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Some Physical Features of the Miramichi Estuary

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SOME PHYSICAL FEATURES OF THE MIRAMICHI ESTUARY

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by

E. L. Bousfield

Introduction

During the course of biological investigations in the Miramichi area in 1950 and 1951, a considerable body of data on the distribution of salinity, temperature, water transparency, and other physical features of the Estuary was obtained. Limited observations of this kind had been carried on in the estuary during the Miramichi Fisheries Investigation of 1918 (Huntsman, 1945), by Rogers (1940), and more recently by field officers of the Fisheries Research Board of Canada. Changes in the shoreline and bottom topography have been studied (Cross, 1951) and a prediction of the circulation in the outer Estuary has resulted from a recent tidal and current survey of the area (Pothergill, 1953). The present account utilizes this previous information in correlating observed changes in the distribution of salinity, temperature, and water transparency with changes in precipitation, river discharge, wind velocity, and other variables, and in predicting the residual or net water circulation in the Estuary.

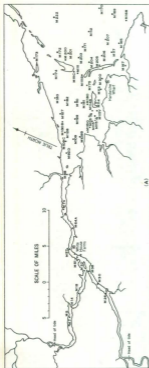
Methods

A series of hydrographic stations was established inside the Estuary proper and in the Gulf of St. Lawrence, in the immediate offing of the mouth of Miramichi Bay (fig.1). These stations were visited by means of a small motor boat at weekly intervals during the summer of 1951. A few stations had previously been visited in August, 1950. Water samples for the measurement of temperature

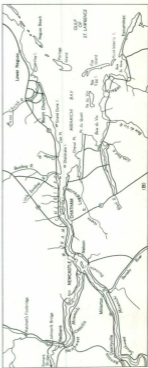
and salinity were obtained by means of a portable plankton pump. Bottom sediments were sampled by means of a small iron dredge, and an Ekman bottom sampler.

Water temperatures accurate to the nearest 0.1 C. were taken by means of a mercury thermometer held directly beneath the outlet hose of the pump and read while completely immersed in the outflow. Heating or cooling of the water while passing through the rubber intake hose and pump was of small magnitude (0.0 to 0.1 C.) owing to the short length of hose exposed to both surface water and air temperatures and to the rapidity with which the water was pumped. The specific gravity of the sea water was determined by float hydro-meter, and the salinity, accurate to one-tenth of one part per thousand, was calculated from Knudsen's Tables. Water transparency was approximated by the use of the Secchi Disc. Wind direction and velocity were estimated in the Beaufort scale. Rough approximations of the velocity and direction of surface currents were sometimes made by timing the drift of the boat, and these values were substantially in agreement with the published information on tidal currents in this Estuary.

Measurements of the discharge of the Miramichi River and several of its tributaries were undertaken at one period in 1960, and at three-week intervals during the summer of 1961. As flow gauges at Blackville had been discontinued in 1933, measurements of river flow at certain key locations in the main drainage basins were obtained in the following manner. A point in the River was selected where current velocity was at least one foot per second and the channel fairly regular. The rate of flow as obtained from the average time (of three trials) of passage over a measured distance of 100



(A)



(B)

Figure 1. Topographical features of the Haverhill Estuary.

(A) Principal hydrographic stations, (RS)

(B) Place names, rivers and roads (Courtesy R. A. McKinnon, Charlton, N. B.)

feet, of a wood chip dropped in mid stream. The surface velocity obtained was then multiplied by the rapid stream factor of 0.9 to give the average speed of flow for the cross section. The average width and depth of the River at the site were measured by steel tape, and the discharge values then calculated (Tables III and IV).

Values for the daily and mean monthly discharge of the Southwest Miramichi River at Blackville, 1918 (fig. 1), and for air temperature and precipitation were obtained from publications of the Government of Canada (3,4).

Geographical Features of the Estuary and Watershed

1. Topographical Features

The Miramichi Estuary is a large embayment of the east coast of New Brunswick, Canada, in which the entire surface drainage of the Miramichi Watershed, 5450 square miles in area, meets and mixes with the salt water of the Gulf of St. Lawrence (fig. 1, text). The headwaters of the principal drainage basins, the Southwest Miramichi with its chief tributary, the Renous River, and the Northwest Branch with its chief tributary, the Little Southwest Miramichi River, rise a few miles east of the St. John River and flow eastward for nearly 100 miles to the head of tide at Quarryville and Redbank, respectively (fig. 2). The total length of the Estuary along the main channel from the head of tide in both branches to the mouth at Portage Island is almost fifty miles (80Km.). The inner or river portion of the Estuary is formed by the tidal sections of the Northwest and Southwest Miramichi Rivers which merge just above Newcastle and, thus combined, flow eastward between sandstone cliffs to the river mouth at Sheldrake Island (fig. 2). The outer or bay portion into which drain several small tributaries of north and south shores

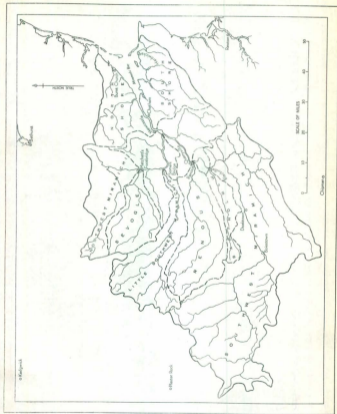


Figure 2. Principal drainage basins of the Merrimack Watershed.

forms a triangle about 20 miles long from its western apex at the river mouth to its base at the eastern end. The Bay is cut off from the Gulf by a chain of sandy islands of which Neguec Beach, Portage, and Fox Islands are the largest. Inside the Bay are several lesser islands and sand bars of which Ile du Vin, situated two miles from the south shore, is the largest.

2. Submarine Physiography

The Miramichi is a shallow coastal plain estuary. The average depth at lowest normal tides (datum of soundings) for the entire Estuary, obtained by the method used by Ketchum (1951), is 13.0 feet. In the main channel, the range of depth is between 20 and 50 feet, and the average depth is about 25 feet (fig. 3). The mean high water depth of the entire Estuary is 16.5 feet. The upper limit of the littoral zone, the tidal zone, occupies a vertical range of five to six feet. From the mouth of the Estuary, depths increase gradually in a seaward direction to the sub-littoral zone (165 feet) more than 25 miles offshore in the Gulf.

Bottom sediments in Miramichi Bay consist mainly of sand, mud, or a mixture of both containing shells and small stones (fig. 3). Deposits of pure sand extend in from the Gulf mainly along the north side as far west as Grande Dune Island, 8.5 miles above the mouth. Mud flats occupy much of the River bottom and inner Bay. Sandy mud mixed with small stones, shells, eel grass, and detritus are found mainly along the inshore shallows. Rocky outcrops, largely soft sandstone, are best developed near Point Escuminac but also occur inside the estuary at Point du Quart, Burnt Church, Oak Point, and upriver along the banks to Newcastle, 28.2 miles above the mouth. A few glacial till boulders, some of large size, are particularly

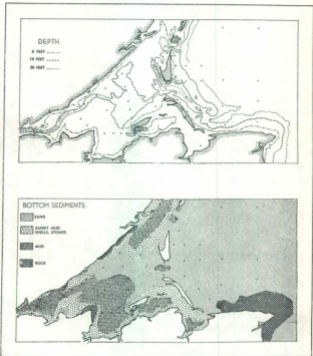


Figure 3 Submarine Physiography of the Misnichi Estuary

conspicuous around Egg and Vin Islands, at Oak Point, and west of Napan Bay.

Hydrology

1. River Flow

River discharge is a primary factor controlling the distribution of salinity and magnitude of residual or non-tidal circulation in the Estuary. The monthly mean values of river discharge have been estimated for the drainage basins above Newcastle, junction of the two main branches of the Miramichi River, and are given in Table I. Owing to the heavy annual precipitation (mean = 38.5 inches) and to the steep drainage gradients near the headwaters, the run-off from the Watershed is large. The Estuary receives about nine-tenths of its fresh water from the Watershed above Newcastle and the remainder from north and south shore streams below that point.

Following the break-up of river ice in mid April, the River discharge reaches an annual peak (28,000 cubic feet per second). As evaporation increases and the supply of melt water decreases, the discharge correspondingly decreases to a minimum value late in August and early September (4400 c.f.s.). A second smaller peak discharge occurs in November (9000 c.f.s.). The winter minimum discharge (2900 c.f.s.) is reached in February.

The estimation of the monthly values of river discharge at Newcastle (Table I) was based on two sources of data: (1) published river discharge measurements at Blackville, Southwest Miramichi River, for the years 1918-1933, and, (2) present river discharge measurements at the junctions of the main tributaries just above the head of tide. Both sets of data may be compared by expressing them in terms of the monthly mean discharge per unit area (c.f.s.

Table I. Monthly Mean Discharge of the Miramichi River at Blackville and Newcastle.

Month	River Discharge (cubic feet per second)	
	Southwest Miramichi R. at Blackville (drainage basin of 1950 sq. miles)	Miramichi R. at Newcastle (drainage basin of 4500 sq. miles)
January	1760	4100
February	1230	2900
March	2420	5650
April	11500	27000
May	11900	28000
June	3670	8500
July	2120	4950
August	2070	4850
September	1890	4400
October	3340	7800
November	3870	8000
December	2800	6000

Table II. Drainage Areas of the Principal Drainage Basins of the Miramichi Watershed. (Measured by Planimeter from Canadian Topographic Sheet 21 N.E.)

Drainage Basin	Area (sq. miles)
Southwest Miramichi R. (above Blackville)	1945
" " " (Blackville to Newcastle exclusive of the Rencous)	445
Rencous R. (above Quarryville)	580
Total Southwest Miramichi R. (above Newcastle)	<u>2970</u>
Northwest Miramichi R. (above Matchett's foot- bridge)	390
Big Sevogle River (" " ")	310
Little Southwest Miramichi R. (above Somer's Bridge)	495
Northwest Miramichi R. (remainder above Newcastle)	330
Total Northwest Miramichi R. (above Newcastle)	<u>1525</u>
Total Miramichi Drainage Basin at Newcastle	<u>4495</u> (4500)
North Shore Rivers (below Newcastle)	395
South Shore Rivers (below Newcastle)	435
Miramichi Bay	120
Total Drainage Area below Newcastle	<u>950</u> (950)
Total Miramichi Watershed (at Portage Island)	<u>5445</u> (5450)

per square mile) for the individual drainage basins concerned. The surface areas of component drainage basins and the total area of the Miranichi Watershed are given in Table II. The areas are given, for convenience, above points at which discharge measurements were taken.

The run-off per unit area during the summer is similar in all drainage basins above Newcastle, and therefore the run-off a given basin may be assumed directly proportional to its area. The river discharge at Newcastle is thus 2.3 times that of the Southwest branch above Blackville, as shown in Table I. The drainage per unit area was derived mainly from data for the summer of 1951 from measurements of river discharge at selected stations above Newcastle (Table III), and below Newcastle to the Gulf (Table IV). Based on five sets of observations on four drainage basins above Newcastle, the average summer discharge, per square mile, for all rivers combined (80% of the total drainage area above Newcastle) was 1.3 c.f.s. The values for both Northwest and Southwest branches agree with this closely, whereas those of the Renous and Little Southwest differ from it by 25%, probably owing to local variations in run-off from day to day when the measurements were made. The average summer discharge of the Southwest branch at Blackville over the fifteen-year period, 1918-1933, was also 1.3 c.f.s. per square mile. As the drainage area of the Southwest branch is nearly one-half that above Newcastle (Table II), the unit discharge of the Southwest branch is thus probably representative of the entire Watershed. The estimated mean monthly discharge values for the Watershed above Newcastle are therefore 2.3 times greater than the corresponding values at Blackville, as shown in Table I.

Table III. Measured Discharge of Tributaries of the Miremichi River, N.B., during 1950 and 1951.

Drainage Basin	Drainage area above point of measurement (sq. miles)	Measured Discharge (c.f.s.)					Total Discharge (5 dates)	Average Ratio $\frac{\text{Discharge}}{\text{Area}}$
		1950		1951				
		Aug. 17	June 6	July 10	Aug. 2	Aug. 28		
Northwest Miremichi (above Matchett's)	391	160	1310	555	590	165	2580	1.32
Little Southwest Mir. (above Somer's Bridge)	497	340	1600	800	850	410	4000	1.61
Rencous River (above Quarryville)	580	180	930	730	630	480	2940	1.02
Southwest Miremichi (above Quarryville)	2100	1600	5130	3200	2150	1800	13690	1.32
Total	3568	2280	8970	5285	4080	2855	23410	
Mean Discharge/sq. mile							<u>1.0</u>	<u>1.3</u>

Table IV. Measured Discharge of Tributaries of the lower Miramichi R. and Bay.

NORTH SHORE TRIBUTARIES OF THE MIRAMICHI RIVER BELOW NEWCASTLE, N.B.						
Stream	Site of Discharge Measurement	Date (1951)	Time (A.D.S.)	Temp. (C.)	Discharge (c.f.s.)	
French Fort Creek	Detour Highway Bridge	Aug.10	2:00 p.m.	12.5	15	
Stewart Brook	At Highway culvert	Aug.10	" "	12.9	1	
Douglastown Stream	Above H'way bridge	" "	3:00 p.m.	15.6	2-3	
McKeown Stream	Highway culvert	" "	" "		1	
Stothart Stream	" "	" "	" "		1	
Goodfellow Stream	" "	" "	" "		2	
Hamilton Brook	" "	" "	3:15 p.m.	16.9	6	
Big Brook	" "	" "	" "		1	
Gordon Brook	" "	" "	" "		1	
Little Bartibog R.	Below bridge (H'y 8)	" "	4:00 p.m.	17.7	70	
Big Bartibog R.	At Bartibog Bridge	" "	4:30 "	18.3	160	
Oyster River	At Highway #11	" 15	2:00 "	19.0	9	
Burnt Church R.	" " "	" "	4:45 "	19.1	41	
Total Discharge, N.shore rivers					<u>315</u>	
SOUTH SHORE TRIBUTARIES OF THE MIRAMICHI RIVER BELOW NEWCASTLE, N.B.						
Napan River	At Highway #11	Aug.17	7.30 p.m.		8	
Black River	" " "	" "	7:45 p.m.		12	
" "	" " "	Sept. 2	3:55 p.m.	17.9	23	
Little Branch R.	Old Planing Mill	" "	4:30 p.m.		8	
Harton's Creek	At Shore Road	" "	4:50 p.m.		9	
Baie du Vin R.	Buckley's Bridge	" "	2:15 p.m.	17.5	55	
MacInnis Creek	At Shore Road	" "	1:15 p.m.		13	
Dennison's Creek	" " "	" "	1:00 p.m.		7	
French Brook	1 mile above H'dw'ke	Aug. 27	6:00 p.m.	18.0	2/3	
Meadow Brook	W. Branch Eel R.	" "	4:40 p.m.	18.0	1	
Scotfield Brook	Eel River	" "	5:00 p.m.	19.3	2½	
Eel River (combined)	Thiereau's Bridge	" "	3:30 p.m.	20.5	26	
Portage River	East Branch (J'tion)	" "	4:00 p.m.	20.2	7½	
	West Branch (")	" "	" "	18.3		
Savoy Brook	Road at Baie Ste. Anne	" "	4:30 p.m.	25.0	½	
Total Discharge, S.shore rivers					<u>160</u>	

The remainder of the Miramichi Watershed (that below Newcastle) is composed of north and south shore tributaries having approximately equal drainage areas. Combined, these make up less than one-sixth of the total Miramichi drainage area. The combined discharge of north shore rivers during August (Table IV) was almost twice that of south shore rivers. This difference may be attributable to differences in precipitation, subsurface drainage, and steepness of gradient between the relatively swift north shore rivers and the low-lying, moisture-retaining peat bog streams of the south side. During August, the unit discharge of these tributaries combined is approximately 0.6 c.f.s. per square mile, whereas that of the main part of the Miramichi Watershed above Newcastle is 1.0 c.f.s. per square mile (Table III). The total run-off from the north and south shore basins is therefore only one-tenth ($1/6 \times 0.6$) that of the total Miramichi Watershed, and its influence on estuarine salinities, relative to that of the main river, is small.

2. Relation of River Flow to Precipitation

A comparison of available data for the daily river discharge during the summer and fall of 1918 with the corresponding data for daily precipitation (fig. 4) shows the river discharge is closely related to precipitation over the entire Watershed, that peak river discharge normally occurs within two days of peak precipitation, and that prolongation of high or low periods of surface run-off depends upon the duration of the rainy or dry spell, respectively.

A comparison of total monthly precipitation and corresponding monthly mean river discharge at Blackville for the years 1918 to 1933 shows in general that the monthly mean value of river discharge

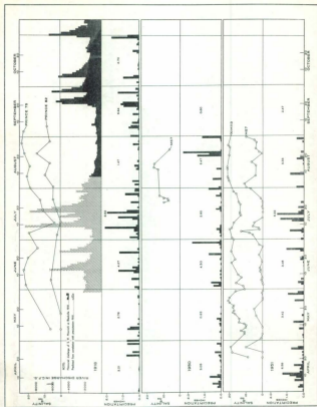


Figure 4. Daily and total monthly precipitation at Chatham, N. H., during spring and summer months, 1959, 1960 and 1961, showing corresponding fluctuations in the measured and predicted discharges of the Mt. Mitchell Run at Blacksville, 1959, and in the predicted discharges of the Mt. Mitchell Run at Blacksville (Prince 14, M 17) and in Mirabelle Bay at Waikiki (Prince 15, M 113) 1959 and 1960.

tends to be proportional to the total precipitation of the same month. The relationship appears to be strongest during the summer and fall, but weakest in the spring. The prediction of monthly mean discharge values based solely upon the total monthly precipitation is not dependable, except within wide limits, however, owing to lag run-off from precipitation of previous months, to seasonally variable evaporation, and in the spring, to lag run-off from melting snows.

On the basis of these relationships (above) it is possible to predict from precipitation data along that the river discharge was below normal during the spring and summer of 1950, but was abnormally high during comparable periods of 1951 (fig. 4).

Hydrography

Water temperature, salinity, transparency, and general meteorological conditions of the Miramichi Estuary were measured at weekly intervals during the summer of 1951, and the normal pattern of each of these variables was determined. Variations in the typical pattern of salinity, temperature, and transparency were related to abnormal river flow and wind velocity.

1. Salinity

The horizontal distribution of salinity in the river and bay portions of the Miramichi Estuary are shown in figures 5 and 6, respectively. The horizontal gradient of salinity ranges from fresh water (0 ‰) at the head, to almost fully marine (20-27 ‰) conditions at the mouth in the Gulf of St. Lawrence. Surface salinities are normally less than 3 ‰ in the river above Boishebert I'd (M20), less than 10 ‰ above Sheldrake I'd (M88), and less than 23 ‰ above Portage I'd (M111). The steepest

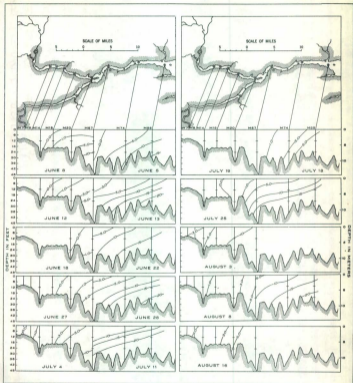


Figure 5. The distribution of salinity (‰) in the river portion of the Miranichi Estuary at weekly intervals during June, July and August, 1961.

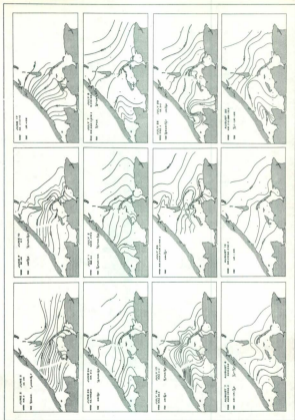


Figure 6. The surface distribution of activity $C/100$ in Mizushima Bay at weekly intervals during July, July and August, 1960.

horizontal gradients of salinity are about $1^{\circ}/\text{oo}$ per mile, and are located near the river mouth (fig. 7). The difference in salinity between high and low water at a given location is about $2^{\circ}/\text{oo}$ to $3^{\circ}/\text{oo}$, and seldom more than $5^{\circ}/\text{oo}$. The surface isochalines in the Bay (e.g. on June 2 and 3) slant diagonally across, rather than perpendicular to, the principal longitudinal axis of the Estuary, owing to the effect of the earth's rotation on the circulation.

Strong vertical gradients of salinity are normally present, as illustrated by the sections along the river channel (fig. 5). The difference in salinity between surface and 24 feet (near the bottom) is greatest near the river mouth (more than $10^{\circ}/\text{oo}$), and least (less than $1^{\circ}/\text{oo}$) near the landward limit of salt water in the river, and offshore in the Gulf. The seaward flow of fresh water at the surface, and the landward counter drift of salt water along the bottom, maintain the salinity stratification in spite of strong mixing action by tidal currents and at times by the wind.

Variations from the normal pattern of salinity distribution were most pronounced on July 16 and 17 in the Bay (fig. 6) and on July 18-19 in the River (fig. 5). Salinities were abnormally low at this time owing to the prolonged heavy precipitation and heavy freshets during the week of July 12-18. The effect of the wind is most clearly shown in the Bay on June 17 when a strong onshore wind upset the "Coriolis" pattern. The offshore wind of July 23 reinforced the seaward drift at the surface and created an upwelling of salt water in the lee of Portage and Fox Islands.

A general increase in salinity during June and early July is shown in figures 5 and 6. During this period, river flow decreased markedly as the spring melt-waters disappeared and evaporation

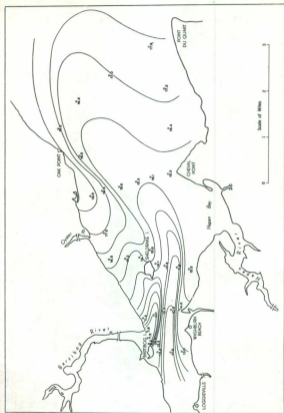


Figure 7. Surface salinity at the mouth of the Mississippi River, August 30, 1952.
 Time - 10:12 A. M. - 1:15 P. M. Wind S. E. 1-2 Miles $\frac{3}{8}$ F. - L. W.

increased. Salinities reached a summer maximum again during August.

The surface salinity at River station M57 and Bay station M113 during the summer of 1951 and part of July and August, 1950, may be related to the corresponding precipitation as shown in figure 4. Salinities at both stations were exceptionally low following heavy precipitation in mid April, at the end of May, and in mid July in 1951, and in late August in 1950. Surface salinities at equivalent stations of the Miramichi Fisheries Expedition in 1918 (also fig. 4) show a corresponding drop during exceptional precipitation and river discharge in July, and a return to normal during dry weather as in August. In absence of salinity data for much of 1950, it is probable, therefore, that the upriver penetration of salt water in that year was much greater and remained so for longer periods than that in 1951. Thus, in May, June, and July of 1950, precipitation and river discharge were much below normal, salt water probably reached its extreme possible limit of penetration upriver, and probably remained at this level during most of the summer. In 1951, however, precipitation and river discharge were much higher than normal and salt water was very largely restricted during much of the summer to the main river below Boishebert Island.

2. Water Temperature

The annual cycle of water temperature in the Miramichi Estuary parallels that of the air. From mid November to April 1, average air temperatures are below the freezing point and reach a minimum of 10-15 F. during February. The winter freeze-up in the river lasts from December 1 to mid April and the ice is about two feet thick. The water warms rapidly during May and June and summer surface maxima

of 18-22 °C. are reached in July and August. It cools rapidly again during October and November to the freezing point in December. During the summer of 1951 the average air temperature and the average water temperature were about 1 °C. and 2 °C., respectively, above that of 1950.

The surface distribution of temperature in the Bay is part of the Estuary shown in figure 8. During the summer, the surface water of the River and Bay are usually 1 ° to 2 °C. warmer than those of the Gulf immediately off the mouth of the Estuary. Surface temperatures of the south side of the outer Estuary (Bay) are warmer than those of the north side owing to the influence of the Coriolis acceleration on the circulation. Freshets temporarily decrease surface temperatures as shown on July 16 and 17. Strong offshore winds tend to equalize temperatures throughout the Estuary, as on June 17, and offshore winds create an upwelling of cold water in the lee of the land, as on July 23.

A perceptible thermocline is usually present, particularly when the corresponding halocline is well marked. Surface temperatures are often 2-3 °C. higher than those at a depth of 25 feet (bottom) although wind stirring and diurnal heating and cooling tend to reduce the magnitude of this difference.

3. Water Transparency

The distribution of water transparency in the Miramichi Estuary at weekly intervals during the summer of 1951 is shown in figure 9. Transparency inside the Estuary is normally much less (Secchi Disc = 6 to 8 feet) than that of the Gulf of St. Lawrence (S.D. = 20 feet). The low transparency of the Estuary proper is attributable to the influx of turbid river water which also shows a brown stain during

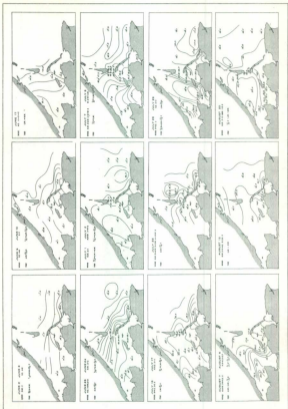


Figure 4. The surface distribution of temperature ($^{\circ}\text{C}$) in Miramichi Bay at weekly intervals during June, July and August, 1981.

exceptionally heavy run-off, to the stirring up of bottom sediments by tidal currents and winds, and probably to the population of phyto- and zooplankton. The headwaters and south side of the Bay are normally less transparent (S.D. = 6 feet) than those of the outer Bay and north side (S.D. = 8 feet) owing to the influence of the earth's rotation on the circulation. Abnormally low transparencies were observed on July 7 and 8 and August 20, following strong winds, and on July 16 and 17, following exceptionally heavy river discharge.

4. Tidal Currents

The most conspicuous feature of the circulation in the Miramichi Estuary is the oscillating seaward and landward movement of the water associated with the rise and fall of the tide. The mean rise of tide from the datum (Portage Island) during the summer is 3.5 feet (Tide Tables, 1951). At Cassilis, near the head of tide on the Northwest branch, high water occurs $1\frac{1}{2}$ hours later and low water 3 hours later than at Portage Island.

The tidal curve varies over a period of two weeks from a regular semi-diurnal curve with two equal high waters and two equal low waters in each day to an almost pure diurnal curve, with only one clearly defined high water and a prolonged stand at low water (Cross, 1951). The basic data for the direction and velocity of tidal currents in the outer Estuary (fig. 10) have been obtained from nautical charts, and field observations, corrected to the results of Pothergill (1953). Surface currents of $1\frac{1}{2}$ to 3 knots are encountered at the entrance to the Bay and in the River during mid flood and mid ebb. Surface velocities tend to be somewhat higher and of longer duration on the ebb than on the flood owing to the river flow.

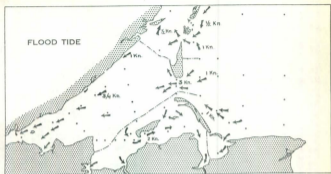


Fig. 10 Surface Tidal Currents in the Miramichi Estuary.

Related to the openings from the Estuary into the Gulf of St. Lawrence, there are four principal regions of water circulation, as demarcated by the interrupted lines in figure 10. On the flood, the main body of water passes in from the Gulf between Portage and Fox Islands, across the Bay, and thence on up the River. On the ebb, the reverse seaward movement across the Bay takes place. The data of Pothergill (1953) on the velocity of tidal currents provide further evidence that the landward movement on the flood is strongest on the north side, and the seaward movement on the ebb is strongest on the south side of the Estuary. Lesser tidal exchanges take place north of Portage Island (Neguac Gulley), through the south side of the main entrance and around Vin Island, and directly from Baie Ste. Anne through two small passages on either side of Huckleberry Island. Considerable mixing and overlapping of the main water mass with that of the south side of the Bay takes place between Portage and Fox Islands at the mouth. Mixing appears to be strongest in the Bay where the wind action augments that of the tide.

The amount of tidal exchange with the Gulf may be derived from the exchange ratio, r , having the value

$$r = \frac{P}{P + V}$$

where P is the intertidal volume, and V the low tide volume (Ketchum, 1951). Assuming the surface area at high water equal to that at low water, P may be represented by the mean rise of tide, and $P + V$ by the mean depth at high water. Owing to the diurnal inequality in the rise and fall of tides in the Miramichi area, the mean tidal difference, in this instance 2.4 feet, may be used for P . The

mean depth at high water for the entire Estuary, obtained by the method of Ketchum (1951) is 16.5 feet (13.0 + 3.5 feet). Substituting values, r becomes $\frac{2.4}{16.5} = 0.15$ (approx.). Thus the proportion of water moving seaward during each tidal cycle which does not return on the following flood is approximately 15%.

5. The Residual or Non-Tidal Drift Circulation

Owing to inequalities in the velocity and duration of tidal currents, the residual or net displacement of water through any complete cross-section of the Estuary during a complete tidal cycle, is in a seaward direction. The fresh water of the river, being of lower specific gravity than salt water, tends to remain near the surface. As a result, the net seaward drift takes place near the surface. The salt water entrained with the fresh (as brackish water) on its seaward movement at the surface, is replaced by means of a residual landward counter drift of salt water along the bottom.

The net direction and velocity of non-tidal drift with depth in the Miramichi Estuary may be obtained in two ways. The first is by direct measurement of tidal velocities over a continuous series of tidal cycles according to the procedure of Fritchard (1952). Such measurements were not obtained during the present investigation, however. The second is by analysis of the vertical distribution of salinity throughout a complete tidal cycle at several reference stations throughout the Estuary.

The effect of the circulation on the vertical distribution of salinity is indicated by measurements of salinity at six-foot intervals from surface to bottom at River station MS7, at two-hour intervals during a complete tidal cycle (fig. 11, diagram B).

Temperature changes (diagram A) also illustrate the difference in hydrographical conditions at this station between high and low water and between day and night. Salinities at surface and bottom were lowest at low water (at both surface and bottom) but were highest at the bottom at high water, and at the surface at mid flood and mid ebb. This last observation infers that tidal mixing is greatest when tidal velocities are greatest. Little change in salinity took place in the halocline (about 12 feet in depth), during the complete tidal cycle.

The observations on the salinity cycle also suggest that the circulation in the Miramichi is like that in the Chesapeake estuarine system studied by Pritchard (1952). In this system, the net non-tidal drift is maximal in a seaward direction at the surface and in a landward direction near the bottom, and minimal at some intermediate depth (the level of no net motion), as illustrated in figure 11, diagram C. The net drift maintains a steady state vertical distribution of salinity which takes the form of an inverse tangent function. Pritchard (1952a) has proposed a mathematical relationship for the prediction of the net velocity vs. depth curve from the corresponding salinity data provided mean tidal velocities at reference stations in the Estuary are known. For the present, it may be noted that the level of no net motion occurs above the inflection point in the generalized salinity curve (diagram C), a distance approximately equal to one-quarter the total depth of the inflection point. In the Miramichi Estuary, a strikingly similar salinity curve was obtained by averaging the salinities over the tidal cycle (diagram B). This curve is shown in diagram D. The inflection point of the salinity curve is about 12 feet in depth.

The level of no net motion at this station would therefore be about 9 feet in depth, as indicated. This level estimated from the results of only one such series of measurements over a complete tidal cycle, is probably close to the average value for the entire Estuary. Pritchard (1952a) has shown that the level tends to vary somewhat depending on the location in the Estuary. Owing to the effect of the Coriolis force, the level tends to be somewhat lower on the right-hand, and higher on the left-hand side of estuaries of the American Atlantic coastal plain (subject to further investigation). An average value for the level of no net motion in the Miramichi Estuary would probably be about ten feet.

The net drift at various depths in the Miramichi Estuary may be estimated on the assumption that Pritchard's relationship between tidal velocities and non-tidal drift derived from studies in the James Estuary is applicable here. The assumption is partly justified by the close degree of similarity between the Miramichi and James Estuaries in size, River discharge, depth, tidal range, and direction of flow. The net-drift velocities cannot as yet be calculated from the salinity equation of Pritchard (above) since even the most recent tidal studies in the Miramichi area (Pothergill, 1953) do not give sufficiently adequate mean tidal velocities for reference stations in the area. However, Pritchard (1952a) has shown that, in the James Estuary, the mean non-tidal velocity in both upper and lower water layers is approximately one-fifth the magnitude of maximum tidal current velocities at those depths. At Miramichi River, station M57, the maximum surface tidal velocity is about 2 knots (fig. 10), and the residual drift velocity therefore about 0.4 knots. In Miramichi Bay and James Estuary, where

maximum tidal currents are less strong ($3/4$ to 1 knot), the net velocity of the surface drift in the seaward direction is between 0.18 to 0.2 knots, and that of the bottom current in the flood direction is between 0.1 to 0.2 knots.

Summary

1. The present account describes certain physical features of the Miramichi Estuary, New Brunswick, based on the results of investigations in 1950 and 1951, and on previous information.
2. Variations in the distribution of salinity, temperatures, and water transparency observed in 1951 are correlated with changes in precipitation, river discharge, wind velocity, and other variables.
3. The principal features of the tidal circulation are described. During a complete tidal cycle the water exchange with the Gulf of St. Lawrence is approximately 15%.
4. The residual or non-tidal circulation is described. Owing to the large and seasonably variable discharge of the Miramichi River, a net seaward drift, strongest on the south side of the estuary, of brackish water near the surface, and a landward counter drift, strongest on the north side, of more saline water near the bottom is superimposed on the oscillating tidal currents. The boundary between the two opposing layers of drift, the level of no net motion, is approximately 10 feet in depth.

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