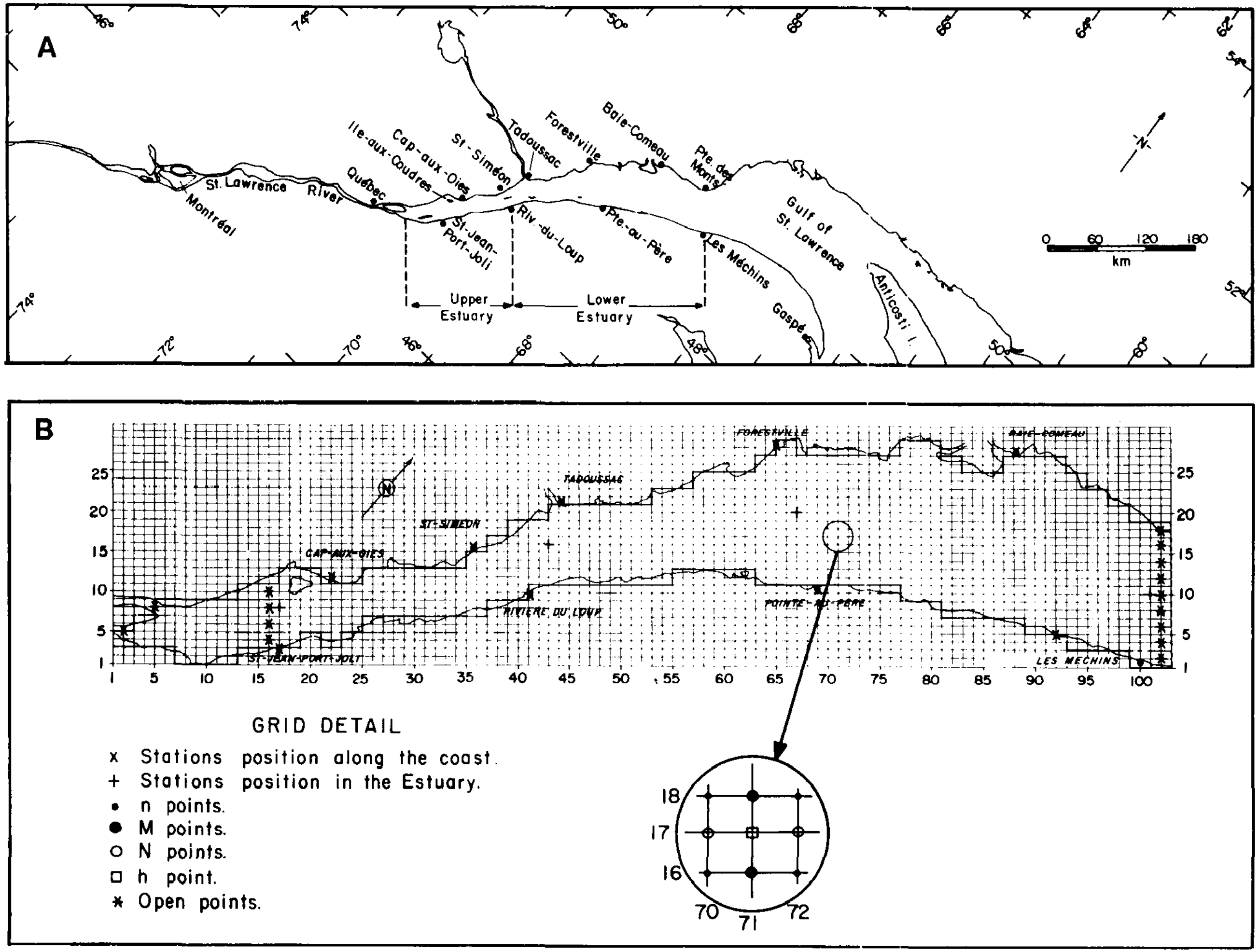

Fig. 1. — The St. Lawrence Estuary (A) Location of stations; (B) Grid detail.

Previous tidal models include those of VINCENT (1965), PARTENSCKY and LOUCHARD (1967), KAMPHUIS (1968), PARTENSCKY and WARMOES (1970), OUELLET and CHEYLUS (1971), PRANDLE and CROOKSHANK (1972), and PARTENSCKY and MARCHE (1974). Although the results from all these studies are quite interesting, it was felt that a model for the propagation of tides in the estuary is required for the following reasons. With the exception of the model by PRANDLE and CROOKSHANK (1972), all the other models referred to are analytical in nature and could not include the topography in a refined manner, as would be possible in a numerical model. PRANDLE and CROOKSHANK (1972) used a combination of one and two dimensional numerical models, but did not make use of real tidal data for the five important tidal constituents in this estuary, namely M_2, S_2, N_2, K_1 and O_1. For this reason, their results could not directly be compared with actual observations.

The numerical model used here is two dimensional and makes use of real tidal data as input. As is traditional with tidal models, homogeneity of the water column is assumed and vertical integration has been made in the equations of motion and continuity. Since the estuary is wide enough for the earth's rotation to have influence on the structure of the tide, Coriolis force is included.

Next, we will briefly consider the limitations of the model. Although it would have been desirable to model the tidal propagation from the western end of the Anticosti Island (fig. 1A) to Quebec City, this was not done here due to the following reasons. Computer storage limitations did not permit us to extend the model eastward of Pointe-des-Monts. In the region between Ile-aux-Coudres and Quebec City, due to the constrictions and shallowness, nonlinear advective terms would be important. Again computer storage limitations prohibited inclusion of this part of the estuary. Thus the model extends from Ile-aux-Coudres on the southwest side to Pointe-des-Monts on the northeast side, and at both ends it is open.

The estuary is covered with ice during December to April, but in this study no account was made for this. Finally, freshwater discharge from the rivers is not included, but we believe this to be a second order effect. Although no new techniques are presented here, this study is probably the first tidal model for the St. Lawrence Estuary that included topography and real tidal data.

THE MATHEMATICAL MODEL

The dimensions of the estuary are such that a cartesian coordinate system will be sufficiently accurate. However, we found it convenient to adapt the spherical polar coordinate model developed by FREEMAN and MURTY (1976). In this study, the independent tide as well as water level variations due to meteorological causes are omitted. Then the linearized, vertically integrated equations of motion and continuity are (HEAPS, 1969; FREEMAN and MURTY, 1976):

$$\frac{\partial M}{\partial t} = 2\,\Omega N \sin\phi - \frac{gh}{a\cos\phi}\cdot\frac{\partial\eta}{\partial\chi} - \frac{\tau_{B\chi}}{\rho} \quad (1)$$

$$\frac{\partial N}{\partial t} = -2\,\Omega M \sin\phi - \frac{gh}{a}\cdot\frac{\partial\eta}{\partial\phi} - \frac{\tau_{B\phi}}{\rho} \quad (2)$$

$$\frac{\partial\eta}{\partial t} = \frac{-1}{a\cos\phi}\ \frac{\partial M}{\partial\chi} + \frac{\partial}{\partial\phi}\,(N\cos\phi) \quad (3)$$

where χ is longitude (positive eastward), ϕ is latitude (positive northward), a is the radius of the earth, Ω is the angular velocity of earth's rotation $h(\chi, \phi)$ is the water depth, $\eta(\chi, \phi, t)$ is the deviation of the water level from its equilibrium position, g is gravity, t is time, τ_B is the bottom stress, ρ is water density, and M and N are the χ and ϕ components of the volume transport.

As mentioned above, the model is open at both ends (Ile-aux-Coudres at the southwest end and Les Mechins at the northeast end). The water level η is specified at both ends, based on actual tidal observations. A simple scale analysis similar to that of FREEMAN and MURTY (1976) showed that the acceleration

$$\left(\frac{\partial M}{\partial t}, \frac{\partial N}{\partial t}\right)$$

terms, Coriolis terms and surface gradient

$$\left(\frac{\partial\eta}{\partial\chi}, \frac{\partial\eta}{\partial\phi}\right)$$

terms will be of the order of 10^{-4} sec^{-1} whereas the bottom friction term will be about a tenth of this value. However, in very shallow water, bottom friction becomes more important.

As is shown in fig. 1B, the grid system has 103 points in the direction of the length of the estuary and 29 points in a transverse direction. The grid size is 3.7 km in the χ direction and 2.8 km in the ϕ direction. The grid was drawn such that M, N points fall on closed boundaries and η points fall on open boundaries. Central finite difference scheme is used both in space and time, except for the dissipative term which uses forward differences. Conjugate Richardson lattice scheme was used to ensure computational stability. In this leap-frog scheme the horizontal flow components M, N are evaluated at even time steps. For the exact forms of the finite difference forms see FREEMAN and MURTY (1976).

The initial condition was of no motion everywhere. A time step of $\Delta t = 24$ seconds was used. The output is M, N, η as a function of time. From these, tidal current ellipses and co-amplitude and co-phase lines are constructed.

The important tidal constituents for this estuary are M_2, S_2, N_2, O_1 and K_1. The boundary condition on η at both open ends is prescribed as

$$\eta_I(\chi, \phi) = A_I(\chi, \phi)\cos[\sigma_I - P_I(\chi, \phi)] \quad (4)$$

where I denotes the constituent and A_I and ϕ_I are the observed amplitude and phase of the constituent.

RESULTS

Water level variations

The co-tidal and co-amplitude lines for the tidal constituent M_2, inside the St. Lawrence Estuary, are shown in figure 2A. Examination of the slope of the co-amplitude lines indicates that water level is higher along the north shore compared to that along the south shore. This difference increases westward from 10 cm at Pointe-des-Monts to 50 cm near Ile-aux-Coudres. The increase in water level along the north shore is due, in part, to the fact that semidiurnal and diurnal tides from the Gulf of St. Lawrence are both propagating into the estuary along that shore. The bathymetry and funnel shape of the estuary may also contribute to this difference; the north shore is characterised by very steep side while a broad sub-tidal platform and islands are found along the south shore.

Contrary to FARQUHARSON (1970), the semidiurnal tidal oscillation M_2 between Tadoussac and Ile-aux-Coudres has an amplitude increasing rapidly from 150 cm at the former to 240 cm near the latter, then decreasing again to 160 cm near St-Jean-Port-Joli. In this part of the estuary, a major break-in-slope and change in regional depths along the axis of the channel occurs near the confluence of the Saguenay River and the upper estuary, where the bottom rises drastically from a depth of approximately 350 m to 25 m over a 16 km distance. Furthermore, near Tadoussac the estuary width is approximately 23 km, whereas upstream of Quebec City it narrows to about a mile (1.6 km) in width. The cotidal lines tend to radiate from some imaginary point near Cap-aux-Oies.

The co-phase lines indicate that the M_2 tide enters the estuary first along the north shore. At the estuary mouth, near Les Méchins, the M_2 tide has a phaselag of 48° which increases to 59° at Pointe-au-Père, to 78° at Rivière-du-Loup and to 136° at St-Jean-Port-Joli. For a discussion of time lags associated with the occurrence of low water in the St. Lawrence system see LEBLOND (1978).

Figures 2B and 3 (A, B) present the model results for the other three important tidal constituents, namely S_2, N_2 and K_1 respectively, and, while they do not differ significantly from the M_2 cotidal chart, they are included for completeness. The results show that within the St. Lawrence Estuary, the semidiurnal constituents dominate, with rapid change in the co-amplitude and co-phase lines in the area near the Saguenay River entrance and some distortion in the region of Ile-aux-Coudres.

For quantitative comparisons, table 1 gives the numerical model results for the four principal constituents, namely M_2, S_2, N_2 and K_1, as compared with observations from a number of shore-based stations. This table shows remarkably good agreement: phase and amplitude agreement for the M_2 tide are generally less than 5° and 5 cm respectively. Agreement between observed and predicted values for S_2, N_2 and K_1 is, as would be expected, similar to the M_2 agreement. The results obtained for O_1 tidal constituent (not shown) indicate, however, some distortion

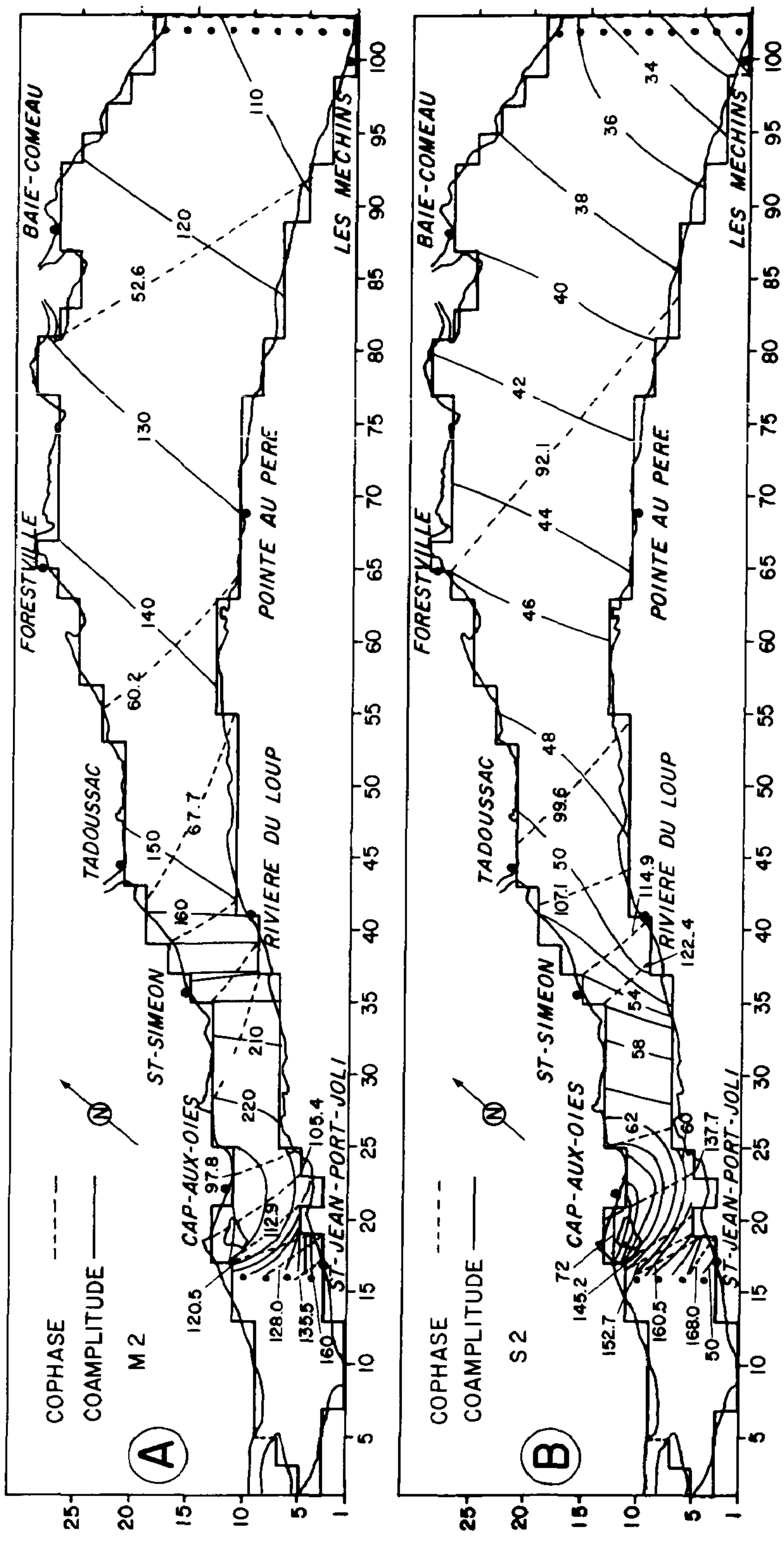

FIG. 2. — Co-phase and co-amplitude lines for: (A) M_2 and (B) S_2 tidal constituents in the St. Lawrence Estuary.

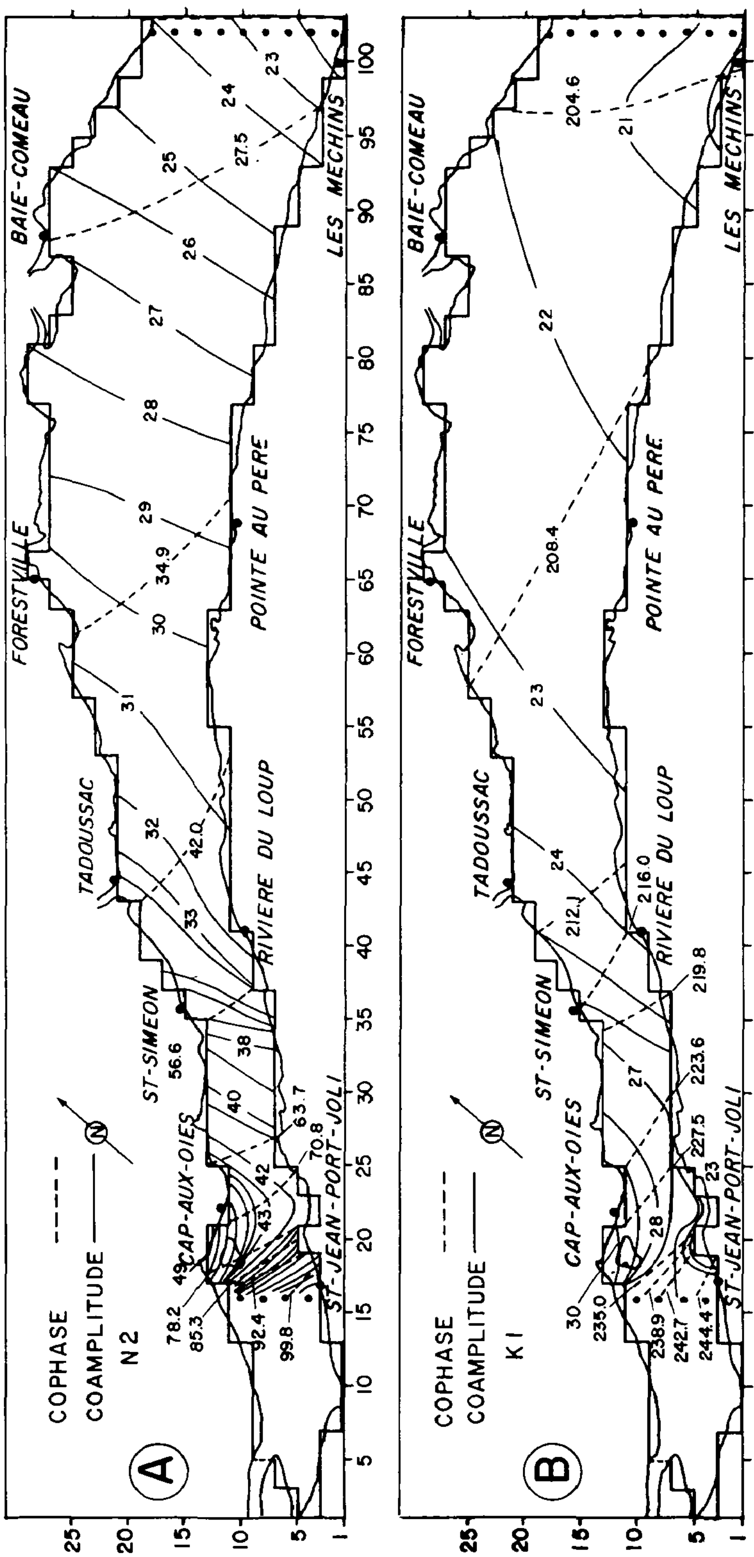

Fig. 3. — Co-phase and co-amplitude lines for: (A) N_2 and (B) K_1 tidal constituents in the St. Lawrence Estuary.

Table 1

Observed and calculated tidal constituents in the St. Lawrence Estuary

Station	Tidal constituent	Amplitude (cm)			Phase (°)		
		Obs. Sta. Data (1)	Numer. results (2)	Difference (1) – (2)	Obs. Sta. Data (3)	Numer. results (4)	Difference (3) – (4)
Tadoussac	M_2	155.4	155.1	0.3	67.8	66.9	0.9
	S_2	49.5	50.0	– 0.5	105.0	102.7	2.3
	N_2	31.9	34.0	– 2.1	45.4	41.8	+ 3.6
	K_1	24.0	24.3	– 0.3	205.0	211.4	– 6.4
	Total	260.8	263.4	– 2.6			
Forestville	M_2	141.1	140.1	1	52.2	57.3	– 5.1
	S_2	44.6	46.1	– 1.5	97.4	92.1	5.3
	N_2	24.3	30.0	– 5.7	32.4	33.8	– 1.4
	K_1	24.2	23.0	+ 1.2	200.7	207.6	– 6.9
	Total	234.2	239.2	– 5			
Baie-Comeau	M_2	118.5	123.1	– 4.6	47.2	49.3	– 2.2
	S_2	37.6	39.1	– 1.5	83.1	85.4	– 2.3
	N_2	24.4	26.6	– 2.2	24.9	27.5	– 2.6
	K_1	22.2	22.0	0.2	199.0	205.4	– 6.4
	Total	202.7	210.8	– 8.1			
Rivière-du-Loup	M_2	150.8	155.0	– 4.2	79.9	77.7	2.2
	S_2	48.1	48.1	0.0	115.8	114.9	0.9
	N_2	34.9	32.1	2.8	53.4	49.1	4.3
	K_1	23.2	24.0	– 0.8	208.3	216.7	– 8.4
	Total	257.0	259.2	– 2.2			
Pointe-au-Père	M_2	126.6	130.1	– 3.5	53.6	58.5	– 4.9
	S_2	41.5	43.0	– 1.5	89.0	92.5	– 3.5
	N_2	29.3	28.5	0.8	31.0	35.1	– 4.1
	K_1	24.1	22.0	2.1	204.1	208.7	– 0.6
	Total	221.5	223.6	– 2.1			
Matane	M_2	114.0	112.1	1.9	49.0	52.6	– 3.6
	S_2	30.5	36.0	– 5.5	84.0	88.8	– 4.8
	N_2	23.5	24.5	– 1.0	27.0	28.8	– 1.8
	K_1	22.0	21.1	0.9	191.0	206.1	– 15.1
	Total	190.0	193.7	– 3.7			
Les Méchins	M_2	93.1(*)	100.0	– 6.9	48.0(*)	48.0	0.0
	S_2	28.8	29.1	– 0.3	84.3	84.3	0.0
	N_2	19.8	22.1	– 2.3	24.0	24.0	0.0
	K_1	21.1	21.0	0.1	202.7	202.7	0.0
	Total	162.8	172.2	– 9.4			

(*) Observed data at Ste-Anne-des-Monts, 40 km east of Les Méchins.

in the region between Matane and Les Méchins. This discrepancy can probably be explained by the uncertainties in the specified boundary conditions as well as the small amplitudes of this constituent, making direct comparison with gauge observations difficult, and thus further interpretation is not attempted.

In order to complete our study, we analysed the water level variation with time for each of the five tidal constituents, separately and together. Examination of the model results (LEVESQUE, 1977) shows that maximum amplitude for the M_2 tide may reach a value of 250 cm at Cap-aux-Oies, decreases to 150 cm at St-Jean-Port-Joli and to 100 cm at Les Méchins. The behaviour of all other tidal constituents is similar to that of M_2; that is, the amplitude decreases always as the south shore and the downstream end of the estuary are approached. If we examine the water level at a particular station, we realize that the semidiurnal tidal constituent M_2 is the dominant one, followed by S_2, N_2, K_1 and O_1. Furthermore, excellent agreement is obtained between the model results and values of the same harmonic constituents calculated by FORRESTER (1972) from water level data at selected regions across the St. Lawrence Estuary (table 2). Both FORRESTER's results and those deduced by the model presented in table 2 are the mean vertical tide for each region.

Table 2

Mean Vertical Tide (cm) at selected regions in the St. Lawrence Estuary

Harmonic constituent / Region	M_2			S_2			N_2			K_1		
	A	B	Diff.	A	B	Diff.	A	B	Diff.	A	B	Diff.
Cap-aux-Oies St-Jean-Port-Joli	195	186	9	59	59	0	42	33	9	25	25	0
St-Siméon Rivière-du-Loup	160	158	2	50	48	2	33	31	2	25	24	1
Tadoussac	152	156	−4	50	50	0	32	31	1	23	25	−2
Forestville Pointe-au-Père	133	132	1	42	42	0	29	25	4	23	23	0
Baie-Comeau Matane Les Méchins	113	116	−3	32	34	−2	25	24	1	21	23	−2

A: Numerical model results.
B: From FORRESTER (1972).

Next, we will examine the total tidal variations with time, and consider the effect of all five constituents together, and compare the model results with actual gauge observations obtained at selected stations along the estuary. Runs are made for a period of 72 hours starting at 0 hour of the 15th day for each of the months of January, April, July and October 1975. Only the results for five stations are presented here, and are shown in figure 4. This figure shows that the model produced a good overall reproduction of tidal propagation throughout the estuary. However,

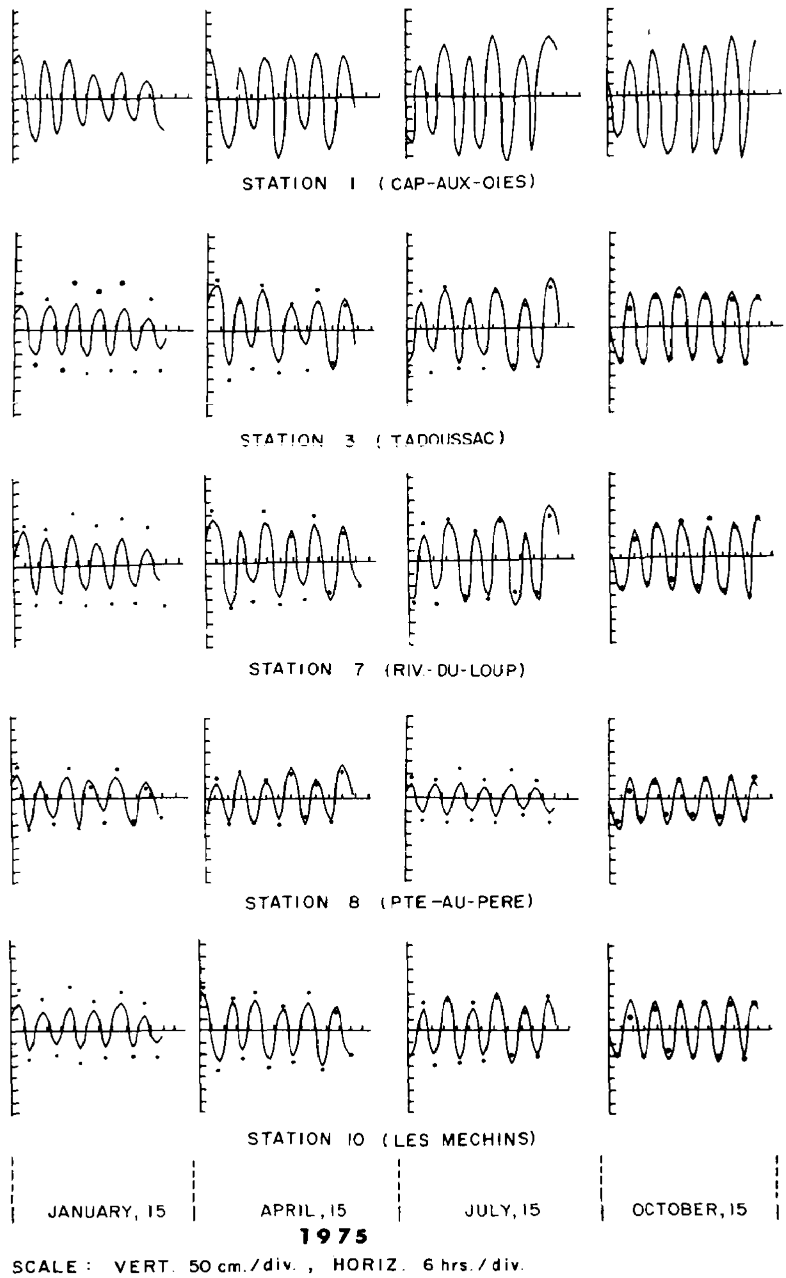

FIG. 4. — Water levels at selected stations in the St. Lawrence Estuary.

large discrepancies between the observed and calculated values occur during the winter period. This can be explained by the fact that the St. Lawrence Estuary is characterized at that time of the year by the presence of ice cover. As mentioned before, no account was made in the present study for the presence of ice cover which can influence the calculated sea level in the estuary during that period.

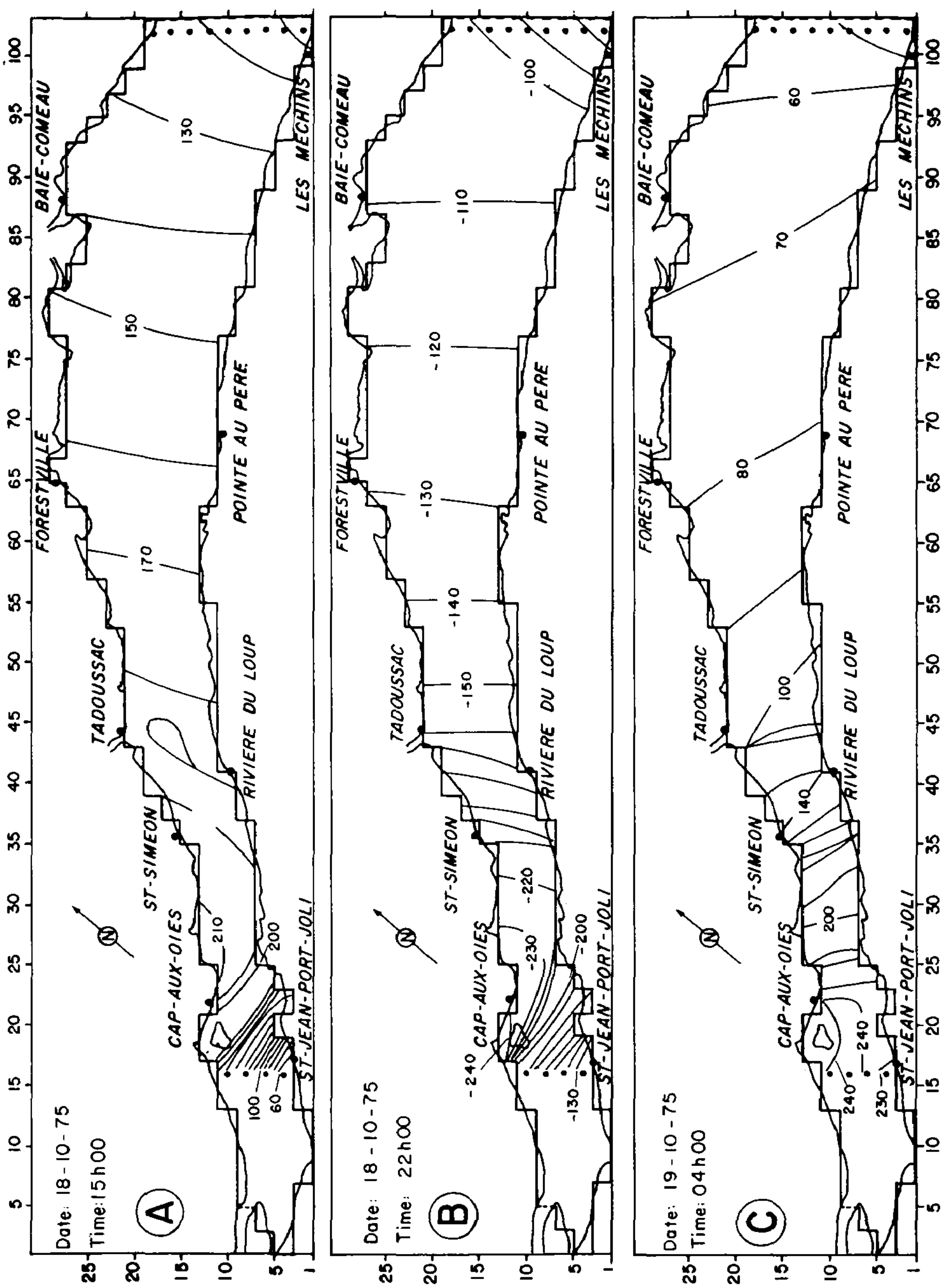

Fig. 5. — Water level contours in the St. Lawrence Estuary on 18 October 1975.

According to the model results, tidal amplitude attains its lowest values in the southeastern part of the estuary and increases towards the west and north. In October, tidal amplitudes increase from 100 cm at Les Méchins to 260 cm at Cap-aux-Oies. On the other hand, the largest difference between high and low waters is always found in the northwestern part of the estuary, particularly at Cap-aux-Oies. At this station, tidal range increases rapidly from 380 cm in January to 440 cm in April and reaches a value of 510 m in October.

Figure 5 shows the water level contours at the flood and ebb tides on 18 October 1975. These contours, which illustrate the propagation of the wave fronts across the estuary, were prepared using the water level at each grid point as generated by the model and taking into account the five tidal harmonic constituents. During flood tide, tidal waves propagate progressively along the north shore until Tadoussac. In this part of the estuary, differences in water level between the north and south shores are less than 5 cm. The highest level is found near Cap-aux-Oies and decreases rapidly southward in the direction of St-Jean-Port-Joli where it reaches its lowest level at that station. The rapid change in water level between both shores at the upstream boundary of the model can be attributed in part to the changes in the axial direction of the estuary, and in part to the abrupt rise in bottom topography just beyond Tadoussac where the estuary becomes narrow. In addition depths of up to 200 m are found in the North Channel which runs parallel to the north shore while, in contrast, a broad subtidal platform of 10 m or less is developed along the low-lying south shore. As expected, this picture is reversed during ebb tide conditions; the surface water attains slopes of exceptional steepness in the upstream part with a higher level along the south shore. In the lower part of the estuary, the decrease is moderate and the surface profile of the wave is regular with the slopes small.

Horizontal motion

It is evident that tides play an important role in mixing the waters of the estuary. Tidal currents exert a profound influence by the turbulence they produce. This tends to break down the separation between the upper fresher waters and the more dense deep oceanic waters, thus initiating a vertical mixing of the two. Therefore, a knowledge of the tidal streams along the estuary is essential in order to understand the mixing processes.

Tidal streams are calculated, using the present model, at selected stations for each of the five tidal constituents. As can be seen in figure 6, the magnitude and rotary character of the M_2 tidal streams decrease downstream and southward of Cap-aux-Oies, with minimum values found in the southeastern part of the estuary. Maximum currents of the order of 2 knots are found along the north shore between Tadoussac and Ile-aux-Coudres (Stations 2 and 3) and decrease to 50 cm/s in the opposite side of the estuary (Station 7). For the rest of the stations, tidal currents have an amplitude of the order of 25 cm/s. It is of interest to note that the orientation of the ellipses is largely topographically determined and is in general parallel to the main axis of the estuary. Except at stations 1, 4 and 10, the M_2 tidal current ellipses show clockwise rotation of the current vector. Near Tadoussac (Station 3) a strong transverse current of the order of 50 cm/s is noticed. Since no opening boundary was considered for the Saguenay River, this transverse component of the tidal currents is due in part to the rapid change of bottom topography at that location, and in part to the presence of a progressive internal semidiurnal tide of the Poincaré type and a diurnal tide of the Kelvin type propagating seaward from the inland end of the Laurentian Channel, as observed by FORRESTER (1974).

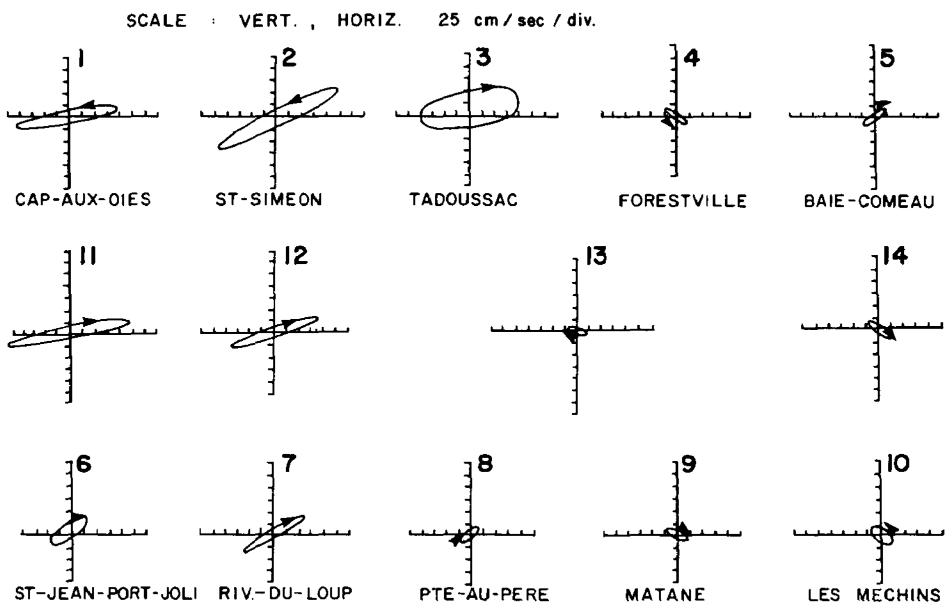

FIG. 6. — Tidal ellipse for M_2.

The S_2 and N_2 current ellipses (not shown) behave in a similar manner as the M_2 streams: that is, a decrease in amplitude from west to east and south, a change in the orientation of the ellipses which in general are parallel to the axis of the estuary, and a weak transverse current at most of the stations compared to that at Tadoussac. For any particular station, the M_2 tidal stream has the maximum amplitudes, followed by the S_2 and N_2 respectively. For example, at station 11 the model results show an amplitude of 125 cm/s for M_2, 65 cm/s for S_2 and 38 cm/s for N_2. The K_1 tidal ellipses are plotted in figure 7. The intensity of the tidal currents varies from one station to another and its behavior is similar to that of M_2, S_2 and N_2 current ellipses. However, at stations 10 and 14 near the mouth of the estuary the amplitudes of the K_1 tidal streams are much greater than for the other streams, but the orientations of the ellipses are similar. The K_1 tidal current ellipse at station 10 shows clockwise rotation of the current vector, opposite to that for M_2 stream, which is in agreement with the observations given by FARQUHARSON (1970).

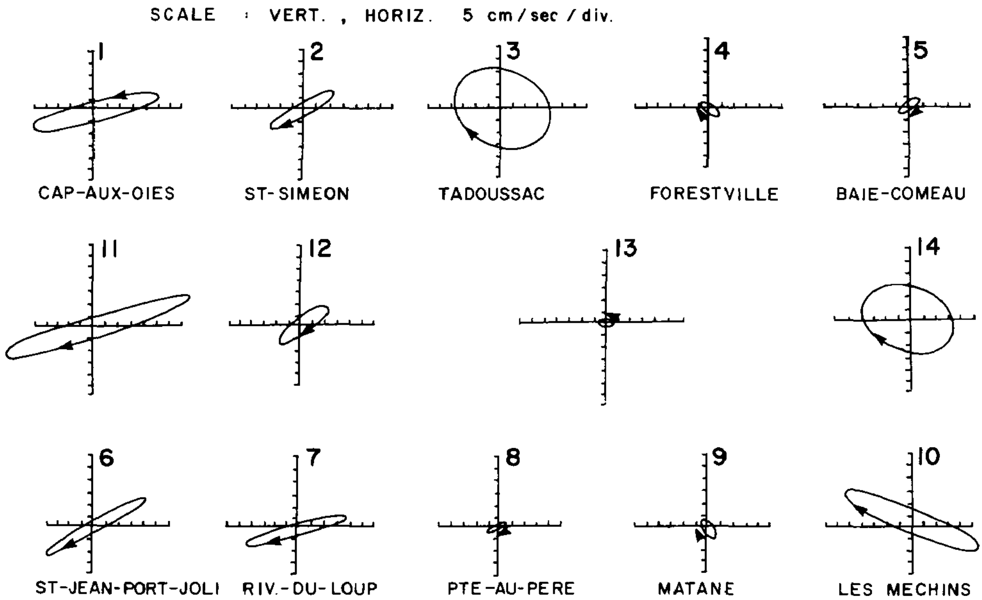

FIG. 7. — Tidal ellipse for K_1.

From observed surface elevations and the continuity considerations, FORRESTER (1972) has calculated the average tidal streams for seven harmonic constituents (M_2, S_2, N_2, K_1, O_1, M_4 and MS_4) through several sections across the St. Lawrence estuary. For quantitative comparison, table 3 shows FORRESTER's results for selected regions together with values obtained by the present model and those deduced from direct current measurements in three of the cross-sections. In comparing the calculated and observed data, it must be remembered that the current or

Table 3

Observed and calculated Mean Tidal Streams (cm/s) in the St. Lawrence Estuary

Tidal Const. / Region	M_2			S_2			N_2			K_1		
	Calculated		Observed	Calculated		Observed	Calculated		Observed	Calculated		Observed
	M*	F**	F**	M*	F**	F**	M*	F**	F**	M*	F**	F**
Ile-aux-Coudres	112	116	120	41	30	29	32	20	21	28	8	7
Rivière-du-Loup	90	89	–	24	24	–	17	16	–	13	7	–
Tadoussac	95	69	–	39	4	–	27	13	–	21	6	–
Pointe-au-Père	18	14	12	5	4	3	3	3	3	3	1.4	1.3
Les Méchins	20	18	16	8	6	6	6	4	4	12	1.8	1.5

* Model results.
** From FORRESTER (1972).

tidal stream calculated by the model or by continuity for a particular cross-section is the average value for the entire water column, and that the current meter results are values for a single depth. The model results reported in table 3 for a particular region are the mean of all grid points over the entire region. FORRESTER (1972) concluded that tidal streams calculated by continuity are believed to be more accurate estimates of the average flows than could be obtained by direct current measurements. Except for the K_1 tidal constituent, table 3 shows that the amplitudes of the semidiurnal tidal streams are generally of the same order of magnitude as those calculated by FORRESTER. The general discrepancy of the K_1 tidal stream can probably be explained by the fact that the horizontal motion computed from our numerical model is not accurate near the two (open) boundaries, especially for the diurnal tide. Unfortunately the two stations Ile-aux-Coudres and Les Méchins are at the open boundaries. At Pointe-au-Père the agreement was much better, while at Rivière-du-Loup and Tadoussac no observational data exists for comparison.

SUMMARY AND CONCLUSIONS

Earlier models of the St. Lawrence Estuary either did not consider the topography or used hypothetical tidal data as input. The present model incorporates both these features and calculates the total tide as a combination of the five important constituents, namely M_2, S_2, N_2, K_1 and O_1. In this study the independent tide generated in the estuary directly by the astronomical forces is neglected as being insignificant, and water level deviations due to meteorological forcing are also not included. The area of the model is from Ile-aux-Coudres to Les Méchins. Both the upstream and downstream ends are treated as open boundaries where the observed tide is used as input.

The calculated water levels are compared with observed values as well as values from earlier works. The agreement in the water levels is better during the period when there is no ice present. In the present model no allowance was made for the freshwater input into the estuary from surrounding river systems.

An examination of table 3 shows that FORRESTER's (1972) results are somewhat closer to the observed values for all components of the tidal streams at the various stations considered. At the outset it may not be obvious why the differences between the present two-dimensional model results and observations were slightly greater than the differences between FORRESTER's results and observations. The explanation is that FORRESTER (1972) used the continuity equation to fit the observed data and in a strict sense his work is not a predictive model. Therefore a direct comparison between FORRESTER's results and the present model may not be too appropriate. However, in an absolute sense, our results agree quite satisfactorily with observation (the discrepancy for the K_1 constituent appears to stem from the fact that our input data for this constituent appears to be in error).

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