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SALINITY-STRUCTURE, TEMPERATURE-DISTRIBUTION AND TRANSPORT
MECHANISM IN THE ST. LAWRENCE ESTUARY

By

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SUMMARY

The results of three surveys conducted in the estuary of the St. Lawrence River, from September 22 to 23, 1959, from February 18 to 25, 1963, and from May 21 to 24, 1963, are summarized and the distribution of salinity, temperature and velocities reported.

Applying Pritchard's definitions (Ref. 1) for the different types of estuarine mixing, the circulation pattern varies from well-mixed with nearly vertically homogeneous conditions at the head of the estuary to moderately stratified in the section below. In the deep section below the mouth of the Saguenay River highly stratified conditions prevail.

On the south side of the channel the water is appreciably fresher than on the north side except off the mouth of the Saguenay River. Progressing seaward, the depth of the fresher surface layer decreases along the north shore and increases along the south shore. During freshet, the fresh water content of the surface layer increases appreciably along the south side.

During the February survey, temperatures in the intermediate and lower layers were 3 to 4 degrees centigrade in the deep section and 0 to 1 degree, above the mouth of the Saguenay. In the surface layer, temperatures during February were higher on the north side than on the south. In May, this trend was reversed.

From the evidence, it was concluded that there are two principal motions, a longitudinal two-layer circulation and transverse motions imposed on these two layers by the rotation of the earth. The transverse motions can be divided into stationary motions and into motions due to tidal oscillations and seasonal fresh water changes.

All these motions are either controlled or influenced by the amount of fresh water in the system. Retaining fresh water during the higher discharge season in spring and summer and discharging it to the system in the colder seasons of the year with the intention of equalizing the run-off for power generation and navigation must alter the flow regime, modifying the salt and temperature structure of the system. The change most felt should be to temperature, giving a general rise throughout the year. This change should even modify the climate of the region.

Careful studies are therefore required to find the effect of these man-made hydrological changes on the system and to find ways of counteracting them.

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SALINITY-STRUCTURE, TEMPERATURE-DISTRIBUTION AND TRANSPORT-

MECHANISM IN THE ST. LAWRENCE ESTUARY

1.0 INTRODUCTION

An estuary, as defined by marine scientists, is a semi-enclosed body of coastal water within which the sea water mixes with the fresh water from the land drainage. In the St. Lawrence River, the point farthest upstream where salt water of oceanic origin was measured was near Orleans Island, 17 miles below Quebec City. The estuary therefore begins here and includes the section of the river to below Pointe des Monts, where the water enters the Gaspé area, an embayment of the St. Lawrence Gulf system.

The estuarine channel, as shown in Figures 1 and 2, is a funnel-shaped bay, varying in width from 12 miles above the mouth of the Saguenay River to about 30 miles near Baie Comeau. The maximum depth increases from about 30 feet in the shoal area of Orleans Island to 180 feet above the Saguenay. Off the mouth of this river, the bed drops abruptly to 1000 feet and remains at this depth throughout the rest of the system.

The main sources of fresh water are the St. Lawrence River, the Saguenay River and a group of rivers consisting of the Bersimis, the Outardes and the Manicouagan. The St. Lawrence enters the system at Orleans Island, the Saguenay at a point halfway along at Tadoussac, while the group of rivers joins the estuary above Baie Comeau. The inflow from this group has been considered as a single river effluent, since their mouths are not far apart.

All major inflows, except that of the St. Lawrence River itself, enter the system from the north shore; the inflow from the south shore being insignificant. This should be noted and remembered when analysing the data.

During the periods of the surveys, the inflow of fresh water was found to be fairly uniform, as shown on Figure 4. In the month of February, the inflow from the St. Lawrence varied from 300,000 c.f.s. to 280,000 c.f.s. and in May from 370,000 c.f.s. to 320,000 c.f.s. The Saguenay inflow, which is artificially controlled, changed very little during the surveys and was 25,000 c.f.s. in February and 65,000 c.f.s. in May. The combined inflow from the group of rivers was also not subject to great variations except during the survey in May. Their discharge was 25,000 c.f.s. in February and 50,000 c.f.s. during the first half of May, but increased to 140,000 c.f.s. during the survey.

Considering the system as a whole, it can be said that the fresh water inflow was quite constant for four to six weeks preceding each survey, and that the discharge in May was 60 percent greater than in February. The sudden increase in the discharge from the group of rivers could have affected only the immediately adjacent area in the lower part of the estuary since there was obviously insufficient time to influence other sections.

The average air temperatures during the surveys were representative for their seasons. At Quebec City they were as shown on Figure 5; being of the order of -13°C . in February, preceded by a period of one month of similar temperatures, and rising to $+12^{\circ}\text{C}$. in the May survey. The transition through zero degree was at the beginning of April.

It is evident that tides play an important role in mixing the river effluents with the sea water from the ocean; the prime source of this mixing being the turbulence resulting from the oscillating motion of the tide. In the St. Lawrence estuary, tides have considerable amplitudes. Their maximum range on entering the estuary is 6 to 7 feet, but they are augmented within the system so that their ranges are nearly doubled when they reach the upper end.

Tidal data recorded on February 11, 1959, and plotted on Figure 3 in the form of wave profiles (2-hour lines), indicate that the wave undergoes drastic modifications to its configuration while progressing through the estuary. In the lower part, the increase in range is moderate and the water surface profiles of the wave are regular and gently sloped. But, above Father Point where the bay narrows into a funnel-shape, and then farther upstream where the channel becomes shallow, the tide range increases more and more rapidly and the water surfaces achieve slopes of exceptional steepness. During this process, the slope of the wave front increases faster than that of the downstream wave shoulder. In this way the wave builds up a steep front of water which rushes over the shallow section of the estuary like a surface wave over a beach. One cannot escape the feeling that, if this continued, a bore would ultimately occur. An outstanding example of this is the condition at 1700 hours (Fig. 3) when the water level at Quebec was near Low Water, whereas only 60 miles downstream, at Point aux Orignaux, almost High Water existed. The difference in water elevations between these two locations was, at this particular moment, 12 feet.

From this brief description it may readily be appreciated that mixing imposed on the estuary by the tide is appreciably stronger in the upper part of the system than in the lower.

In the system as a whole, therefore, we have the continued inflow of fresh water from the river and the tributaries

into the estuary on the one hand, with the salt water pressing inward from the sea on the other. The two bodies of water interact and the primary mixing is provided by the turbulent diffusion induced into the system by the tidal motion. The depth of the channel and the tide characteristics have their influence on the degree and extent of mixing.

Inspiring the survey was the well-known fact that in the estuary of the St. Lawrence ice accumulates more along the south side of the river than on the north, during the winter. In support of this, aerial observations revealed that the ice along the north shore of the river is more translucent and therefore younger than along the south shore where the ice is mostly packed and snow-covered.

This feature seems to indicate that surface water is deviated toward the south shore, while warmer water of the underlying layers is diverted more toward the north shore.

To our knowledge, no attempt had been made to study this section of the river from this viewpoint. Marine scientists have been more concerned with the Gulf and have once or twice made single traverses along the lower part of the estuary and into the fjord-like Saguenay River.

2.0 SURVEY AND EQUIPMENT

The surveys were conducted from the C.G.S. "Detector", a ship channel survey vessel, the C.C.G.S. "Tupper", a buoy ship able to navigate in the ice of the St. Lawrence during the winter, and the C.C.G.S. "Puffin", a shallow draft vessel built to supply outposts in the Canadian North.

In 1959, two positions were surveyed, including current velocities, during a tide cycle at Pointe aux Orignaux; in 1963, seven survey sections along the estuary were occupied during both the February and May surveys. Some minor variations in location occurred and some stations were omitted, as ice in February did not permit entry to certain restricted areas of the estuary. In May, an additional section was added between Ile aux Coudres and the Saguenay River.

In each survey section three or four stations were occupied across the channel and water samples were taken from the surface to the bed, using Knudsen reversing bottles. The temperature was measured at the individual sampling depths by deep-sea reversing thermometers, and the density was measured on board the ship by stem hydrometers. Since we were in coastal waters, where great differences in density are found, this method can be considered sufficiently accurate. From the densities and

the temperatures measured, the salt content of the water was calculated.

The current velocities at Pointe aux Orignaux were measured with Ott directional current meters.

The field data collected are on file in the Hydraulics Section of the Mechanical Engineering Division.

3.0 HYDROGRAPHIC OBSERVATIONS

The data of the survey are graphically reported on charts showing the variation in the properties of the water along three longitudinal sections of the estuary (Fig. 6-9, 12, 13) and in horizontal sections at depths of 30, 100, 200, 400 and 800 feet (Fig. 10, 11, 14, 15). For regional description and for evaluating important features, additional charts have also been developed.

3.1 Distribution of Salinity

The salinity distributions in the longitudinal sections (Fig. 6 and 8) immediately reveal that the distribution patterns in the estuary differ appreciably, the lines of equal salinity referred to here as isohalines being more inclined and more closely spaced in the shallow upper part than in the deep section of the estuary. The sections will be discussed separately, beginning with the deep one.

3.1.1 Distribution Below Tadoussac

The bulk of the water is located in the deep, fjord-like central part of the channel. The isohalines of this section are almost horizontal with a slight tilt upward in the seaward direction. This feature indicates that the water becomes less saline on its way inward, but the gentle slope of the lines also indicates that mixing is very slight. Vertically, the isohalines are more closely spaced toward the surface than in the deeper layers. This is more readily demonstrated on the vertical salinity distributions plotted on Figure 16. Here the lines are almost vertical throughout the deep water but slope in the upper layer. The slope in May was greater than in February and the point of discontinuity in the distribution line was located between 100 and 300 feet below the surface. Below this level, the water is homogeneous and is highly saline; above it, the water becomes progressively fresher toward the surface, as also observed by Lauzier and others, Ref. 7. It is evident that at this level the water is divided into two zones, an underlying zone which occupies approximately four-fifths of the channel and contains sea water, and an upper shallow zone comprised of a mixture of salt and fresh water. The zones are more sharply defined in May than in February.

A third zone, 15 to 20 ft. deep, also containing homogeneous water, was located at the surface. This zone was created by the mixing action of the wind. Since its depth is small compared with the other zones, it will not be dealt with in greater detail.

The outstanding feature of the underlying zone is its salt content which ranges from 33 to 35.5 parts per thousand. When compared with the Atlantic Ocean and its coastal regions, it is evident that it is relatively undiluted sea water. It therefore can be concluded that this water enters the Cabot Strait and penetrates from there 500 miles inland without undergoing any noticeable change through contact with the fresh water from the St. Lawrence system.

Since the underlying zone contains only sea water, all fresh water from the system must be transported and mixed with salt water only in the upper zone. The salt water for mixing is entrained from the lower zone by upward moving of salt water with apparently no downward movement of fresh water. Thus the salt content of the upper zone increases seaward. This is also described by G.L. Picard in Ref. 7.

Comparing the results of the two surveys in the central section of the estuary (Fig. 16), it is shown that the saline content of the lower layer had not altered from February to May; in the upper layer, however, drastic changes took place during this period.

In February, a well-defined two-layer system still existed at E_{1-2} below Tadoussac. This two-layer system, however, became less distinct when it reached the lower end of the estuary. Contrary to this, in May, the two-layer arrangement was well-defined over the entire length of the estuary.

Since the fresh water inflow in May was appreciably greater, it was surprising to discover that the depth of the upper zone in May seems to have decreased compared with that in February. The vertical salinity distribution in Figure 16 demonstrates this feature and also illustrates that this is achieved by concentrating fresher water in the surface layer. Tully (Ref. 4), observed the same phenomena in the Alberni Inlet, British Columbia. He concluded that the freshet having, by nature, a shorter duration than is required by the system to establish a new displacement equilibrium for the temporarily increased discharge, overruns the surface layer of the upper zone.

Generally speaking, it therefore appears that the salinity structure of the deeper portion of the central section is quite stable for part of, and probably most of, the year. Mixing in this part of the channel is slight, occurring almost exclusively in the upper zone. Seasonal changes in fresh water

discharge seem to affect only the upper zone where quite strong changes occur.

The salinity distributions along both sides of the estuary (Fig. 6, 8) differ from that of the central part. Along the north side, the isohalines slope appreciably more than in the centre, implying that either mixing is stronger or, more probably, fresher water in the upper zone is drawn off from this side and replaced by more saline water from the deeper zone. On the south side, the reverse occurs. Here, the isohalines slope downward in contrast to the remainder of the estuary, indicating that fresher water from the upper zone accumulates along the south shore at a rate faster than the system can mix to maintain a constant level of salinity. As has been mentioned previously, there is no fresh water inflow of any significant quantity along the south shore. Consequently, the fresher water which accumulates on this side must be supplied from the upper zone of the estuary and from the two inflows, the Saguenay River and the group of rivers entering the system on the opposite side. The displacement of this water can only take place with a cross motion shifting the fresher water in the upper zone southward and the saltier water in the lower zone northward.

As may be expected, this feature appears more clearly in the results from May than in those from February. This is demonstrated on Figure 20, where the salinity distribution of the cross section near Pointe des Monts is plotted for both surveys. The slope of the isohalines had not changed sufficiently to be noticed. In May, however, the surface layer of the upper zone became appreciably fresher.

For the channel in general, it may therefore be stated that the fresher water from the system diverts toward the south shore where it accumulates into a layer increasing in thickness seaward (Fig. 18). The process obviously accelerates when more fresh water is present. The "overrunning" characteristic of freshets, which has been described while dealing with the central part, may play an important role in this displacement.

At the head of the deep section the bed suddenly rises from depths of more than 1000 feet to less than 180 feet. Here the fjord-like Saguenay River, restricted at its mouth by a high ridge, joins the system; the two bodies of water, the diluted and undiluted, meet and form below this point a well-defined layer system. The interaction between these two bodies of water is less violent than expected. Using the 33 parts per thousand isohaline as a tracer, dividing diluted from undiluted water, it is shown on Fig. 16 and in the longitudinal profiles that the water flowing over the sill maintains its identity throughout the lower section. The thickness of this layer in the centre of the channel is very much the same as the depth over the sill.

3.1.2 Distribution Above Tadoussac

The upper section of the system is shallow with many shoals and islands. This part gives more the impression of an estuary in which fresh water from the river and salt water from the sea are mixed by the oscillating motions of the tide. In some sections a central group of shoals and islands divides the channel into two arms with the north arm generally deeper than the south.

The isohalines, as shown on the longitudinal profiles of Figures 7 and 9, are closely spaced, except in deep holes and over the sill on the north side of the channel. The lines which were almost horizontal in the deep section of the estuary become sloped after entering the shallow part. Progressing upstream, the gradient of these lines increases steadily until the lines are almost vertical at Orleans Island.

These three slope gradients represent the three basic mixing types found in estuaries: nearly horizontal isohalines indicate mixing primarily in the upward direction, sloped lines infer mixing in both vertical and longitudinal directions, and vertical salinity lines suggest that the salt distribution under these circumstances is not governed by a vertical process but rather by lateral and longitudinal transfers.

The nearly vertical isohalines, as they exist at Orleans Island, are exceptional and are due to tidal motion which has become so vigorous that almost vertical homogeneity results. The process which leads to this condition is readily illustrated in the salinity distribution of the horizontal charts shown on Figures 10 and 11. The isohalines are at all depths bent seaward from north to south, indicating that the salinity on the south side is lower than on the north. There is, therefore, not only a variation of salinity in the longitudinal direction but also transversely. This arrangement has been created by two principal factors, the geography of the entrance of the river into the system and the transporting mechanism of the tide. The entrance of the river is so located that during ebb tide the main stream of the outflowing fresher water flows toward the south shore due to its own inertia and the deviating effect of the rotating earth, while the compensating flow of saltier water during flood tide is concentrated in the deep channel along the north side. This displacement within a tide cycle creates a cyclonic circulation which is evident not only at Orleans Island but throughout the entire upper section.

In the channel below Orleans Island, vertical advection adds to this horizontal transfer. Consequently, in this area, mixing occurs both horizontally and vertically, as indicated by the slope in the isohalines.

The distribution patterns from the two surveys of 1963 do not differ appreciably, the water in the channel being generally fresher in May than in February. The distribution plot across the channel at Pointe aux Orignaux, as shown on Figure 19, illustrates this feature. In February, the transition from fresh to salt water (a salt content of 30 parts per thousand) was compressed into a section 50 miles long, located between Orleans Island and Ile aux Coudres, while in May the lines were more evenly distributed throughout this section and more inclined. At a few places the results are less conclusive, particularly near the entrance of the Saguenay River; however, it must be understood that in these confined waters the time of observation with respect to High and Low Water plays an increasingly important role. The two surveys in 1963 were intended to be only of an exploratory nature covering the entire system. A more refined analysis of the conditions during a tide cycle at Pointe aux Orignaux, based on the observation in 1959, is given in Section 4.0.

3.1.3 Discussion

One of the interesting characteristics of the St. Lawrence estuary is that all three basic types of mixing are represented within its boundaries, ranging from nearly fully mixed at the upstream end to moderately mixed and, finally, to almost stratified. According to Reference 1, the stratification in the deep section may also be classified as "fjord type".

On the south side of the estuary, the water is principally fresher than on the north side (Fig. 18), except where the Saguenay River enters the system. In the deep section of the estuary, the depth of the fresher water layer increases along the south shore while decreasing along the north shore. Obviously, there is a displacement of fresher water in the upper layer toward the south shore and a compensating flow of saltier water at greater depths toward the north shore. In the upper section a cyclonic circulation reinforces this cross motion and mixing involves the entire cross section of the channel while, in the lower section, it is confined to a relatively shallow zone below the surface. During spring freshet all the processes tend to become more forceful without changing the character of the distribution.

3.2 Distribution of Temperature

As expected, temperatures and their distribution differed appreciably between the surveys.

3.2.1 Distribution in February

During the February survey, the atmospheric temperature ranged from -18 degrees to -8 degrees centigrade. (All temperatures in this report are in centigrade.) The water therefore was subjected to strong cooling and, consequently, its temperature in the surface layer approached or had already reached the freezing point. This was also evident by the existence of the icefields which, as far as could be observed from the ship, covered 20 to 40 percent of the water surface.

This seasonal cooling created a temperature field which was remarkably well stratified, as illustrated on the longitudinal profile of Figure 12. From the arrangement of the isothermals, it is apparent that the heat in the water was flowing vertically upward to the surface, probably by both thermal and dynamic convection, where it escaped into the air. The vertical temperature distribution shows a regular increase from the surface downward to approximately mid-depth, below which the temperature was quite uniform at 4 to 4.5 degrees.

It is of significance to discover that there is a resemblance between the salinity and temperature structures on both sides of the estuary. As described in the preceding section, the isochalines along the north shore sloped upward, while they sloped downward along the south shore. The same feature, even better defined, exists in the isothermals. This arrangement infers that the temperature in the surface layer increases along the north shore toward the sea, while on the south shore cold water with a temperature between -1.5 and -2 degrees forms an increasingly thick layer toward the Gulf. At Pointe des Monts the thickness of this cold layer has grown to almost 200 feet. From this it must again be concluded that along the north side water having a greater heat content is brought up from lower zones to the surface, whereas cold water from the upper layer is transferred to the south shore where it accumulates. The same feature can be observed in the horizontal charts and on the cross section at Pointe des Monts (Fig. 14 and 20).

In the shallow section of the estuary, temperatures are generally slightly higher (Fig. 12). Heat from the greater depths of the deep section penetrates over the sill into the downstream part of the shallow section, where a temperature gradient of one degree can be found from the surface to the bed.

3.2.2 Distribution in May

In May, the structure of the heat spectrum was changed completely. The temperature of the air rose appreciably since February, and during the survey was between +5 and +15 degrees.

The surface of the estuary was therefore warming rather than cooling. This is reflected in the distribution of the temperatures which, again, are stratified but divided into zones (Fig. 13).

At the bottom of the deep channel, water at 4.5 degrees is still to be found. Proceeding vertically upward the water cools fairly quickly until the intermediate depth is reached. Here a layer of cool water with a temperature less than -0.5 degree is found covering the entire channel. A similar layer was observed by Lauzier in the Gulf of St. Lawrence farther downstream. (Ref.8). The thickness of this layer increases from south to north, the temperature in its centre being colder on the north side than on the south side (Fig. 20). Spread over this body of cold water is a thin layer of warmer water in which the temperature increases toward the surface.

It is evident that the intermediate cold water layer was part of a cold water zone which previously extended to the surface. As soon as the atmospheric temperature exceeded that of the water at the beginning of April, a warmer surface layer formed. The cold water was then trapped between two warm-water layers. To warm up this block of water, heat was being transferred from the surface downward and from the lower layer upward.

In February, the water on the surface was warmer on the north side than on the south side. This was reversed in May, but for the same reason, i.e. the lateral transport. This surface motion, which deviated the cold surface water toward the south shore in February, carried water of appreciably higher temperature than that of the underlying zone in May. The water upwelling from lower zones along the north shore is therefore colder in May and warmer in February than the surface water.

In the upper section of the estuary the heat structure, in May, was greatly affected by the inflow of warmer water from the river which already had reached a temperature of +10 degrees. The isothermals, as shown on Figure 13, sloped upward, suggesting mixing with colder water approaching from below.

The horizontal charts, Figure 15, illustrate that here also the north channel is appreciably colder than the south channel.

The two other main sources of fresh water, the Saguenay River and the group of rivers, do not seem to influence the temperature structure of the estuary to an appreciable extent. This is understandable for the Saguenay River because its water is pre-mixed in the fjord-like arm before it enters the estuary. The whereabouts, in the estuary, of the fresh water discharge from

the group of rivers which, in May, had increased from 50,000 c.f.s. to 140,000 c.f.s., is more of a mystery. While cruising in this area, the water was observed to be of a brown colour being distinctly different from the rest. This water appeared to extend, as far as could be determined by eye, at least half-way across the channel.

In section G, which was the survey section next to this area, an increase in temperature and a decrease in salinity were measured only at positions 3 and 4, located on the south side opposite to these rivers. If these properties are due to the freshet discharge of the group, it suggests that their water passes across the estuary to join the fresher layer along the south shore. This phenomenon would be related to the overrunning characteristics of freshets but in this case would represent a transverse crossing of the main stream.

3.2.3 Discussion

Generally, the temperature structure was quite stratified in the deep section but more homogeneous in the shallow part of the estuary. In February, nearly half of the deep channel was filled with water having temperatures higher than 4 degrees but, in May, this body had cooled appreciably and an intermediate layer of cold water had formed whose temperature ranged from -0.5 to 0.5 degrees. Even under this condition, a considerable amount of heat remained in the water. On the surface a relatively thin layer, which in February was colder and in May warmer than the water below, was spread over the underlying body.

In the shallow section temperatures of the order of zero to one degree were observed in February as far upstream as Ile aux Coudres, where these temperatures indicate a considerable heat content since the freezing point of the water in this area is about -1.0 to -1.5 degrees.

The surface water on the south side was colder in February and warmer in May than on the north side. In both instances, water from the surface layer had accumulated in a zone increasing in thickness seaward.

From this it can be concluded that during the winter, when the atmosphere is colder than the water surface, the estuary is warmer on the north and colder on the south side, while during the rest of the year, when the air is warmer, conditions are reversed. The transition must take place sometime during the beginning of April (Fig. 5). The warming of the surface layer, however, seems not only due to absorption of radiation and convection of heat from the atmosphere, but also to warmer water being carried into the system by the river and tributaries whose waters warm up more quickly in the spring than those of the estuary.

4.0 TRANSVERSE MOTIONS

The outstanding feature of the St. Lawrence estuary system is the convergence of fresher surface water toward the south shore and saltier water from deeper zones toward the north shore.

The deviation of these two bodies of water is initiated by a transverse force, the Coriolis force, which is due to the rotation of the earth. A water particle reacting to this force is deviated perpendicularly to the right of its line of motion in the northern hemisphere. The value of the acceleration due to this force is:

$$a = 2 \omega \cdot \sin \phi \cdot u = \frac{1}{C} \cdot u \quad (1)$$

where ω is the terrestrial angular velocity (rad/sec), ϕ the latitude of the particle's location, u the velocity of the particle (ft./sec.) and $\frac{1}{C}$ the Coriolis parameter (1/sec.). At the latitude 47 degrees north, the location of the St. Lawrence estuary, the value of the parameter is:

$$\frac{1}{C} = 1.0 \times 10^{-4} .$$

It has been established that fresh water leaves the region through the upper zone while sea water required for mixing is transferred inward in the lower zones. In this process, there is a surface of no motion above which the net transport is outward, and below is inward.

The Coriolis force acting on this two-layer flow system deflects both layers to the right of their lines of motion and thus deflects the dominantly outward flowing surface layer southward and the inward flowing water of the lower zones northward. Hence, a greater depth of fresher water should be on the south side of the channel. This was found to occur throughout the entire system, except at the mouth of the Saguenay River, as shown on Figure 18.

The mass or density field also implies this feature. The lines of equal densities referred to as isopycnals, at Pointe des Monts (Fig. 22) in the upper layer at the right hand or south side, are sloped downward to the south, while in the lower layer, particularly in the centre and north side, they are sloped the other way, except along the north shore during the May survey.

This inclination gives a general indication of the principal directions of the relative currents normal to the section. According to a simple rule outlined in Ref. 2, a current at one depth relative to a current at a greater depth flows away if the isopycnals slope downward from left to right in the interval between the two depths and approaches if the curves slope generally the opposite way.

Applying this rule to the cross section of Pointe des Monts, it infers that at the right hand or south side of the upper layer the water flows outward while in the rest of the section it flows mostly inward.

The slope of these density lines is initiated by the deflecting force of the earth's rotation. The force of the pressure gradient resulting from the distribution of these densities and a force which depends upon the slope of the free surface of each layer together balance this deflecting force, provided friction and accelerations are neglected.

In a two-layer flow system, the dynamic conditions are in equilibrium when the pressure exerted against both sides of the interface are equal. This may be expressed in the form:

$$\rho' v' \frac{1}{C} dy + g \rho' dz = \rho V \frac{1}{C} dy + g \rho dz \quad (2)$$

where V', ρ' and V, ρ are velocities and densities in the upper and lower layers respectively, x, y and z the longitudinal, transverse and vertical axes and g the earth's gravitational acceleration.

From this equation, known as Margules equation, the slope of the boundary face may be obtained:

$$\text{tg } \gamma = \frac{dz}{dy} = - \frac{1}{g \cdot C} \frac{\rho V_x - \rho' V'_x}{\rho - \rho'} \quad (3)$$

The inclination of the surfaces within the individual water masses may be derived:

$$\text{tg } \beta = - \frac{V_x}{g \cdot C} \quad (4)$$

The conditions at Pointe des Monts are illustrated schematically on Figure 24. The slope of the interface, in February, obviously is greater than in May. This compression of the surface layer in spring has been observed, as already mentioned, throughout the entire deep section of the estuary.

It can be assumed that the surface of no motion coincides approximately with the isothermal and isohaline surfaces. A study of these lines on Figures 20 and 21 indicates that the depth of no motion follows approximately a line which starts on the surface between survey positions G_1 and G_2 and drops to 500 ft. (152 m) in February and 350 ft. (107 m) in May at the south shore.

This line of no motion separates the flow of a wedge-like surface layer from the remainder of the flow. The salt water which enters the system through the lower layer must leave it again with the fresh water through the surface layer. For reasons of continuity, it therefore must be:

$$Q' = Q + Q_R \quad (5)$$

$$\text{or} \quad A'V' = AV + Q_R \quad (6)$$

where Q' , Q and A' , A are the transport and the cross-sectional area of the upper and lower layer respectively and Q_R is the fresh water inflow.

The velocity difference $V' - V$ can be obtained from Eq. (3):

$$V' - V = g \cdot C \cdot \text{tg } \gamma \cdot \frac{\rho - \rho'}{\bar{\rho}} \quad (7)$$

The approximate volume transported through the layers of the system can thus be computed from Eq. (7) and Eq. (6). The properties for February and May are, respectively:

mean density of upper layer: ρ' : 1.0269 and 1.0248

mean density of lower layer: ρ : 1.0277 and 1.0270

gradient of surface motion: $\text{tg } \gamma$: 0.005 and 0.0035

cross-sectional flow areas of upper layer:

$$A': 28.6 \times 10^6 \text{ ft}^2 \quad \text{and} \\ 20.4 \times 10^6 \text{ ft}^2$$

cross-sectional flow areas of lower layer:

$$A: 97.4 \times 10^6 \text{ ft}^2 \quad \text{and} \quad 105.6 \times 10^6 \text{ ft}^2$$

fresh water inflow: Q_R : 330,000 and 530,000 c.f.s.

According to Eq. (7) the average relative velocities between the two layers, in February, were 1.25 ft./sec. (38 cm. p.s.) and, in May, 2.35 ft./sec. (72 cm.p.s.), and the respective inflows through the lower layers computed from Eq. (5) were 27×10^6 c.f.s. (760,000 cbm.p.s.) and 40×10^6 c.f.s. (1,120,000 cbm.p.s.). The velocities in these lower layers were 0.28 ft./sec. (8.5 cm.p.s.) and 0.37 ft./sec. (11.1 cm.p.s.).

In both cases, the quantity of fresh water amounted to only a little more than one percent of the total transport in the surface layer. Nevertheless, the increase from 330,000 c.f.s. (9,250 cbm.p.s.) in February to 530,000 c.f.s. (14,800 cbm.p.s.) in May seemed to have brought some further 13 million c.f.s. (365,000 cbm.p.s.) of salt water into circulation.

In the foregoing computation it was assumed that the water in both layers was homogeneous. However, this is not true, particularly in the surface layer as shown on Figure 22. Considerations valid for a two-layer system can be applied to continuously stratified conditions by a method used by oceanographers for ocean currents. It permits computation of the current velo-

cities along the entire cross section on the basis of the internal pressure field.

The results of such a computation, using Sverdrup's tables for the anomalies of the specific volume, are shown on Figure 25. Toward the north shore and in the lower layer, the velocities are small and directed inward, ranging from 0.15 ft./sec. (4.5 cm.p.s.) to 0.5 ft./sec. (15 cm.p.s.), while in the upper layer they are directed outward and reach values of 1.7 ft./sec. (52 cm.p.s.) and 3.4 ft./sec. (104 cm.p.s.) in February and May, respectively.

The greatest concentration of high velocities is located along the south shore in a belt lying between 2 and 14 miles off shore. In this strip of water there is a current known as the Gaspé current which is unidirectional; running constantly outward from the St. Lawrence estuary into the Gulf at 1 to 2 knots during normal tides. Its greatest strength is 4 to 5 miles from the south shore.

These observations agree in every respect with the data derived from the internal pressure field. Even the location of the highest current concentration coincides with that computed for the 50 feet surface layer as shown on Figure 25. The Gaspé current, according to this concept, is therefore only the high velocity region of the wedge-like surface layer. The area where the unidirectional current originates was located below Father Point in February and above in May.

Nearly all the fresh water of the system is concentrated and transported in this triangular-shaped upper layer, of which the Gaspé current is a part. As already mentioned, no appreciable quantity of fresh water enters the system from the south shore where the stream is located. The 20 to 40 percent of fresh water which enters from the north shore must therefore cross the estuarine channel immediately to join the flow on the south side. This process is taking place continuously and thus has a stationary character. As has been shown, the deflecting forces for this process are provided by the rotation of the earth.

The transporting capacity of the layer, according to the calculation, is enormous. The volume transport of the relatively shallow and confined flow is as much as the run-off of all continental rivers together. Still more impressive is the sensitivity of the stream to changes in fresh water inflow. An increase of one part of fresh water appears to bring nearly 100 times more salt water into circulation.

This response is most significant. It indicates that a reduction in fresh water inflow will be followed by a decrease in longitudinal and transverse surface velocities. If, for example, the fresh water inflow in May is reduced to that of February, surface currents will drop to about half and around 13 million c.f.s. (365,000 cbm.p.s.) of salt water will be taken out of circulation.

Any reduction of this nature would exert far-reaching influences on the heat and salt budgets of the entire system, the Gulf of St. Lawrence included.

Certainly, it is recognized that seasonal temperature changes affect the pressure field and in this way the strength of the currents. This influence, however, is small compared with that initiated by the fresh water fluctuation.

In the shallow section of the estuary, conditions differ considerably from those of the deep section. In the deep part, as at Pointe des Monts, tides are too small and the period of oscillation too short to impose noticeable modifications on the mass field during a tide cycle. It was therefore assumed that the controlling velocity field in the longitudinal direction is that of the two-layer flow system initiated by the density difference. Thus, for the calculation of the current velocities it was assumed that conditions were stationary - neglecting seasonal changes - ; the Coriolis force $\frac{1}{c} \cdot u$ acting transversely to this motion, therefore also having a stationary character. In the shallow part, at Point aux Originaux, where the tide achieves its greatest range and where the channels and water masses are appreciably smaller, the system starts to respond noticeably to the fluctuating current of the semi-diurnal tide. This was observed during the survey in September 1959, the results of which are shown on Figure 23.

The velocity field, which in this case must be taken into consideration, is a combination of the quasi-stationary two-layer flow pattern and the fundamental current oscillation of the tide. This composite flow differs from that of a system having a similar tide but homogeneous water in that during ebb tide the current velocities in the upper layer are increased while in the lower layer they are decreased. During flood tide this process is reversed, while about half-way between, outflow in the upper layer balances inflow in the lower with zero net motion. These patterns existed at Point aux Originaux, as shown in Figure 23, particularly during the period from Low Water to Half Rising tide. During the other periods this was slightly obscured.

The Coriolis force which acts transversely to this motion must generate, under these circumstances, a transverse oscillation, the period of which is equal to the period T of the semi-diurnal tide but with a phase difference of $T/4$ with respect to the phase of the longitudinal current oscillation. The water is therefore not only subjected to gradient flow in the axial direction but also to oscillatory movements, the surface layer more toward the south shore and the deeper layer more toward the north shore due to the modification of the two-layer flow imposed on the tidal oscillation.

Owing to this transverse oscillation, the surface of the water and the interface between the two layers must also oscillate. The inclination of the surface during the tide cycle has not been measured, but according to Eq. (4), at Half Rising tide, the water level on the south side of the channel should have been approximately 0.5 ft. (15 cm.) higher than on the north side, while at Half Falling tide the water level should have been sloped oppositely with a level difference of approximately 0.2 ft. (6 cm.).

The oscillation of the interface has been observed by measuring the densities during the tide cycle. The results are shown on Figure 26. Plotted on the graph are the axial velocities at Position L and the isopycnal $\rho = 1.017$ which demonstrates the change in slope of the mass field during a tide cycle. It can readily be seen that the period of oscillation of the interface is equal to the period of the tide and that it follows the oscillation of the tidal current by a phase difference of $T/4$ which is about $3\frac{1}{4}$ hours. The interface reaches its greatest slope a short time before Half Rising tide with a gradient slope downward from north to south. To achieve this, water masses of the surface layer have shifted toward the south shore while those in the deeper layers deviated toward the north shore. From then on, the steepness of the interface gradually decreases until it becomes zero at High Water. This level position is maintained for nearly one-quarter of a tide cycle without achieving any noticeable slope in the other direction. The two bodies of water have thus returned to positions having level interfaces without being shifted toward the other side. The integrated motion is therefore toward the south shore in the surface layer and toward the north shore in the lower layer.

The transverse motions involved in this transport are oscillatory but they are associated only with the ebb current. This behaviour indicates that during flood tide there is hardly any velocity difference between the upper and lower layer. This is verified by the velocity survey shown on Figure 23. The current of the two-layer flow system seems to modify the velocity pattern of the basic flood tide current in such a way that the composite current is remarkably uniform from the surface to the bottom. Under such circumstances, the relative velocity between the two layers is zero and therefore no slope of the interface can develop.

Further, a transverse motion, similar in character but seasonal in its occurrence, can be expected to exist in the estuary. In this case the motion is associated with the seasonal increase in discharge, such as freshets. In the shallow section, these increases in fresh water appear to be less effective in promoting a density difference since mixing involves the entire channel, only a downstream displacement of the salt water with some freshening at all depths was observed. In the deep section, however, freshets create currents in the upper layer which are greater than the proportional increase in discharge. As soon as the freshet starts and the current velocities increase, the increased

Coriolis forces, caused by the increase in velocities, are unbalanced by the internal field of forces, which were formed in response to the velocity structure of the preceding fresh water condition. Consequently, a redistribution of the mass field is required which takes place in a transverse circulation relative to the main current. This is comparable with the condition at Point aux Orignaux from half-way between Half Falling tide and Low Water to half-way between Low Water and Half Rising tide. In both instances, the unbalanced force of the earth's rotation is used to generate a transverse motion to shift the surface water more toward the south shore.

From both, observation and measurement, the conclusion can be drawn that freshets, during their rising stages, introduce, particularly in the surface layer, cross currents appreciably stronger than those during the regular discharge season. The rapid transfer of the May freshet water from the group of rivers across the estuary channel might be explained in this way.

Finally, it appears that in the St. Lawrence estuary there are three types of cross motions - one stationary and the other two oscillatory. The stationary cross motion which prevails throughout the year is associated with the longitudinal two-layer flow system which develops progressively toward the sea and in which the two bodies of water form the observed sloped mass field. The inflow from the two principal tributaries located on the north shore contribute to this process of transverse displacement. The other two cross motions are oscillatory by nature, the first being associated with the tidal current and the second with the seasonal increases in fresh water discharges. The first seems to dominate in the shallow part of the estuary while the second prevails in the deep section. In both cases, the surface layer appears to be deviated exclusively toward the south shore.

The temperature records emphasize the same general movement that was observed from the salinity distribution and inferred from the transverse slope of the mass field.

5.0 CONCLUSIONS

In the St. Lawrence estuary, all three basic types of estuarine mixing are found: the well-mixed, with nearly vertically homogeneous conditions at the head of the estuary, the moderately stratified, in the section below, and the highly stratified in the deep section downstream of the mouth of the Saguenay River. These various degrees of mixing are initiated primarily by the turbulent diffusion induced into the system by the tidal motion. While the tide is still moderate and gentle at the lower end of the estuary, its range and current velocities increase progressively upstream, finally reaching nearly bore-like character at the head of the estuary.

In addition to the longitudinal two-layer circulation required for transporting fresh and salt water through the system, there are transverse motions imposed on it by the rotation of the earth. These transverse motions deviate the upper layer toward the south shore and the lower layer toward the north shore.

During freshets, the intensity of both longitudinal and transverse motions increases, particularly in the upper layer. An increase in fresh water inflow from 330,000 c.f.s. (9,250 cbm.p.s.) in February to 530,000 c.f.s. (14,800 cbm.p.s.) in May, with a temperature rise in the upper layer of approximately 5°C., initiated an increase of velocities in the surface layer at Pointe des Monts from 1.7 ft./sec. (52 cm.p.s.) to 3.4 ft./sec. (104 cm.p.s.). The Gaspe current is the high velocity region of this upper layer.

In winter these motions play an important role in the formation and transport of ice. As has been illustrated, in the cross circulation, water with greater heat content is brought to the surface along the north shore, where it maintains a somewhat open channel throughout the winter (Fig. 27), while ice is deviated with the surface layer more toward the south shore where it accumulates. In spring, these motions are magnified and thus assist the estuary to clear itself quickly of the winter's debris.

Can this process be modified and what would be the consequences of such a modification?

The forces which generate the circulation are terrestrial in nature and magnitude. The rate of rotation of the earth cannot be altered, but the force associated with the density difference could be modified by changing the fresh water inflow.

The fresh water inflow to the system is already being regulated; a great number of tributaries being artificially controlled to equalize their discharges for power generation and navigation. The regulation of the Great Lakes, the Ottawa River, the Saguenay River, along with many others, are examples of this artificial control.

Before this regulation began some 50 years ago, the inflow during spring and early summer was at least 20 to 30 percent greater than it is today, while during the rest of the year it was somewhat less. Since then, the run-off has been gradually modified by retaining water during the higher discharge season of spring and summer, and by discharging it to the system during the low discharge season. This regulation of the fresh water inflow must have modified the estuarine circulation so that there was a decrease in the longitudinal and transverse transport during the warmer seasons of spring and summer, and an increase during the colder seasons of fall and winter.

Since the volume of salt water involved in the estuarine transport is nearly a hundred times that of the fresh water, the properties of the salt water must be far more influential than

those of the fresh water. Consequently, in the spring and summer, when the temperature of the underlying salt water from the sea is appreciably colder than that of the fresher surface layer, a reduction in the salt water inflow should result in the surface layer being less strongly cooled since a smaller amount of colder water is available for mixing. Furthermore, the slower surface currents should allow the surface layer to absorb more heat during its passage through the system. The reduction of the current velocities in general should also provide more stable stratification where less dynamic convection occurs, decreasing vertical heat transfer, and thus reducing the intermixing of the warmer surface water with the colder underlayer. All these factors should contribute to warming of the surface layer of the system during spring and summer.

During the low discharge period in the colder seasons of the year, more salt water enters the system now than previously. As this salt water is warmer than the surface layer, more heat should be available to warm the surface layer.

Generally, it can therefore be stated that, in both the warmer seasons, i.e. spring and summer, and in the colder seasons, i.e. fall and winter, the surface temperatures of the water in the estuary and probably also in the Gulf should be increased as a result of the fresh water regulation.

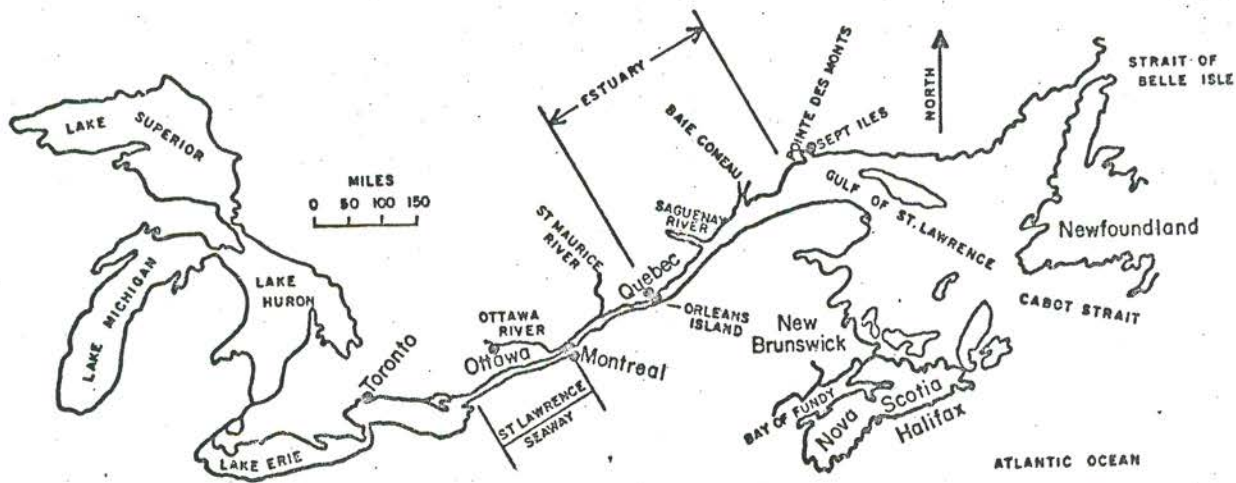
The variation of the temperatures in the surface layer over the years has not been recorded. The changes anticipated herein, no matter how small they might be, must also have influenced the atmospheric temperature of the area. According to the reasoning applied, the regional climate of the Lower St. Lawrence over the last 50 years should have become more continental-like during spring and summer and more maritime-like during fall and winter. If such changes can be traced through air temperature records and thus proven, the modification would represent a man-made change of climate covering an entire region.

Retaining the fresh water peaks from the early spring freshets also has a pronounced influence on the properties and movement of the surface layer, which delays the melting of the ice-cover and restrains its movement and consequent flushing from the estuary. These effects might partly be compensated by the greater inflow of warmer sea water during the preceding winter months.

The question of whether this development is beneficial or not to the region cannot be deliberated here and is, at this stage, irrelevant to the investigation. Since the desire or necessity of retaining fresh water from the higher discharge seasons has not ceased, the huge storage schemes already under construction or in the design stage will continue this transition with further influences on the conditions nature has provided. The effect of these man-made modifications should be recognized and carefully considered.

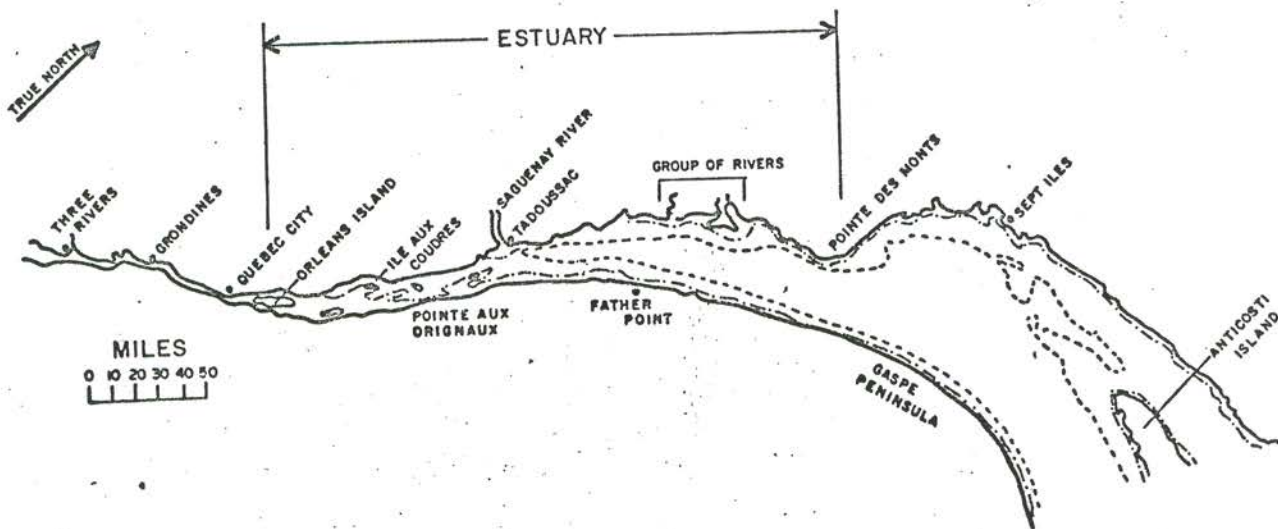
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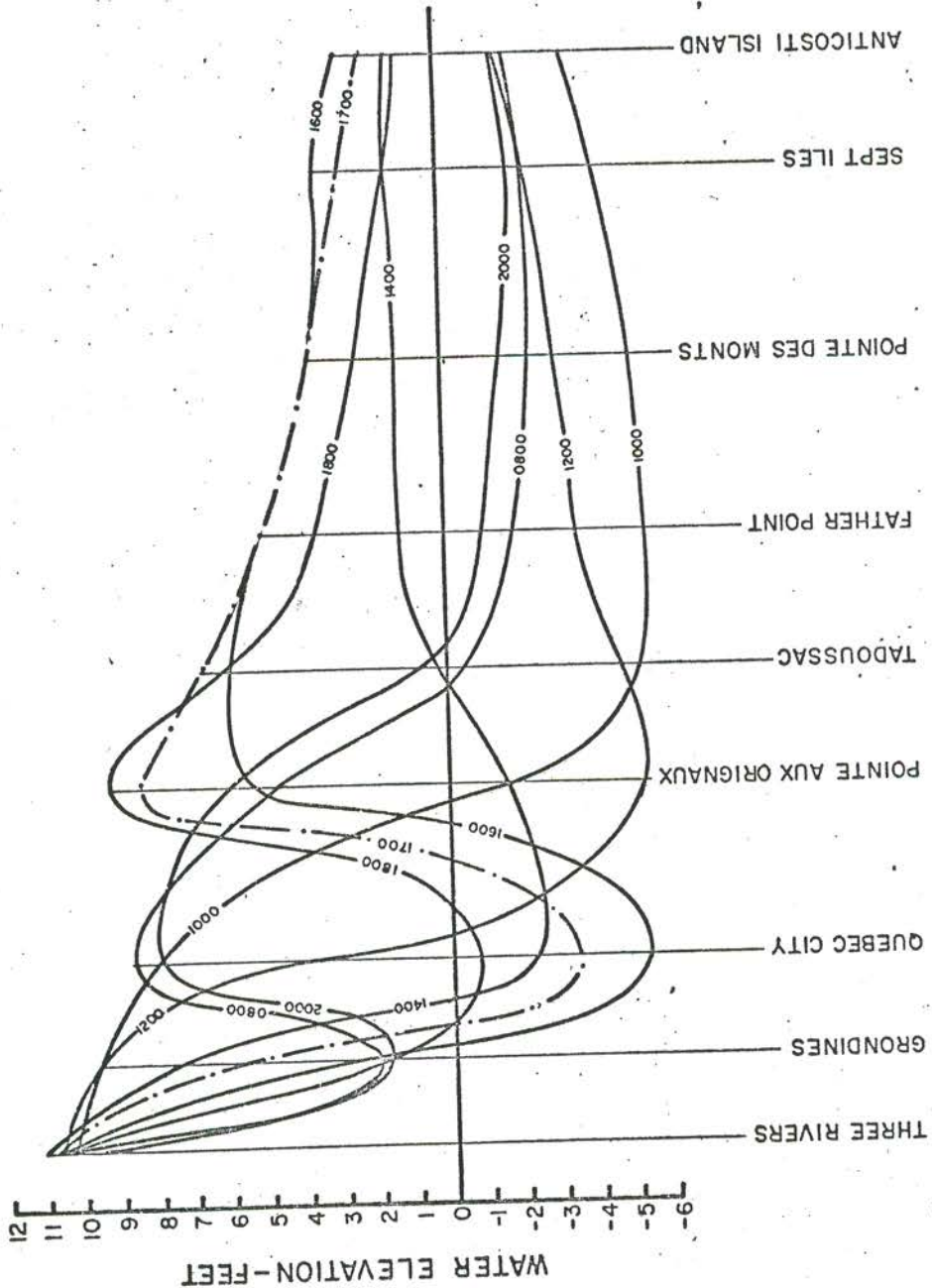


REGIONAL MAP OF GREAT LAKES AND ST. LAWRENCE SYSTEM

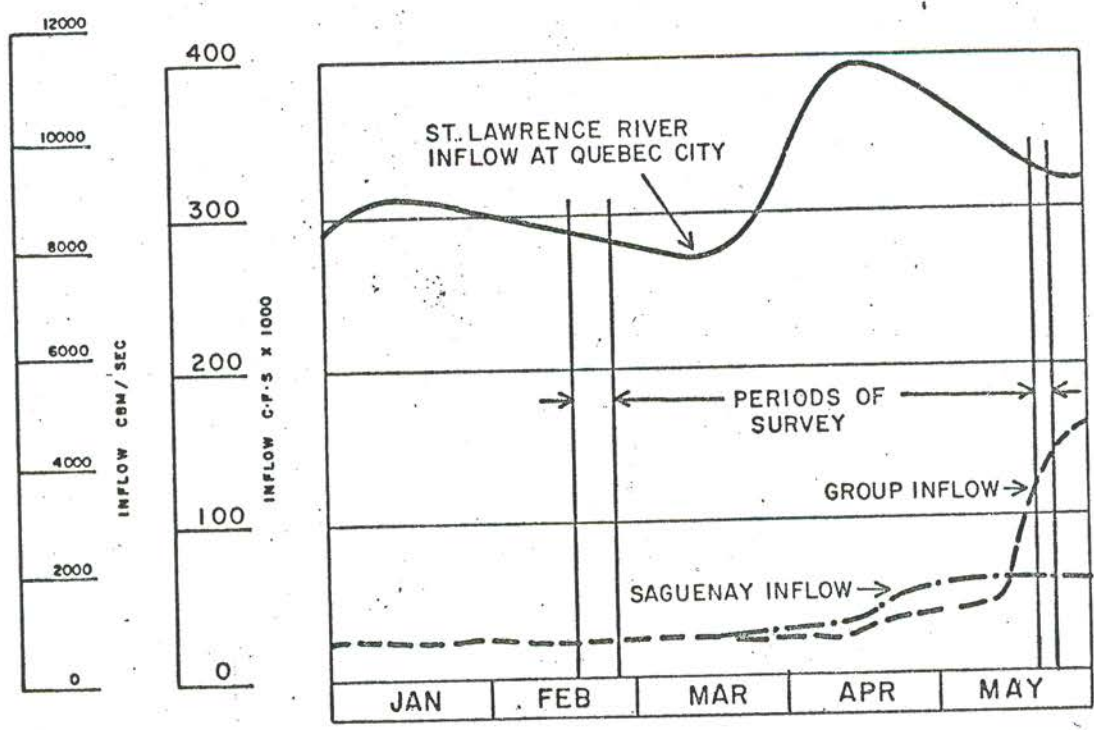
FIG. 2



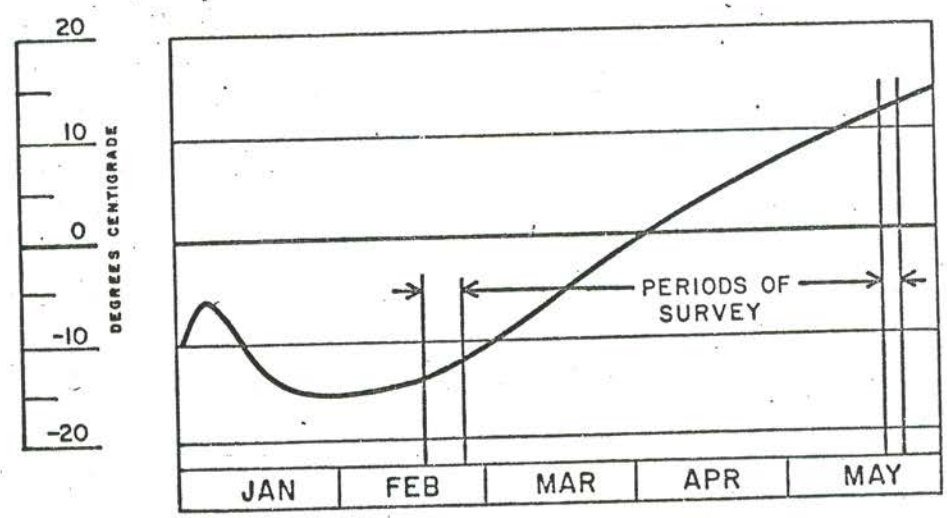
MAP OF LOWER ST. LAWRENCE RIVER AND ESTUARY



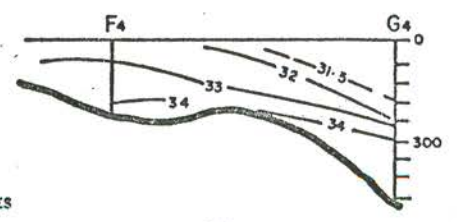
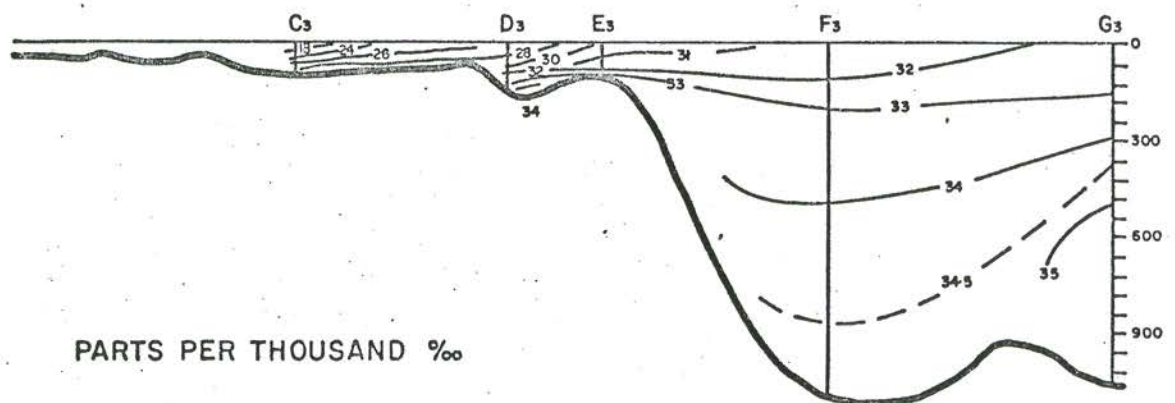
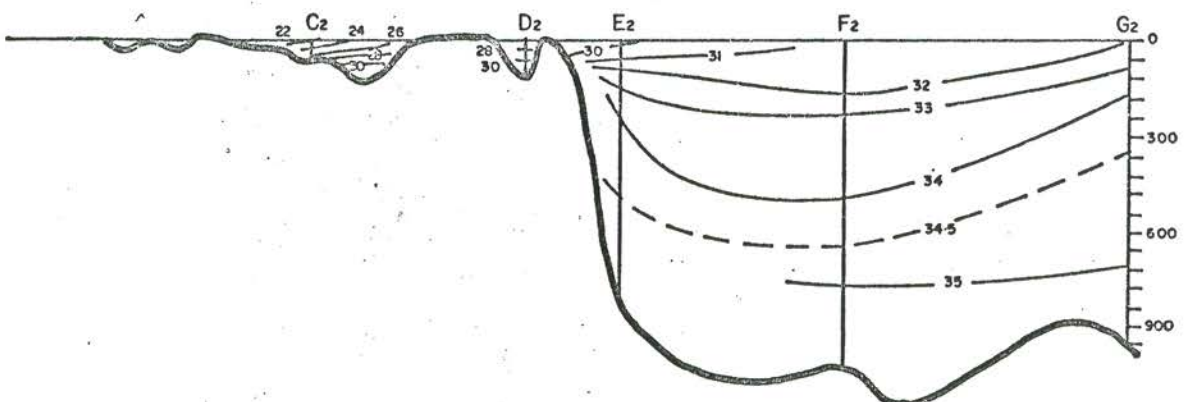
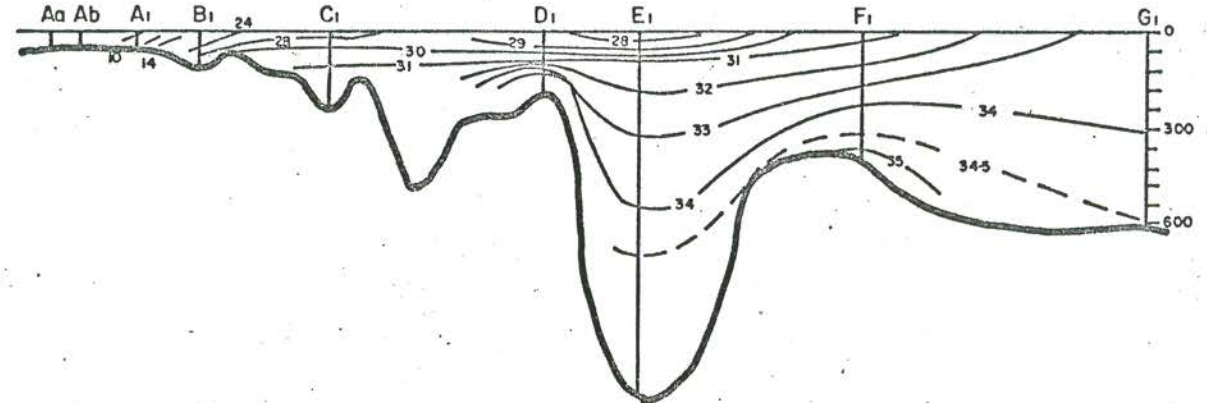
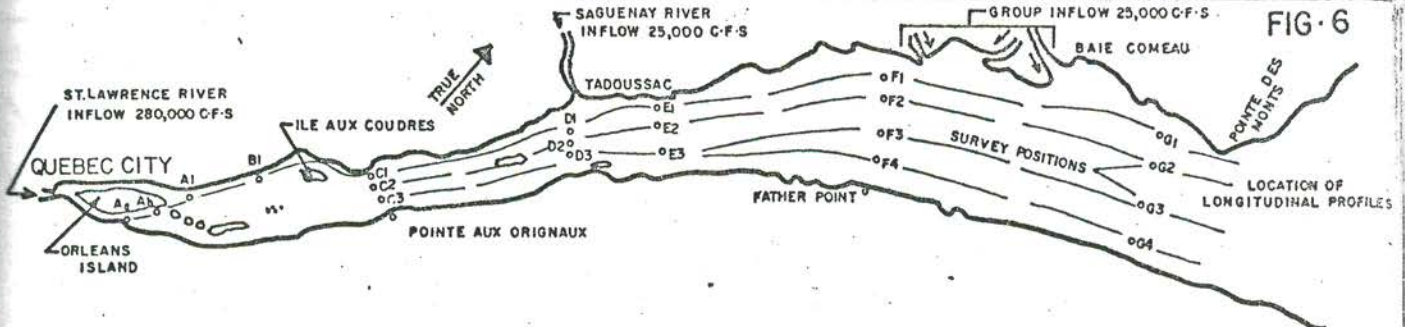
2 HOUR LINES OF TIDE WAVE
FEBRUARY 11, 1959



APPROXIMATE FRESHWATER INFLOW INTO THE ESTUARY FROM JAN 1, TO MAY 31, 1963

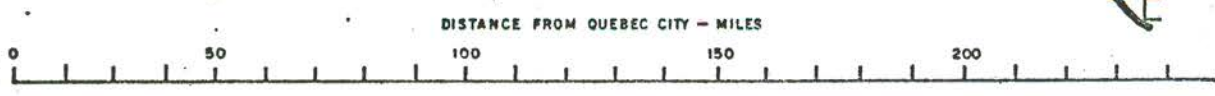


MEAN AIR TEMPERATURE AT QUEBEC CITY FROM JAN 1, TO MAY 31, 1963



PARTS PER THOUSAND ‰

DEPTH IN FEET



LONGITUDINAL SALINITY PROFILES
FEBRUARY 18-25, 1963

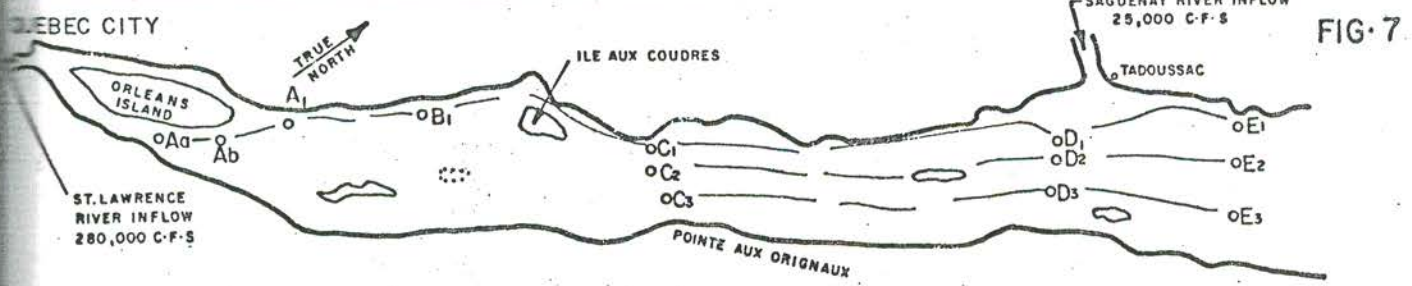
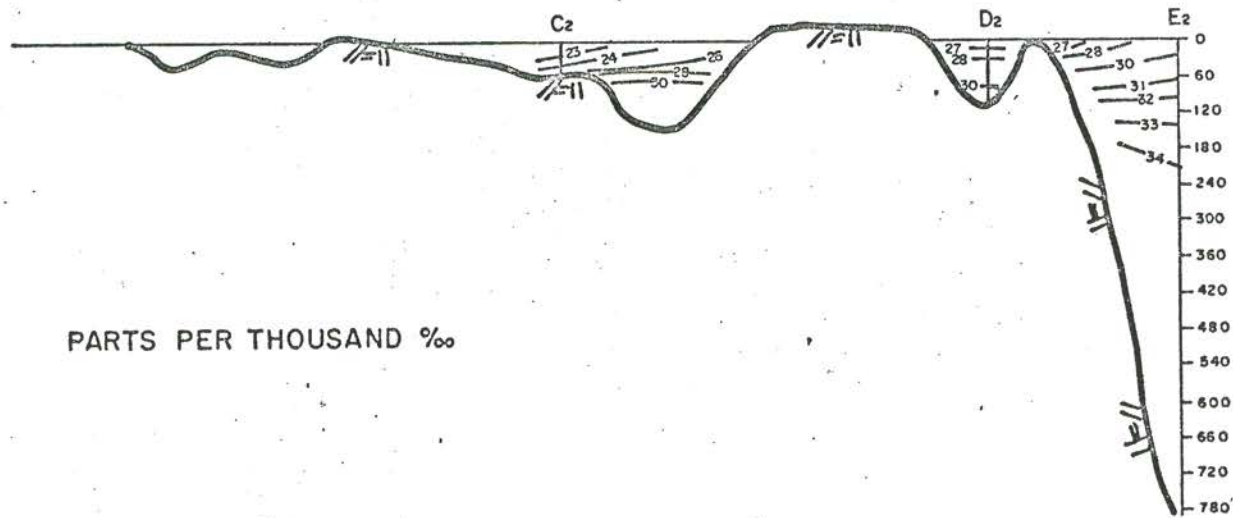
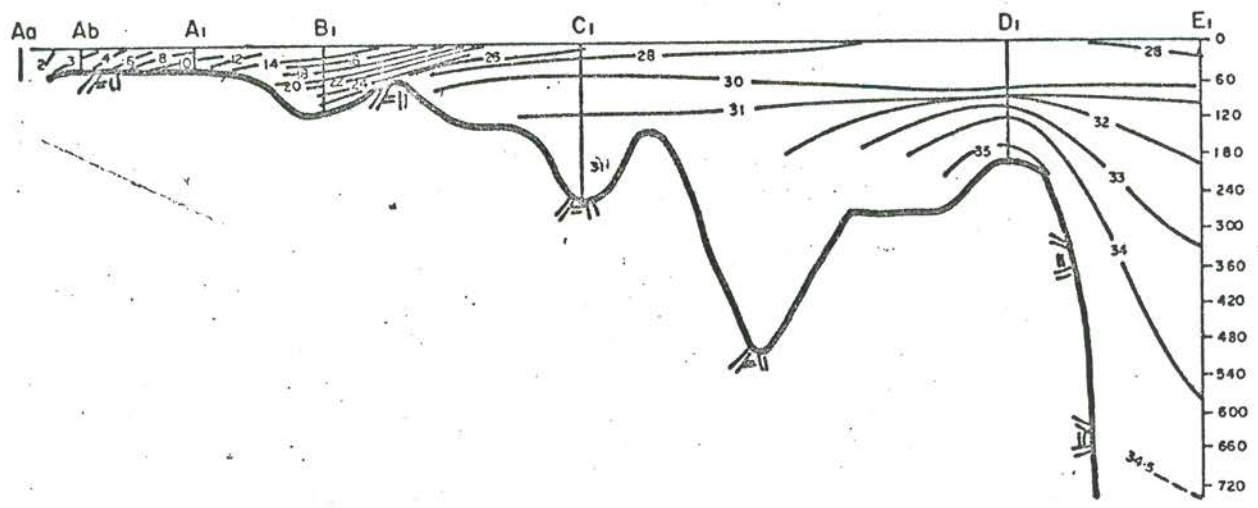
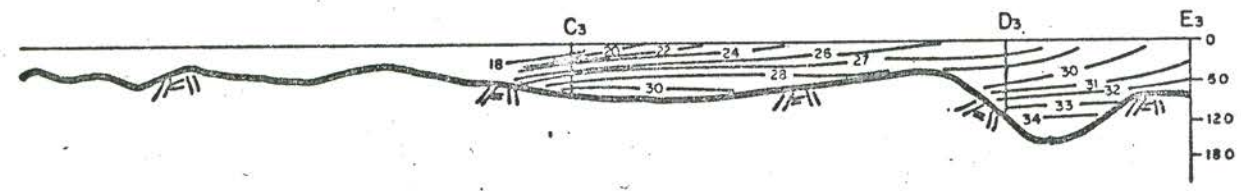


FIG. 7



DEPTH IN FEET

PARTS PER THOUSAND ‰



DISTANCE FROM QUEBEC CITY - MILES

LONGITUDINAL SALINITY PROFILES
UPPER SECTION, FEBRUARY 18-25, 1963

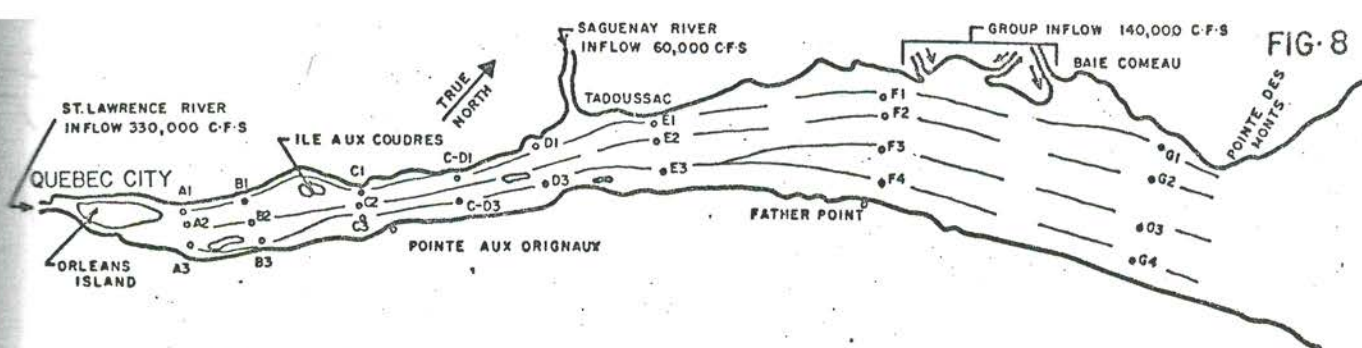
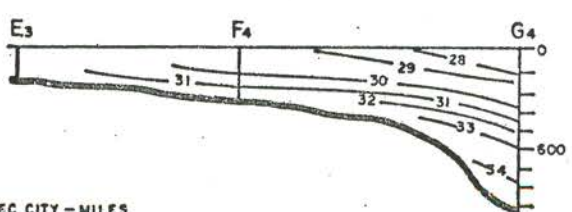
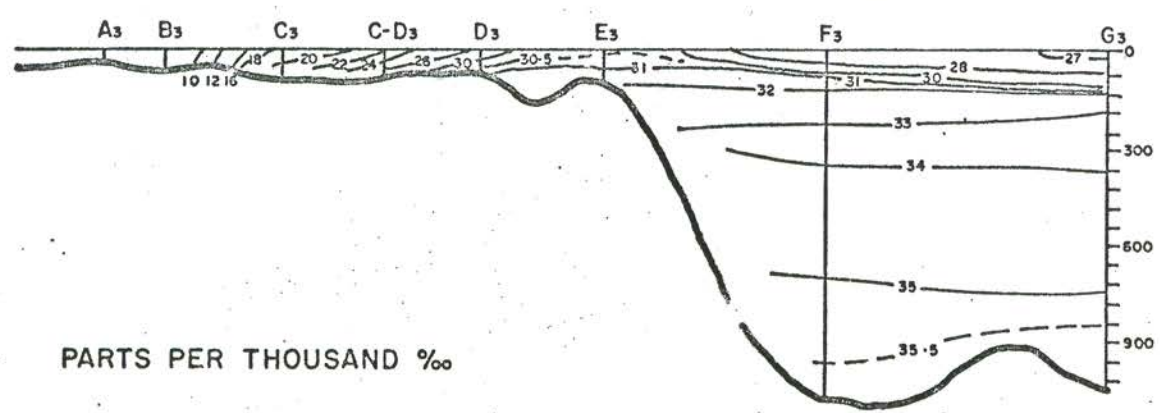
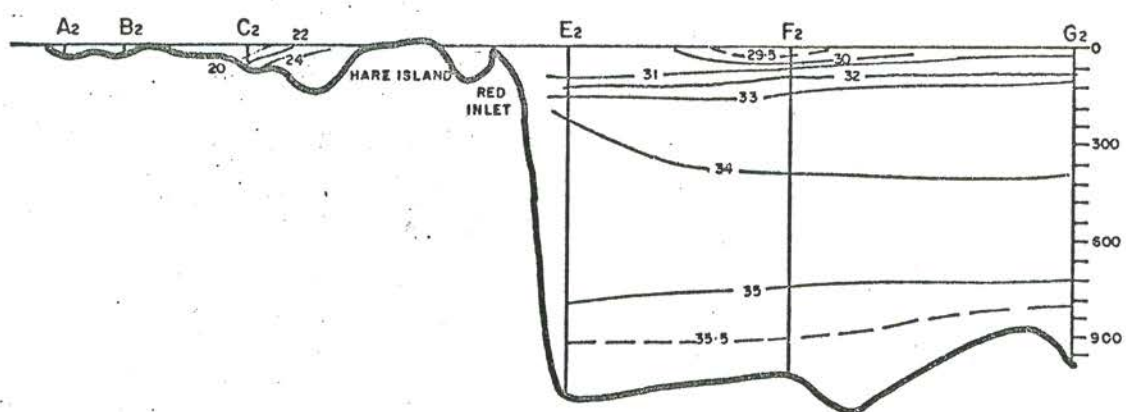
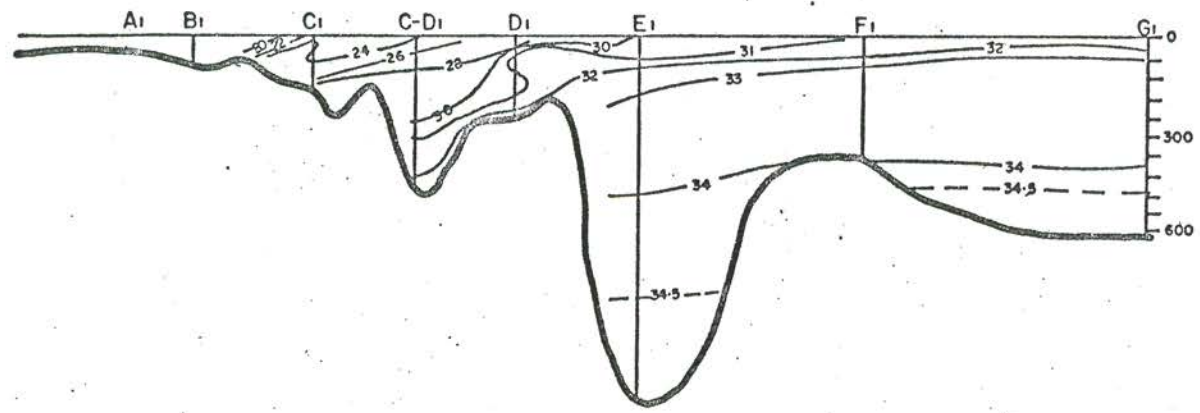


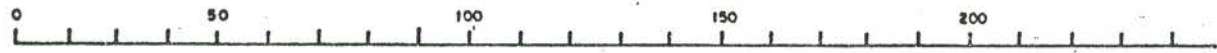
FIG-8



DEPTH IN FEET

PARTS PER THOUSAND ‰

DISTANCE FROM QUEBEC CITY - MILES



LONGITUDINAL SALINITY PROFILES
MAY 21-24, 1963

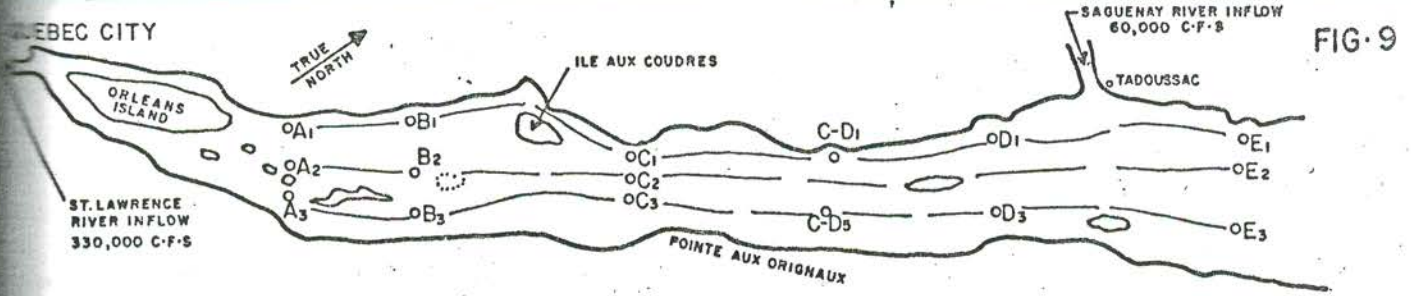
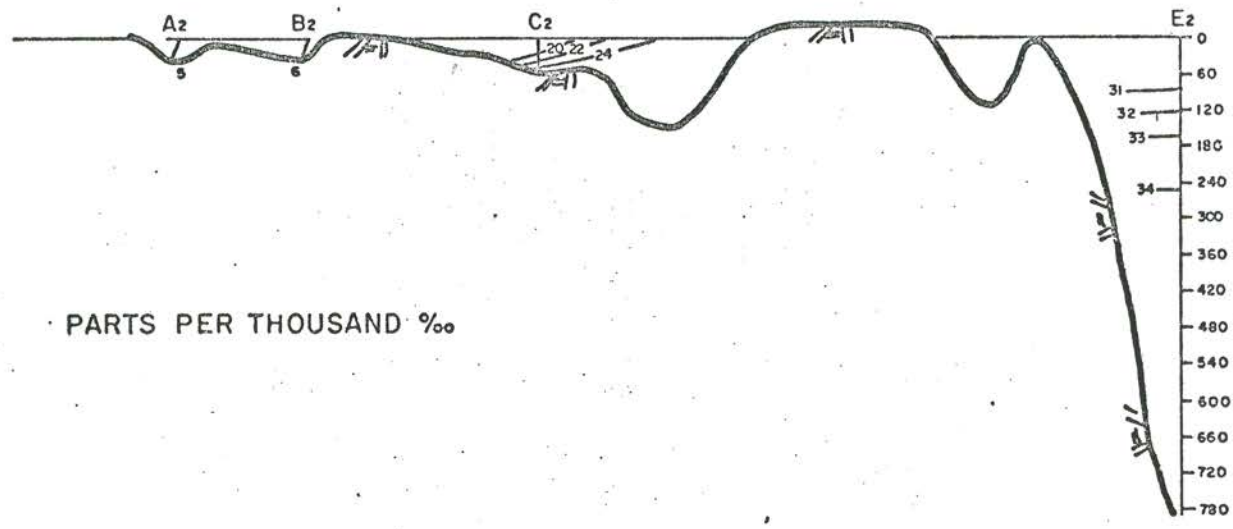
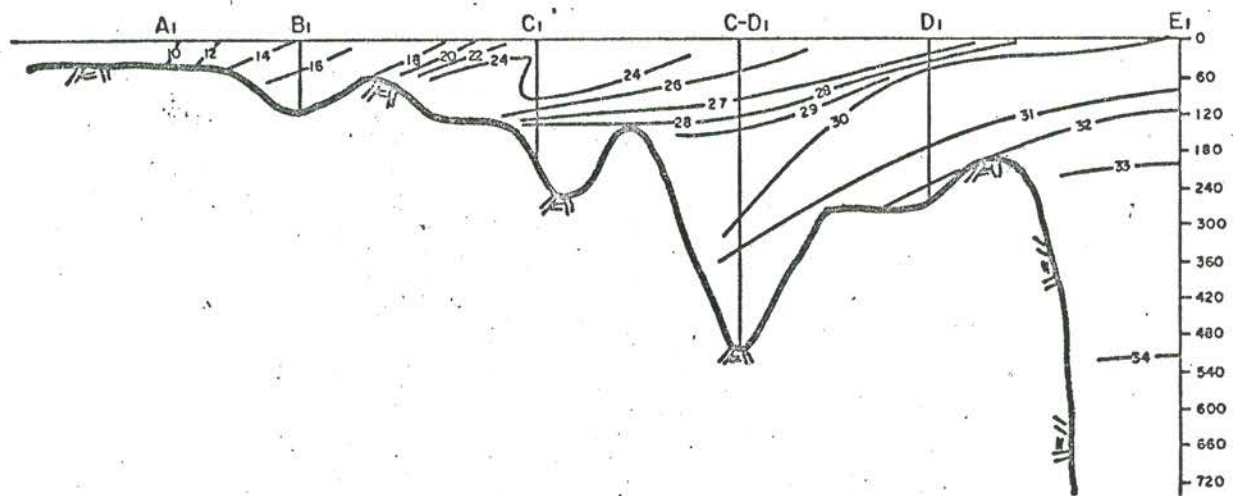
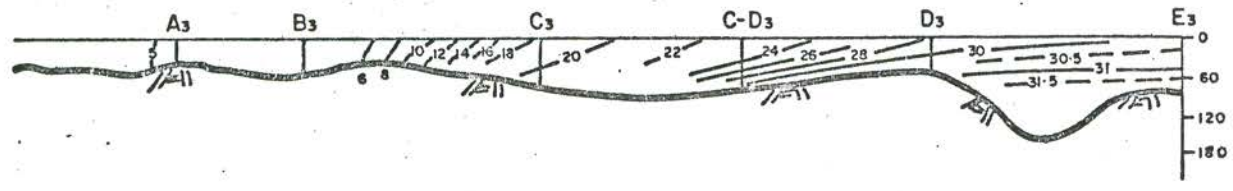


FIG. 9



PARTS PER THOUSAND ‰

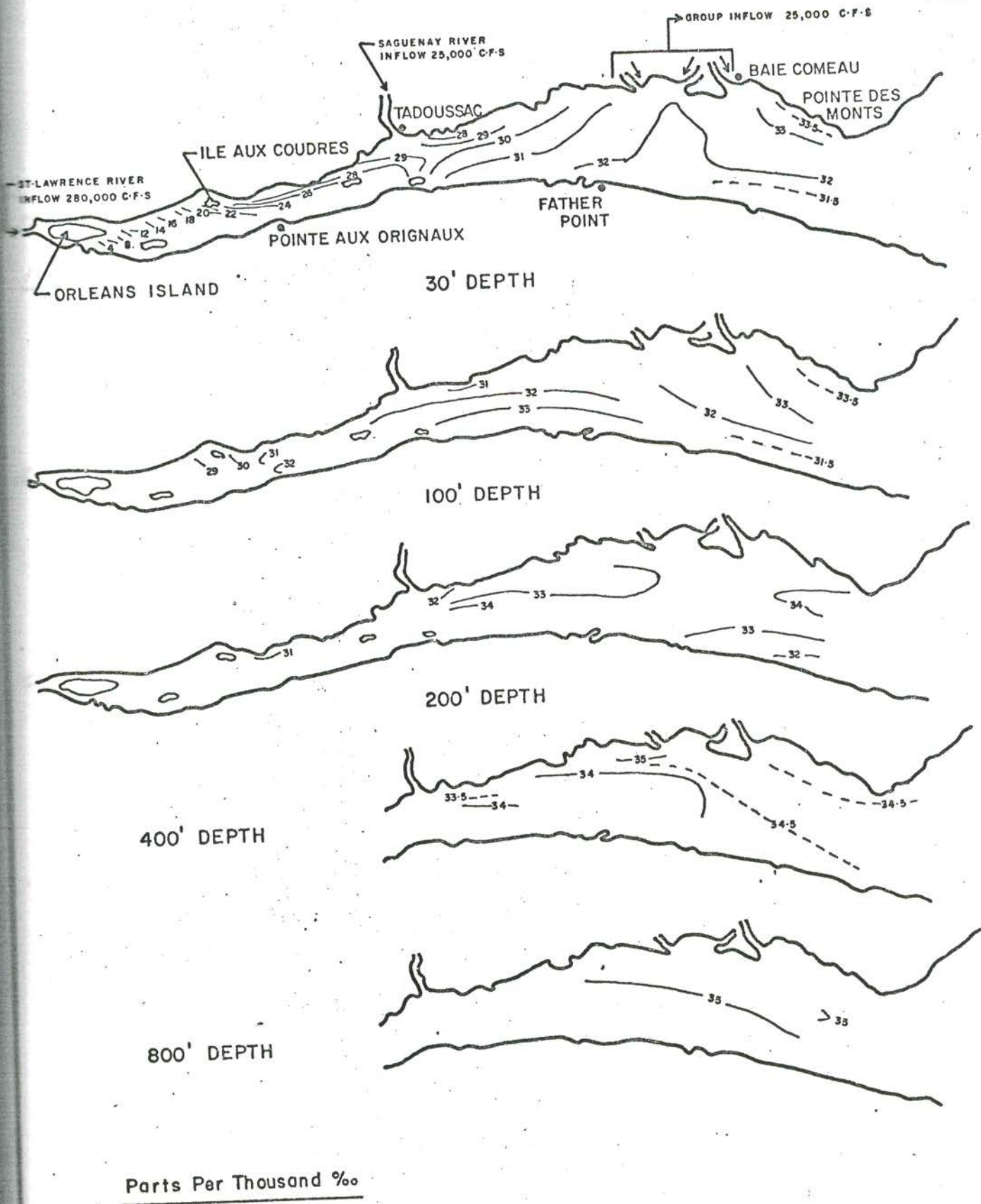
DEPTH IN FEET



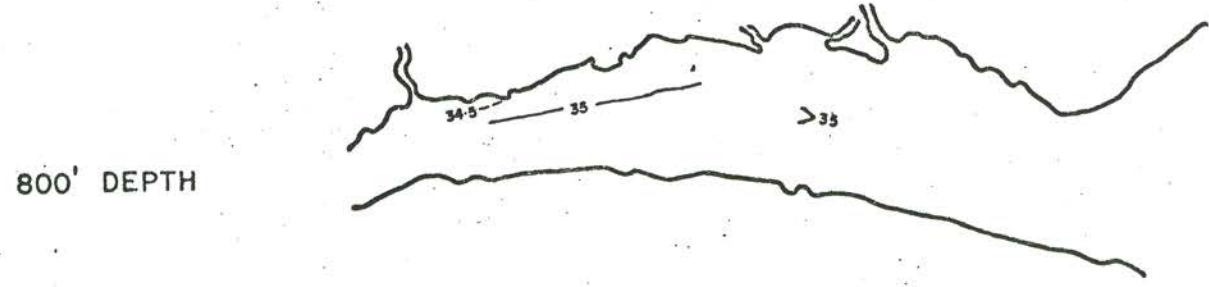
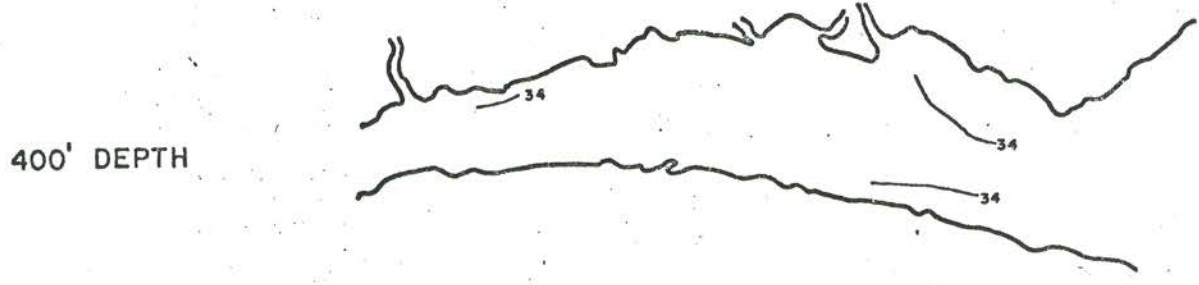
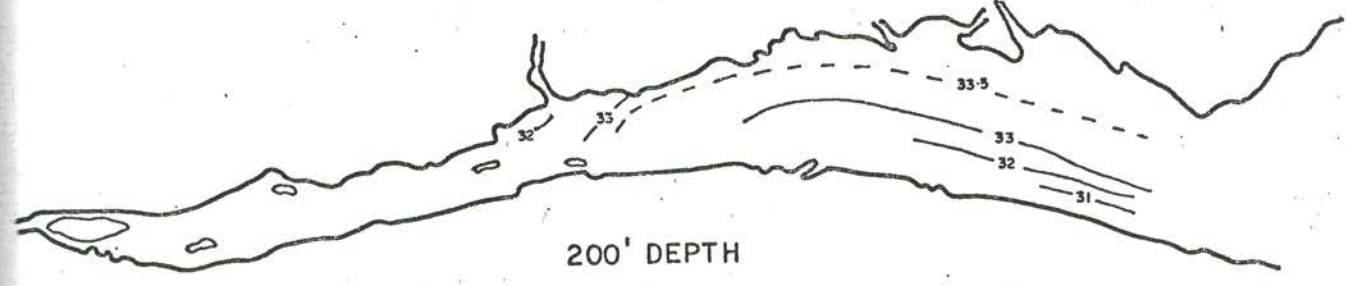
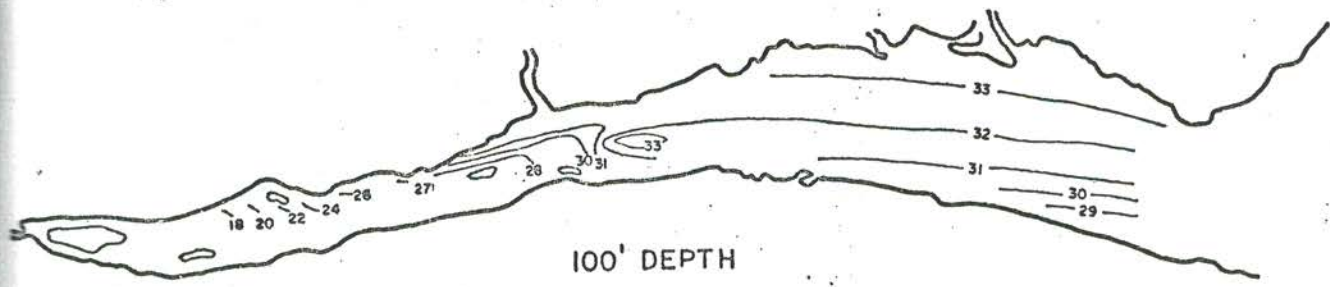
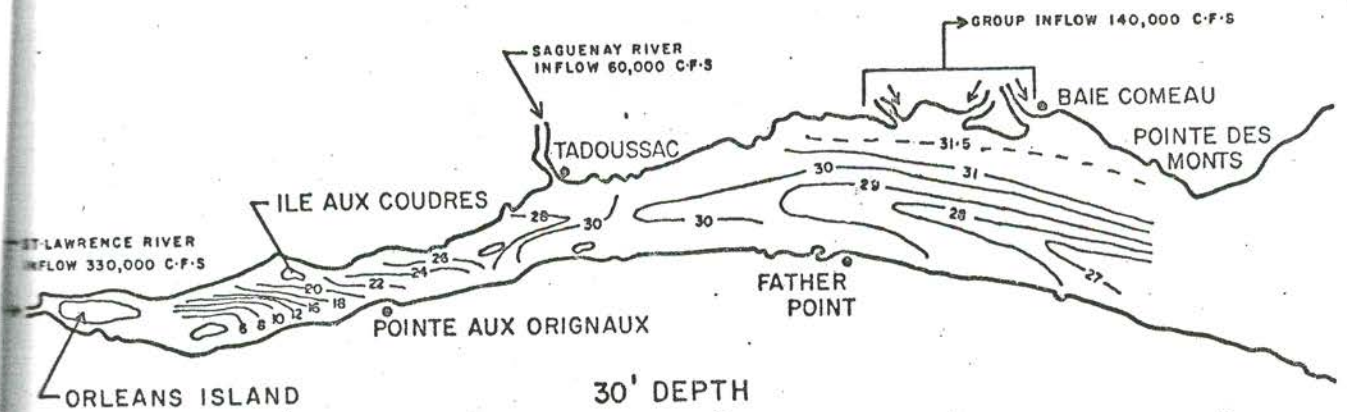
DISTANCE FROM QUEBEC CITY - MILES

50 100

LONGITUDINAL SALINITY PROFILES
UPPER SECTION, MAY 21-24 1963

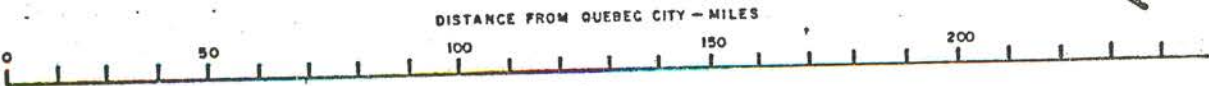
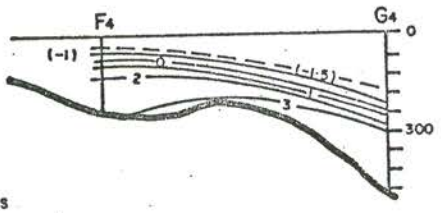
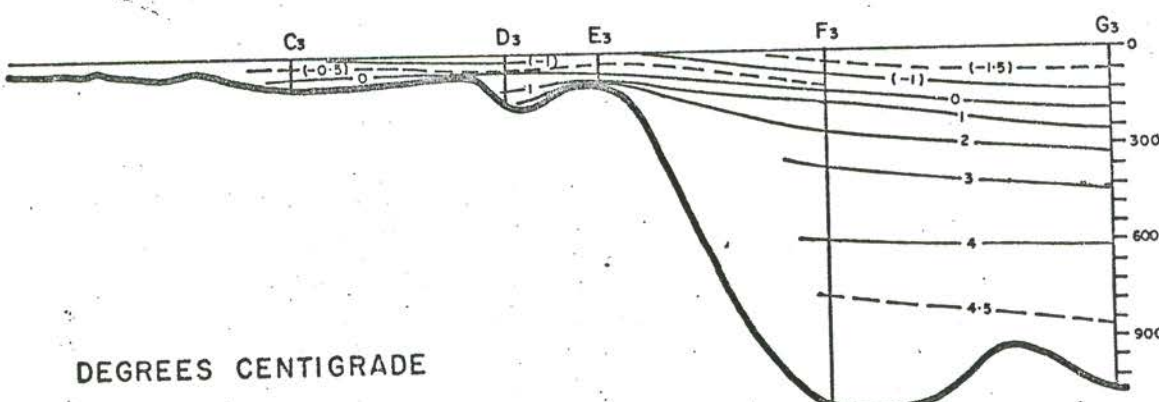
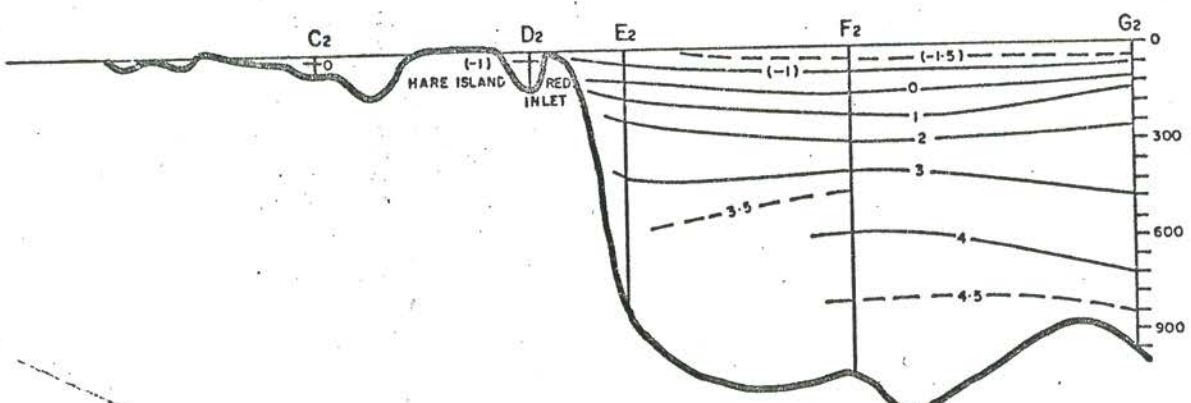
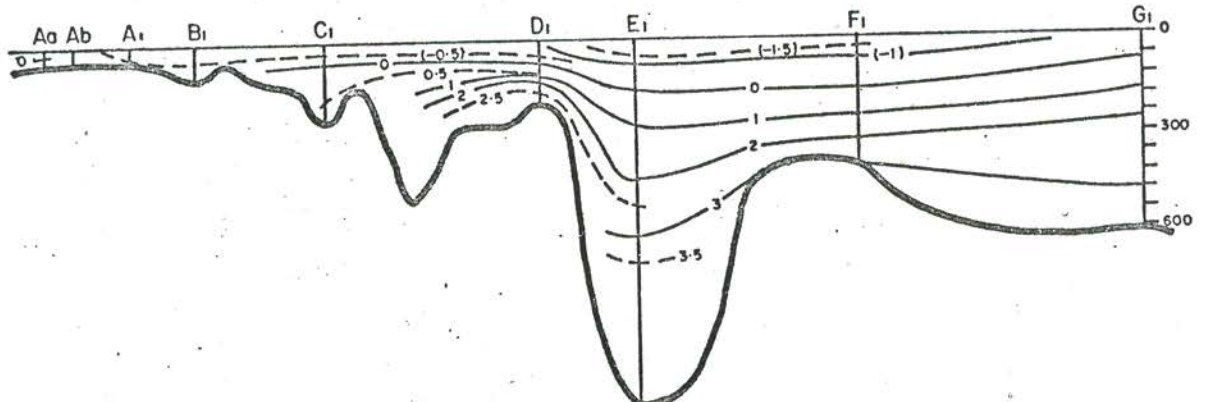
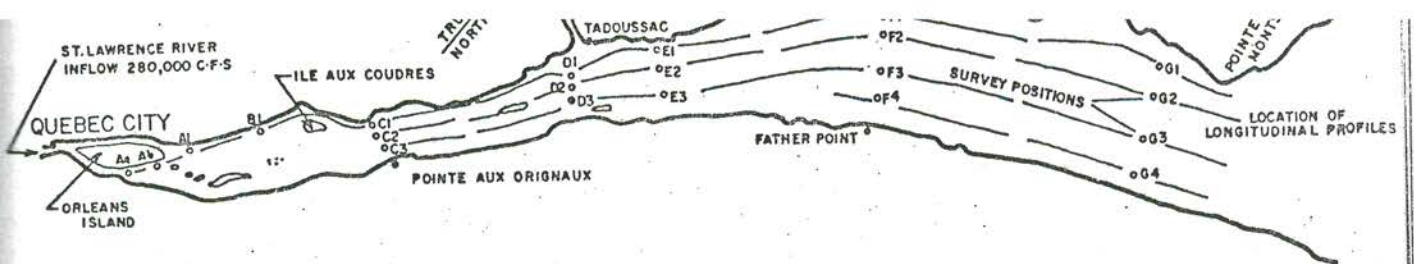


HORIZONTAL SALINITY CHARTS
FEBRUARY 18-25, 1963



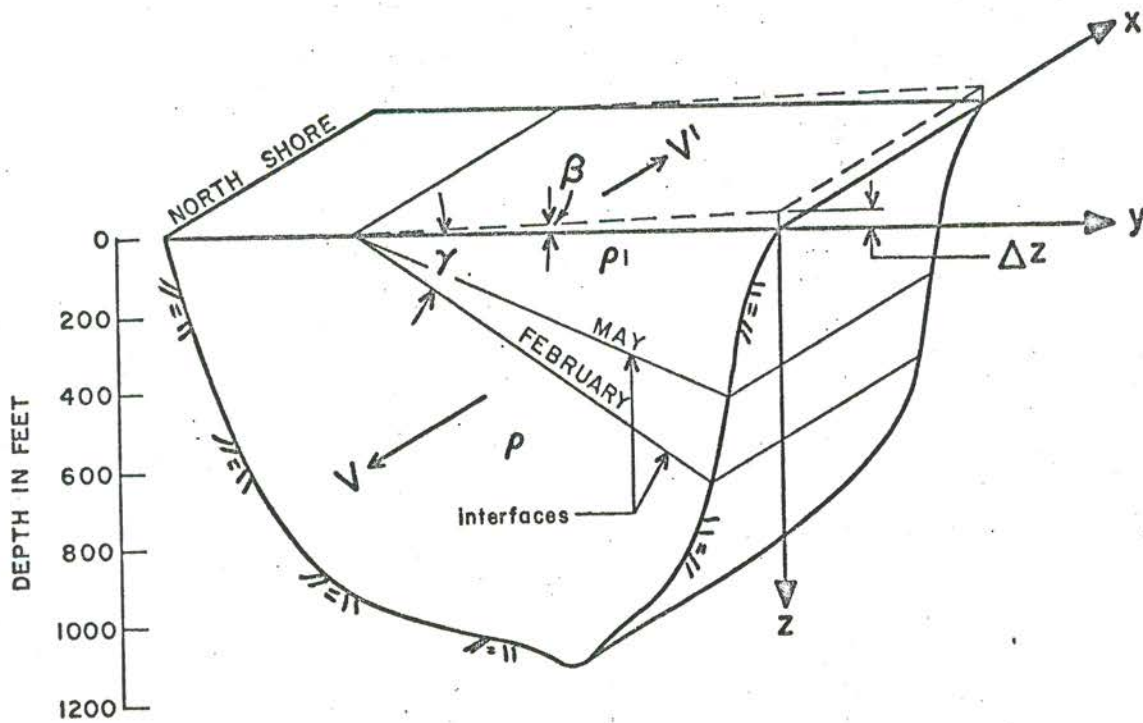
Parts Per Thousand ‰

HORIZONTAL SALINITY CHARTS
MAY 21-24, 1963



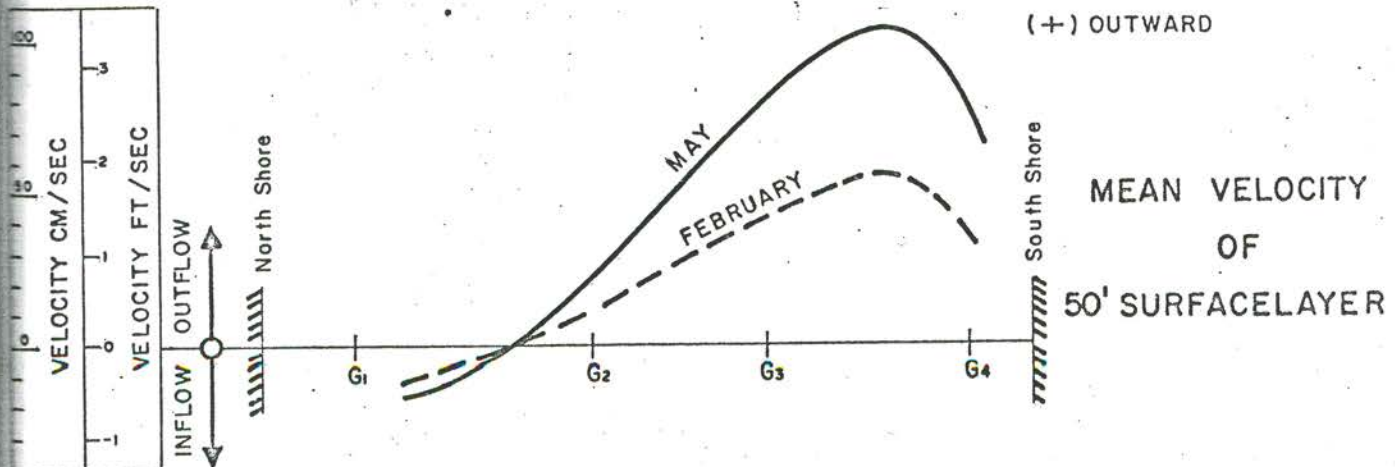
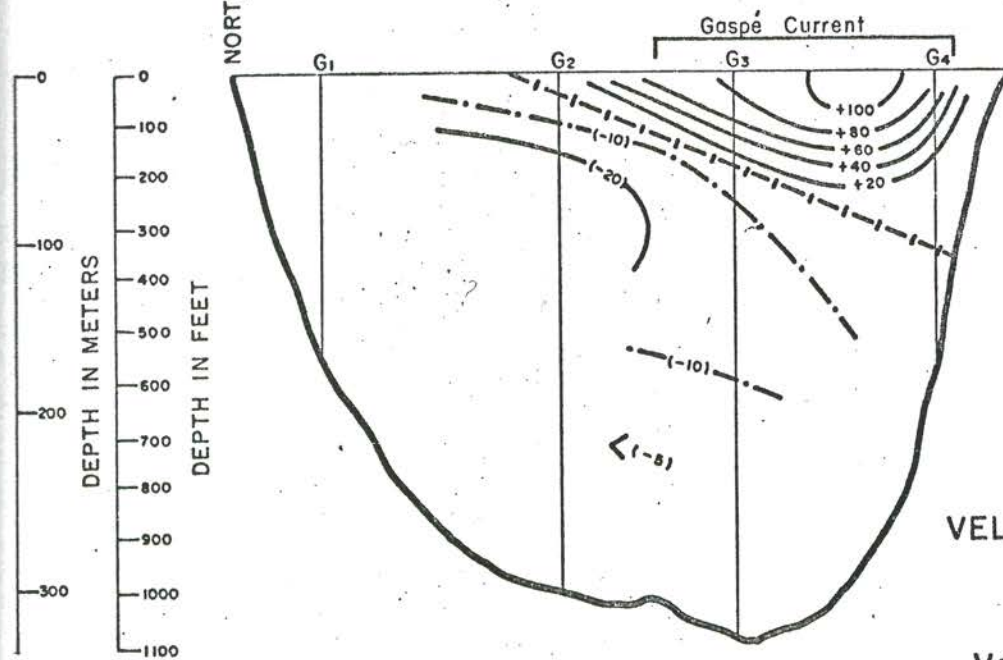
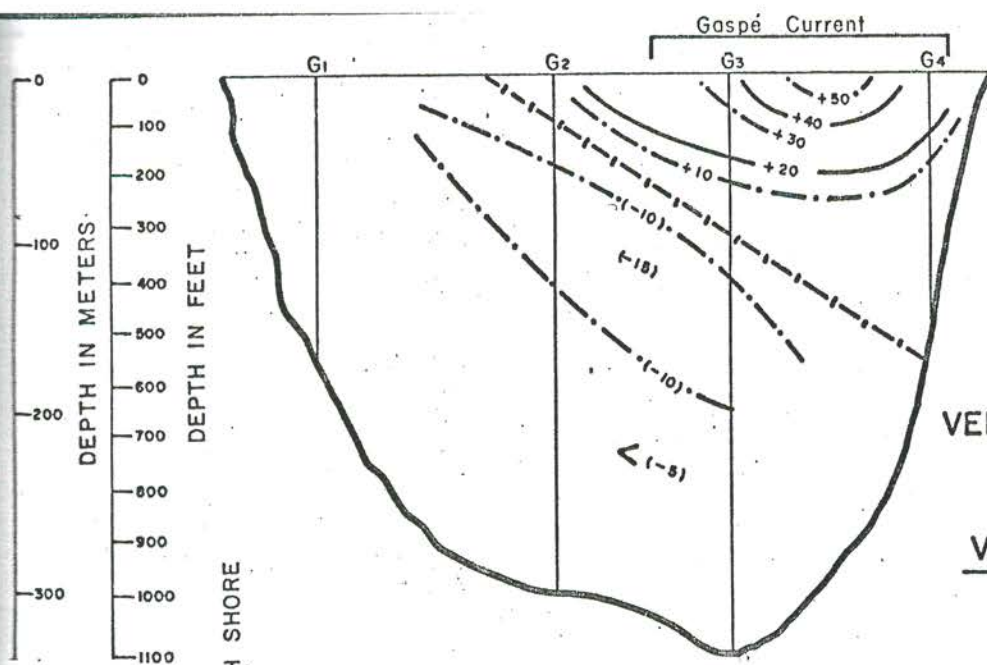
DEGREES CENTIGRADE

LONGITUDINAL TEMPERATURE PROFILES
FEBRUARY 18-25, 1963

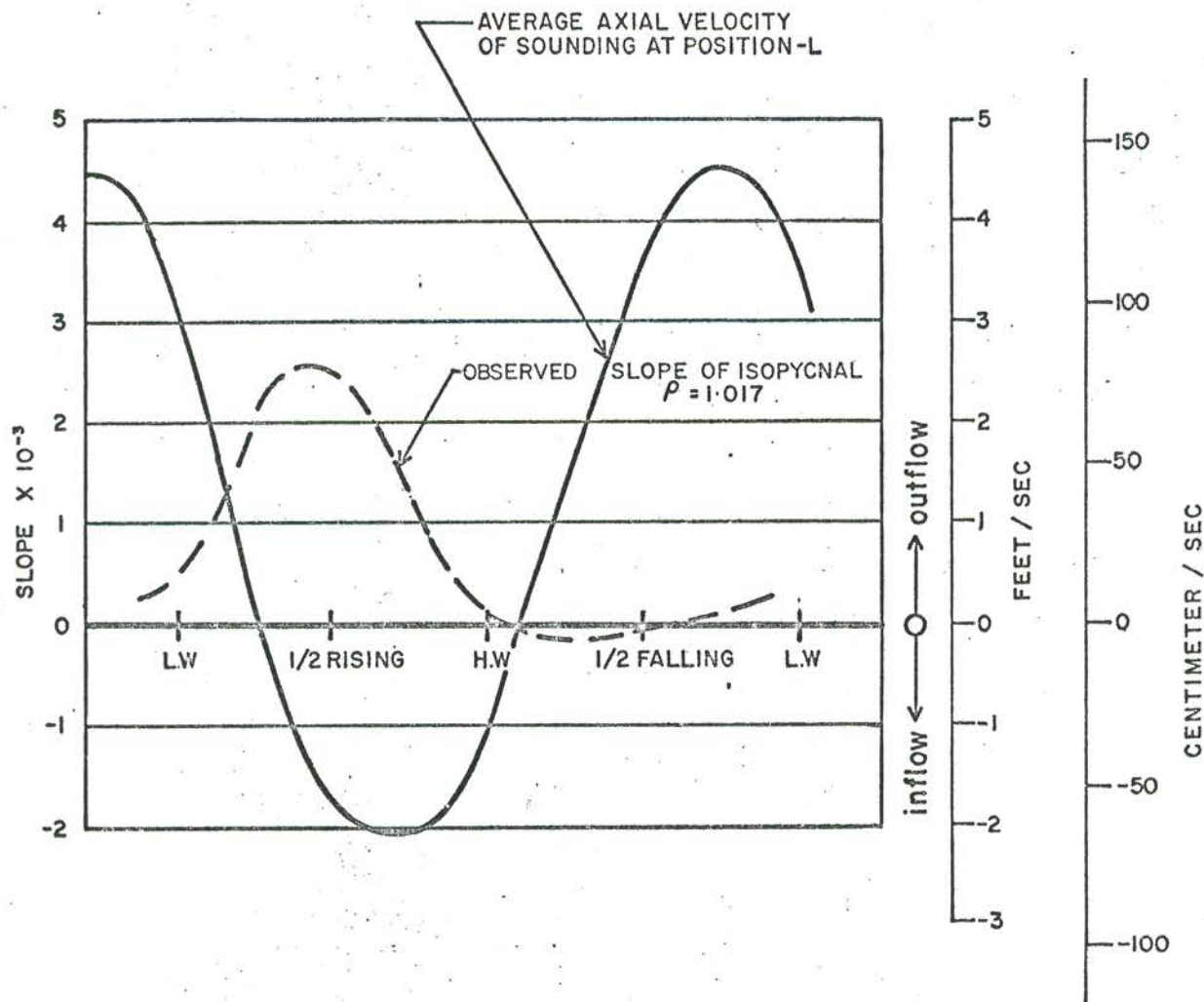


	FEB	MAY
ρ MEAN DENSITY OF LOWER LAYER	1.0277	1.0270
ρ^1 MEAN DENSITY OF UPPER LAYER	1.0269	1.0248

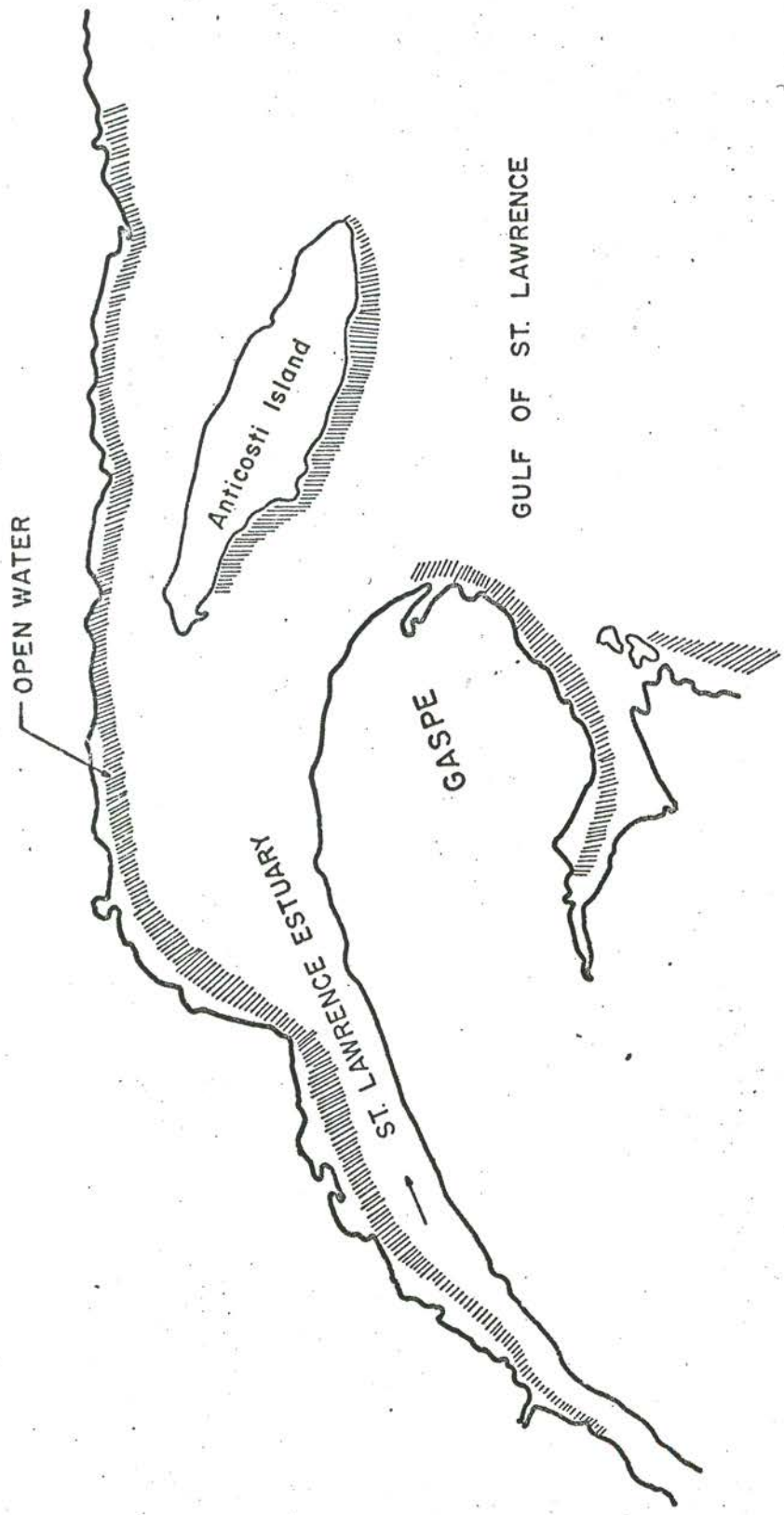
SCHEMATIC REPRESENTATION
 OF TWO-LAYER FLOWSYSTEM
 AT POINTE DES MONTS



CURRENT VELOCITY AT POINTE DES MONTS
CALCULATED FROM INTERNAL PRESSURE FIELD



AVERAGE VELOCITY IN AXIAL DIRECTION (POSITION-L)
 AND CROSSWISE OSCILLATION OF INTERFACE
 DURING A TIDE CYCLE AT POINTE AUX ORIGNAUX



GENERAL AREAS OF OPEN WATER DURING WINTER 1957

EXTRACT FROM GEOGRAPHICAL PAPER No. 14, DEPARTMENT OF MINES AND TECHNICAL SURVEYS, OTTAWA