# Physical Limnology of Saginaw Bay, Lake Huron

Great Lakes Fishery Commission

TECHNICAL REPORT No. 12

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by

ALFRED M. BEETON
U. S. Bureau of Commercial Fisheries
Biological Laboratory
Ann Arbor, Michigan

STANFORD H. SMITH
U. S. Bureau of Commercial Fisheries
Biological Laboratory
Ann Arbor, Michigan

and

FRANK H. HOOPER
Institute for Fisheries Research
Michigan Department of Conservation
Ann Arbor, Michigan

GREAT LAKES FISHERY COMMISSION
1451 GREEN ROAD
ANN ARBOR, MICHIGAN

SEPTEMBER, 1967

# PHYSICAL LIMNOLOGY OF SAGINAW BAY, LAKE HURON[1]

Alfred M. Beeton,[2] Stanford H. Smith,
and Frank F. Hooper[3]

## ABSTRACT

Water temperature and the distribution of various chemicals measured during surveys from June 7 to October 30, 1956, reflect a highly variable and rapidly changing circulation in Saginaw Bay, Lake Huron. The circulation is influenced strongly by local winds and by the stronger circulation of Lake Huron which frequently causes injections of lake water to the inner extremity of the bay. The circulation patterns determined at six times during 1956 reflect the general characteristics of a marine estuary of the northern hemisphere. The prevailing circulation was counterclockwise; the higher concentrations of solutes from the Saginaw River tended to flow and enter Lake Huron along the south shore; water from Lake Huron entered the northeast section of the bay and had a dominant influence on the water along the north shore of the bay.

The concentrations of major ions varied little with depth, but a decrease from the inner bay toward Lake Huron reflected the dilution of Saginaw River water as it moved out of the bay. Concentrations in the outer bay were not much greater than in Lake Huronproper. The proportions of various cations and anions were similar to the average proportions for the freshwaters of the world.

The average flushing time was 186 days, but was 113 days during the period of peak river discharge. The lakeward transport of Saginaw River water ranged from 619 to 2,294 feet per day in the inner bay to 1,410 to 3,000 feet per day in the outer bay on June 7 and October 30, respectively.

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[1] Contribution No. 358, Ann Arbor Biological Laboratory, U.S. Bureau of Commercial Fisheries.

[2] Present address: Center for Great Lakes Studies, University of Wisconsin-Milwaukee, Milwaukee, Wisconsin.

[3] Present address: Department of Wildlife and Fisheries, University of Michigan, Ann Arbor, Michigan.

# Introduction

Bays are among the most productive environments of the Great Lakes. They were the first areas of the Great Lakes affected by human activities that altered their productivity and usefulness as a natural resource (Smith and Snell, 1891). The serious decline in abundance of the more desirable commercial species of fish in Saginaw Bay (Hile and Buettner, 1959) appears to be largely the result of man's activities.

Less is known about the bays than about the Great Lakes proper, and techniques for studying them are poorly developed. This study of Saginaw Bay provided an opportunity to test techniques previously used to evaluate the circulation of marine estuaries by applying them to the study of water exchange of a freshwater bay with the main body of the lake.

Growing concern over the decline of the more valuable fish species led to a cooperative limnological survey of Saginaw Bay by the Michigan Department of Conservation and the U.S. Bureau of Commercial Fisheries in 1956. The bay supported a prosperous recreational fishery and produced about 40% of the U.S. commercial catch of Lake Huron although it constituted only 5% of its area. The catch of lake herring (Coregonus *artedi),* yellow perch *(Perca flavescens),* walleye *(Stizostedion vitreum vitreum),* and whitefish *(Coregonus clupeaformis)* in Saginaw Bay has fluctuated considerably (El-Zarka, 1959; Hile, 1954; Hile and Buettner, 1959) but clearly has declined in recent years.

Most of the early limnological studies of Saginaw Bay concerned the distribution of brine entering the bay from the oil fields and the chemical industry in the Saginaw Valley. The Dow Chemical Company, Midland, Michigan, has conducted some 30 surveys of chloride concentrations in the bay since 1933. An intensive study of the distribution of chloride was made by the Michigan Stream Control Commission from May 1, 1935, to July 2, 1936 (Michigan Stream Control Commission, 1937). Recent studies of water movements in the bay (Ayers, Anderson, Chandler, and Lauff, 1956; Beeton, 1958; Johnson, 1958) suggested that the circulation was similar to that of a marine estuary.

Data collected in the cooperative study by the Bureau and the Department, and independently by the Dow Chemical Company in 1956, are analyzed in this report to (1) extend information on physical and chemical conditions in Saginaw Bay, (2) investigate the relationship between air and water temperatures, and (3) determine the applicability in fresh water of techniques used to evaluate circulation in marine estuaries.

## Morphometry

Saginaw Bay is a large identation on the west shore of Lake Huron 26 miles (42 km) wide at the mouth between Point Aux Barques and Au Sable Point, and 51 miles (82 km) long from the midpoint of a line between these points to the mouth of the Saginaw River (Fig. 1). The bay narrows to a width of 13 miles (21 km) between Point Lookout on the west shore and Sand Point on the east shore. A broad shoal at this constriction (between Charity Island and Sand Point) effectively divides the bay into outer and inner zones. The total area of 1,143 square miles (2,960 km2) is divided about equally between the two zones, but the outer zone is considerably deeper (mean depth 48 feet [ 15.6 m], maximum 133 feet [ 40.5 m] ) than the inner zone (mean depth 15 feet [ 4.6 m], maximum 46 feet [ 14.0 m 1) and contains about 70% of the total volume of the bay. The volume of water above the 18-foot (5.5 m) contour is only 32% for the outer bay, but 80% for the inner zone.

The east shore of the outer bay is rocky; the west shore has extensive sandy areas, although some rock and clay occur near Point Lookout. The shoal around Charity Island and most of the points in the outer bay are rocky. Tawas Point and Sand Point are sand spits.

The inner bay has extensive shallows. A broad sandy flat extends southward from Wildfowl Bay. Another irregular sandy flat extends from the Saginaw River along the west shore to Point au Gres. Several shallow spits off the mouths of small rivers extend over this flat perpendicular to the shore. The two large flats have extensive marshes near shore. Coryeon Reef is a sand and gravel bar between the shore southeast of the Saginaw River and the Charity Islands. Its ridge is about 6 feet (1.8 m) below the surface and it is separated over most of its length from the sandy flat near shore by water deeper than 12 feet (3.7 m).

The bay has several islands, the most prominent of which is Charity Island. A group of marshy low-lying islands (North, Stony, and Katechay) lies southwest of Sand Point. These islands are surrounded by marshy shallows from which there is no clear line of demarcation.

## Collection of Data

Three synoptic surveys were made by the research vessels Cisco, Musky I (Bureau of Commercial Fisheries), and the patrol boat *PB3* (Michigan Department of Conservation) on June 7, August 10, and October 30, 1956. Each vessel made two transects *across* the bay during each survey. The *Musky* I made the innermost transects, the *PB3* the middle transects, and the Cisco the outer transects. Fifty-three stations were established at selected locations along the transects and numbered consecutively, starting with number 1 in the southeast corner of the bay and ending with number 53 off Au Sable Point (Fig. 1). Station 30 was located off the transect to obtain a bottom sample where the bottom was not rocky. Stations 20 and 40 were abandoned because the water was too shallow to navigate safely. The *Cisco* made additional observations at several stations that were not originally scheduled. These stations, designated as 7a, 42a, 49a, 50a, and 51a (Fig. I), have been included in this report.

Surface water samples were collected with a l-pint jar and subsurface samples were obtained with either a Nansen or Kemmerer bottle. Samples were stored in 4-ounce polyethylenebottles. Surface and subsurface temperatures were measured with resistance thermometers aboard the *Musky* I and *PB3.* Surface temperatures were measured by a recording resistance thermograph and subsurface temperatures were obtained with a bathythermograph from the Cisco. Bottom samples were obtained at each station with a Petersen dredge, except at stations 4, 44, and 48 where the bottom was too hard to be sampled. During the first survey sediment samples were taken at each station for a study of the deposits (Wood, 1964). The distribution of the oligochaetes has been reported on by Brinkhurst (1967). Results of analysis of bottom fauna from dredge samples have not been published.

Additional observations of sky and sea state, visibility, wind direction and velocity, and cloud type were recorded by methods outlined by Beeton, Johnson, and Smith (1959). Returns from drift bottles released at a number of stations were analyzed by Johnson (1958).

The Cisco operated in Saginaw Bay and southern Lake Huron from June 3 to November 21, 1956, during which time collections of water, bottom fauna, plankton, fish, and thermal data were made at approximately 3-week intervals at stations 41-53, 60, and 62 in the outer zone, and at stations 60 and 7a in the inner zone (Fig. 1). Additional surface water samples and temperatures were taken and bathythermograph casts made between stations. Analyses of Secchi disc and photometer measurements of light penetration made from the Cisco in the bay and in Lake Huron have been completed (Beeton, 1958). Information has been published on the distribution and seasonal movements of bay fishes (Carr, 1962), and on the food of yellow perch (Tharratt, 1959) and smelt (Gordon, 1961). Thermal and chemical data collected in Lake Huron proper at stations not included in this report were presented by Allen (1964).

The dissolved oxygen was determined aboard the Cisco by the unmodified Winkler method. Hydrogen-ion concentrations (pH)

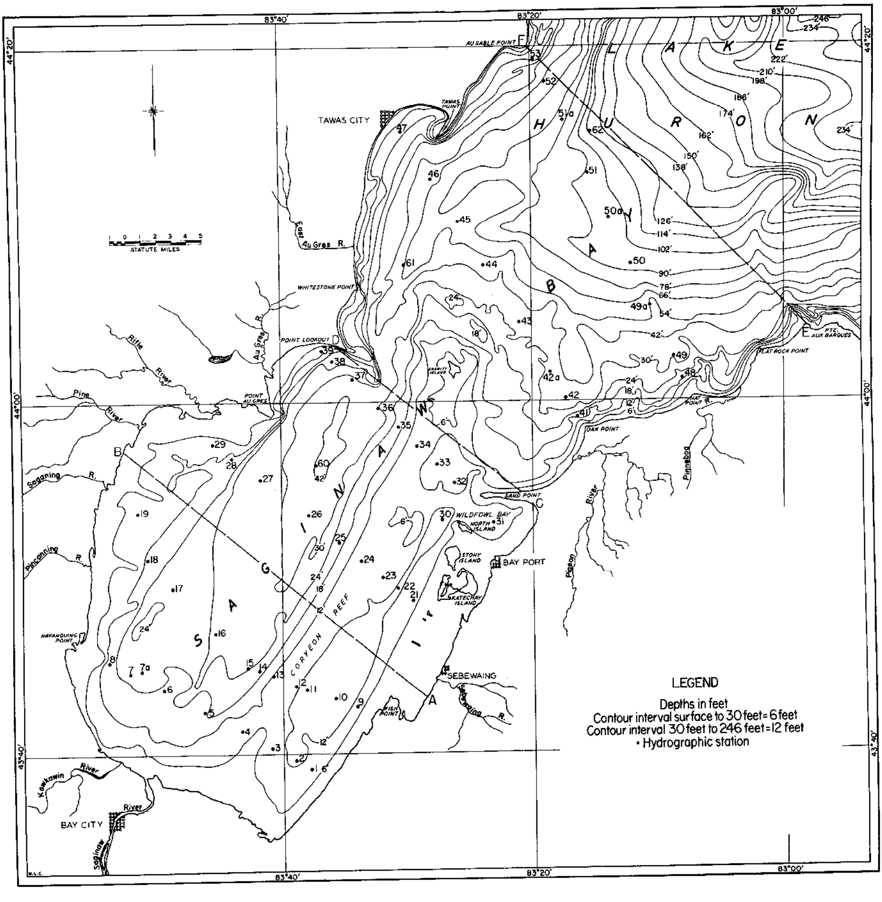


Figure 1. Map of Saginaw Bay showing depth contours and station locations. [Lines A-B, C-D, and E-F indicate transects used for calculations of flushing rates and lakeward transport. Line C-D divides the bay into inner and outer zones, as used in this paper.]

were determined with a Hellige color comparator. All other chemical analyses were made in the Ann Arbor laboratories of the Michigan Department of Conservation and the Bureau of Commercial Fisheries

The Dow Chemical Company used one vessel for three surveys in 1956 (June 21-22, July 20-21, August 24-25). Approximately 200 measurements of specific conductance were made on each survey with a conductivity cell towed behind the vessel. Water samples were collected at 12-14 locations for analysis in their laboratory.

## Laboratory Analyses

### *Data of the Bureau of Commercial Fisheries and Michigan Department of Conservation*

Calcium, magnesium, and potassium determinations were made with a model DU Beckman spectrophotometer with flame photometer attachment. Sulfate was determined turbidimetrically after precipitation with barium (American Public Health Association, 1946) and total phosphorus was measured colorimetrically by the ammonium molybdate method (Ellis, Westfall, and Ellis, 1948). Total alkalinity was determined as methyl orange alkalinity expressed as parts per million (ppm) of calcium carbonate (American Public Health Association, 1946). Alkalinity is used as a general term in this report, since it cannot be assumed that bicarbonate, carbonate, and hydroxide are the only ions involved in the alkalinity titration. It can be assumed, however, that most of the alkalinity was due to bicarbonate ions, since the pH of the bay ranged from 7.8 to 8.4 and the presence of sufficient hydroxide ions in natural waters to affect alkalinity is considered rare (Hem, 1959). Specific conductance was measured in the laboratory with an Industrial Instruments Model RC-16b-1 conductivity bridge and is *given* in mhos/cm x $10^6$ at 18° C $(K_{18}$ x 106).

### *Data of the Dow Chemical Company*

Versenate titration was used to determine total hardness. Chloride was measured by Volhard titration. The barium turbidometric method was used for sulfate determinations.

The relation between chloride content and specific conductance of water samples analyzed in the laboratory was used to estimate chloride content from conductivity measurements made on the vessel.

## Physical-Chemical Characteristics

### *Thermal conditions in the inner bay*

Water of the inner bay had warmed considerably before the first survey on June 7. Surface temperatures ranged from 15 to 20° C (Fig. 2). The shallow littoral water along the west and east shores was warmer than the rest of the bay. A tongue of this warm water (20° C) extended out from the east shore into the open water of the lower bay. This water probably had been warmed in the extensive shallows along the east shore.

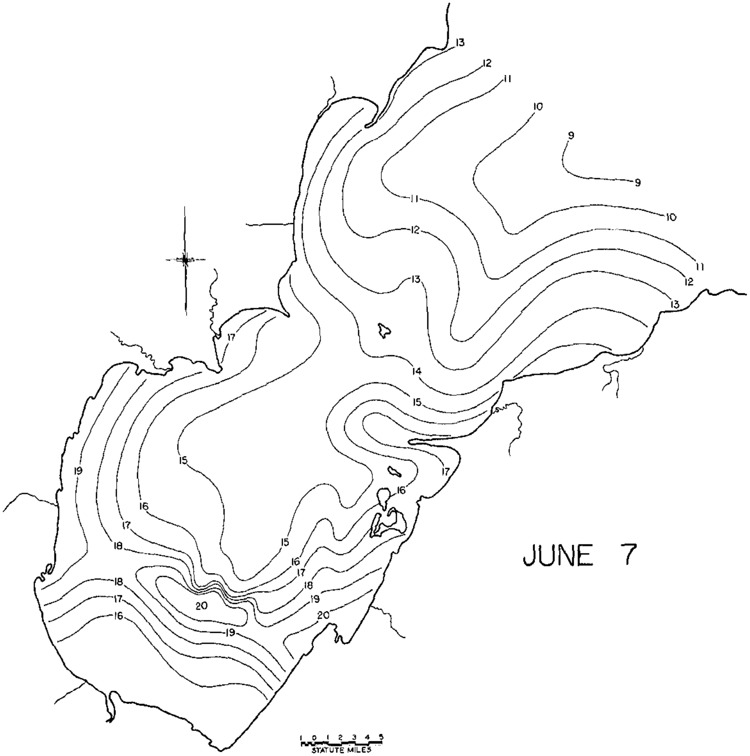
Subsurface temperatures at station 60 show that waters in the deepest part of the inner bay warmed rapidly during June (Fig. 3). By June 20 the difference was only 0.1° C between the surface and 4 meters, and 3.9° C between the surface and 9 meters (Appendix Table A- 1). Warming of the deeper water continued and the inner bay was homothermous by July 22.

The water of the inner bay continued to warm into August (stations 7a and 60) and surface temperatures ranged from 22 to 24° C during the August 10 survey (Fig. 2). The warmest water was in the shallow littoral areas. The progression of warming in surface water was closely similar at stations 7a and 60 (Fig. 3), although these stations are 15 miles (24 km) apart. The surface temperatures at station 7a were 1 to 1.5° C higher than those at station 60 in June and July. This difference could be due to a faster warming of the shallow waters at station 7a or because of the penetration of cooler outer bay water into the inner bay to station 60. Differences in temperatures at these stations were minor after August 1; highest temperatures were on August 12-22.5° C at station 7a and 22° C at station 60.

The inner bay started to cool in late August and cooled rapidly during September. The rate of temperature decline decreased through October, but increased sharply in November. Except during the first week of September at station 60, homothermous conditions prevailed throughout the inner bay during most of this period of cooling. Evidently cooling progressed uniformly throughout the inner bay and by the October 30 survey temperature differences were less than 1° C (Fig. 2).

### *Thermal conditions in the outer bay*

Surface temperatures ranged from 9 to 17° C at the time of the June 7 survey (Fig. 2). The 9 and 10° C isotherms at the mouth of the bay indicate intrusions of open-lake water. The outer bay warmed rapidly during June except for the deeper water at station 62 (Fig. 3). Temperature of the deeper waters at the bay mouth were probably influenced by Lake Huron. Station 61 appeared



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Temperature °C

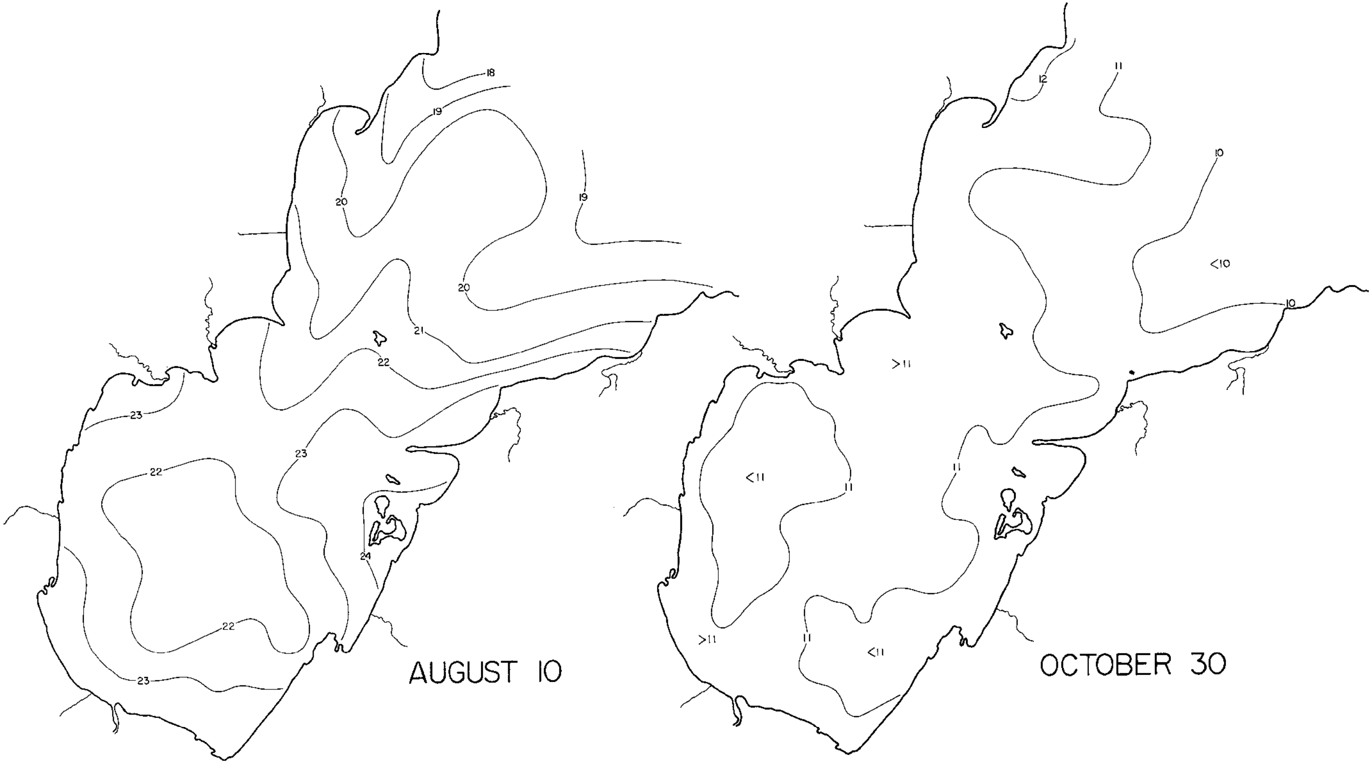


Figure 2. Surface temperatures (°C) of Saginaw Bay during synoptic cruises on June 7, August 10, and October 30, 1956.

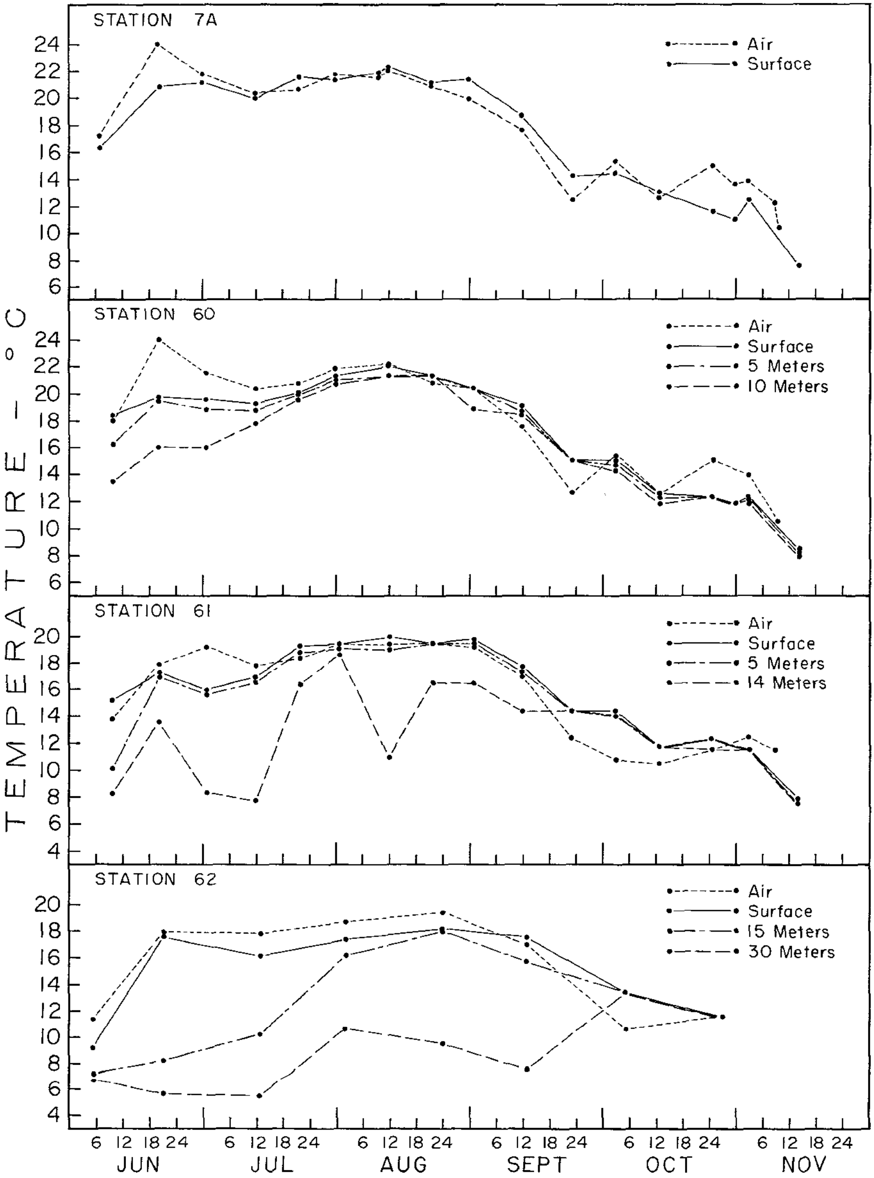


Figure 3. Air, surface, and subsurface temperatures for four locations in Saginaw Bay. Stations 7a and 60 are in the inner bay, and stations 61 and 62 in the outer bay. See Figure 1 for location of stations. [ Moving averages of air temperatures for stations 7a and 60 are from Bay City, those for stations 61 and 62 are from East Tawas. Occasionally measurements were made at depths not shown-see Appendix Table A-1.]

to be in a zone where inner and outer bay waters mixed. The wide fluctuations in temperature at 14 meters at this station undoubtedly reflect intrusions of water masses from the open lake.

Warming to a depth of 5 meters progressed rapidly in the outer bay as it did in the inner bay, but surface temperatures remained about 3° C lower at station 61 and 4° C lower at station 62 than in the inner bay. Some warming at 30 meters occurred at station 62 by early August, but open-lake water at 30 meters did not warm until the 1st week of October (Allen, 1964).

Surface temperatures ranged from 18 to 23° C during the August 10 survey (Fig. 2). The warmest surface water was along the east shore and a tongue of cooler lake water penetrated the outer bay near Tawas Point.

The cooling trend that started in mid-August in the inner bay did not begin until September in the outer bay. Thermal stratification had disappeared at station 61 by August 22 and the water was homothermous throughout the fall (Fig. 3). Cooling progressed somewhat more slowly at station 62. The water was homothermous by early October and water at 30 meters attained its highest temperature (13.20 C, Appendix Table A-l) on October 5.

Surface temperatures varied little from 11° C throughout Saginaw Bay during the October 30 survey (Fig. 2). A small mass of 12° C water occurred near shore north of Tawas Point, and 10° C water occupied most of the eastern half of the outer bay.

### *Relation between air and water temperatures*

Various attempts have been made to establish the relation between air and water temperatures because of the importance of thermal conditions to biological phenomena, and the general availability of records of air temperature where those of water temperatures are not available. Attempts to establish a relationship for day-to-day changes have not been successful. One such study was made on Saginaw Bay in 1904 (Cooper, 1905). Methods based on monthly mean temperatures have been used successfully on South Bay, Lake Huron (McCombie, 1959), and for Lake Erie (Doan, 1942).

Sufficient water temperatures were collected during this study to determine their relationship to air temperatures. The 10-day moving averages of the mean daily air temperature from Bay City showed the closest agreement with trends in water temperatures in the inner bay (Fig. 3, stations 7a and 60). Extreme fluctuations in air temperatures were not smoothed out sufficiently by 5-day moving averages to be representative of water temperatures, and 14-day moving averages did not differ appreciably from the 10-day values. Temperatures from Flint and Saginaw (not illustrated) were usually lower than the surface water temperatures in July and August, but water temperatures at stations 7a and 60 closely agreed with the 10-day moving averages of Bay City air temperatures for July and August. Air temperatures were about lo C lower than water temperatures in September. More uniform air temperatures in October coincided with the reduced rate of cooling of the water. The greatest discrepancy between air and water temperatures occurred during the first 2 weeks of June when air temperatures increased rapidly.

Moving averages for 21 days of daily mean air temperatures from East Tawas agreed well with trends in surface water temperatures in the outer bay (Fig. 3, stations 61 and 62). The 10-day moving averages of air temperatures fluctuated too widely to be representative of the water temperature. Water temperatures to a depth of 5 meters coincided closely with air temperature from the 2nd week of July until mid-September at station 61; the discrepancies were greatest in late June and between mid-September and early October. The trend in surface water temperatures at station 62 was closely similar to that of the 21-day moving averages of air temperatures, although air and water temperatures usually differed by 1° C.

### *Dissolved oxygen*

Dissolved oxygen was measured at five stations (Appendix Table A-l). Station 60 in the inner bay and 61 in the outer bay are used to illustrate changes in the amount of dissolved oxygen in theseareas during June-November, since these stations were visited more frequently than the others.

Changes in dissolved oxygen at station 60 were apparently related to wind and temperature (Fig. 4). Dissolved oxygen content of surface water decreased 1.3 ppm during the period of substantial warming in June (Fig. 3). The greatest difference (1.8 ppm) between the surface and 10 meters occurred in the calm period when the samples were taken, on June 10 (Fig. 4). The lowest percentage of saturation (66%) occurred on June 20 at 9 meters, after this period of calm. The marked increase in dissolved oxygen on July 1 followed a period of higher wind velocities. Differences between surface and subsurface dissolved oxygen were slight over the remainder of the summer when the waters were nearly homothermous. A period of relatively calm weather in the latter part of August preceded the low dissolved oxygen concentration in the deeper water on September 1. Dissolved oxygen increased slightly at all depths as the water cooled and winds became stronger in September, October, and November. Despite this increase, the percentage saturation decreased in the fall as temperature declined.

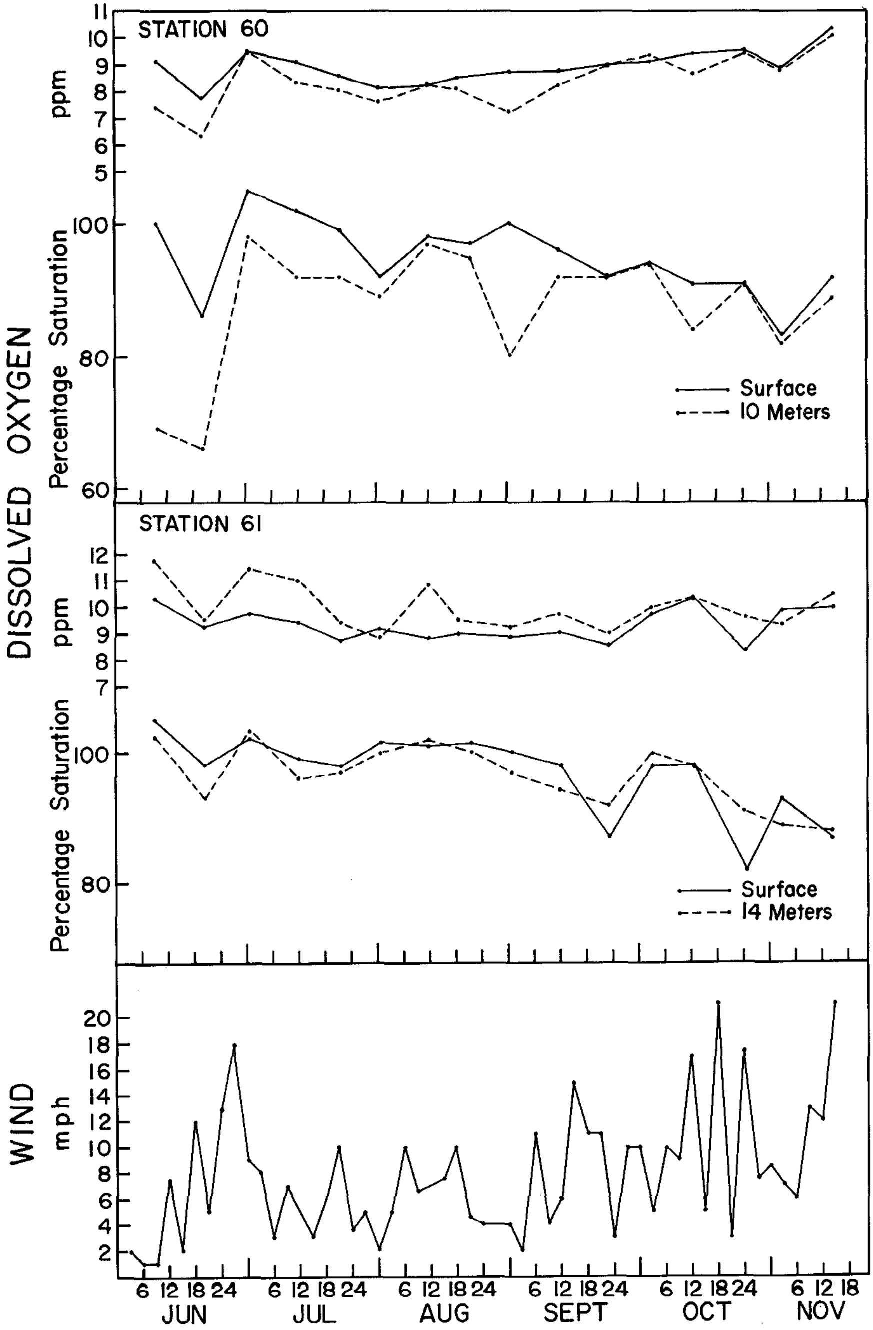


Figure 4. Dissolved oxygen concentrations at two stations in Saginaw Bay and average daily wind velocity for 3-day intervals at East Tawas. 1956.

Changes in dissolved oxygen at the surface in the outer bay at station 61 were similar to those described for station 60, although concentrations were usually 1 ppm greater (Fig. 4). The dissolved oxygen in the bottom water (14 meters ) was usually greater than at the surface and greater than in the bottom water at station 60. This situation undoubtedly resulted from invasion of colder bottom water that originated farther out in the bay or from the lake proper, since the dissolved oxygen values and temperatures frequently corresponded to those observed at stations 62 (Appendix Table A-l) or 63 (Allen 1964, 28 miles [45 km] east of station 62) at comparable depths. Intrusions of lake water into this area also would contribute to the fluctuations in temperature (Fig. 3) and dissolved oxygen concentrations (Fig.4).

### *Hydrogen-ion concentration*

Changes in pH of the surface waters followed the same trend in all areas of the bay. The pH increased from ‘7.9-8.1 in early June to a high of 8.4 in July, then decreased more gradually to lower values in late October and early November (Appendix Table A-l). A similar increase in July and decrease in October and November occurred in the bottom waters at the shallow stations 42, 45, 60, and 61, but the pH showed no trends in the deeper water at station 62 during June-October.

Fluctuations of pH were pronounced at station 62 at the mouth of the bay. The pH of surface water increased to 8.3 in July, dropped to 7.9 in early August, and increased again to 8.2 in late August. The pH of bottom water ranged from 7.6 to 8.0. Changes at this station probably reflected movement of Lake Huron water into and out of the area, since the lower pH values were similar to those of Lake Huron water (Allen, 1964).

### *Distribution of major constituents of Saginaw Bay and River*

The chemical characteristics of Saginaw River water varied considerably due to high but varying concentrations of salts in brine waste discharged to the river (Michigan Stream Control Commission, 1937). DOW Chemical Company’s analyses of Saginaw River water during May, June, and July, 1956, show that concentrations of chloride (as NaCl) ranged from 64 to 614 ppm, total alkalinity (as $CaC03$) from 123 to 187 ppm, sulfate from 70 to 115 ppm, and total hardness (as $CaC03$) from 168 to 434 ppm. These values followed no seasonal trend since discharge of waste brine into the river from storage ponds for chemical wastes was irregular. For example, the chloride content of river water was: 614 ppm on June 13, 1956; 421 ppm on June 20; 199 ppm on June 27; 374 ppm on July 11; 608 ppm on July 18; and 404 on July 25.

Changes in concentrations of the major ions with depth in the bay were much less than differences in surface concentration at various locations (Appendix Tables A-2, A-3, and A-4). Differences in ion content between surface and subsurface waters were ordinarily 1 ppm or less and were within the range of the reliability of the methods of analysis. Concentrations of some ions were higher at the surface than near the bottom, and others were lower at the surface. It appears, however, that in the outer bay the ion content was slightly lower near the bottom than near the surface,

Of the cations in the inner bay water, calcium was highest, magnesium ranked second, sodium third, and potassium fourth (Table 1). Total cation concentrations were very high in June (4.44 epm), were somewhat less in August, and decreased to 3.27 epm in October. Changes in the total cation concentrations were primarily due to changes in amounts of calcium. These values were much greater than for the average freshwater of the world (Table 1).

Concentrations of all ions were considerably lower in the outer bay (Table 2), where they were not much higher than in Lake Huron proper (Allen, 1964). The proportions of the various cations and anions were similar to the average proportions for freshwaters of the world, except for chloride (Gorham, 1957). Chloride, although not high, differed from the world average in that it exceeded sulfate.

The dilution of Saginaw River water as it moved through the bay is shown by a decrease of average concentrations of the major ions and specific conductance from the inner bay to the outer bay (Tables 1 and 2). Near the river mouth the specific conductance was 800 μmhos and the total cation concentration was 6.03 epm on June 7, when conductivity was 206 μmhos and cation concentration was 2.01 epm at the mouth of the bay. The small change in the ratio between total cations and specific conductance throughout the bay illustrates the uniform dilution of river water (Fig. 5). The dilution of the Saginaw River water from the river mouth to the bay mouth must have been due to inflow from Lake Huron, since the discharge from other tributaries was minor (Appendix Table A-5). Lake Huron water had an average conductivity of 174 μmhos and an average cation content of 1.98 epm.

### *Distribution of chemical constituents*

Closest agreement in the distribution of various chemicals measured during the synoptic surveys was among sodium, calcium, sulfate, and conductivity, and least agreement was between these and distributions of potassium, magnesium, phosphorus, and total alkalinity. Some of the differences in distributions may reflect

Table 1. Average chemical characteristics of water samples taken in the inner area (inside line A-B, Fig. 1), of Saginaw Bay in 1956

| Date | Cations | | | | | Anions | | | | Specific conductance ($\mu$mhos 18°C) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Calcium (ppm) | Magnesium (ppm) | Potassium (ppm) | Sodium (Ppm) | Total cations (epm) | Bicarbonate[1] (ppm) | Chloride (ppm) | Phosphorus (ppm) | Sulfate (ppm) | |
| June 7 | 55 | 11.2 | 3.6 | 15.8 | 4.44 | 155 | - | 0.045 | 29 | 553 |
| June 22 | - | | | | | | 57.5 | | | |
| Aug. 10 | 45 | 10.6 | 3.0 | 16.2 | 3.90 | 139 | - | 0.037 | 22 | 463 |
| Aug. 25 | - | | | | | | 61.4 | | | |
| Oct. 30 | 39 | 9.4 | 2.0 | 11.6 | 3.27 | 135 | - | 0.042 | 16 | 391 |
| Average | 46 | 10.4 | 2.9 | 14.5 | 3.87 | 143 | 59.5 | 0.041 | 22 | 469 |
| Average expressed as epm | 2.31 | 0.86 | 0.07 | 0.63 | 3.87 | 2.34 | 1.68 | | 0.46 | - |
| World average freshwater as epm[2] | 1.49 | 0.42 | 0.08 | 0.36 | 2.35 | 1.71 | 0.23 | | 0.37 | - |

[1] Determined from total alkalinity measurements.

[2] Gorham, 1957.

Table 2. Average chemical characteristics of water samples taken in the outer area (between lines A-B and E-F, Fig. 1), of Saginaw Bay in 1956

| Date | Cations | | | | | Anions | | | | Specific conductance (µmhos 18°C) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Calcium (ppm) | Magnesium (ppm) | Potassium (ppm) | Sodium (ppm) | Total cations (epm) | Bicarbonate[1] (ppm) | Chloride (ppm) | Phosphorus (ppm) | Sulfate (ppm) | |
| June 7 | 31 | 8.1 | 1.5 | 4.3 | 2.44 | 117 | | 0.013 | 12 | 270 |
| June 22 | - | | | | | | 13.6 | - | | |
| Aug. 10 | 29 | 7.5 | 1.2 | 3.6 | 2.25 | 123 | | 0.024 | 12 | 253 |
| Aug. 25 | - | | | | | | 8.4 | - | | |
| Oct. 30 | 27 | 7.9 | 1.0 | 2.9 | 2.15 | 113 | | 0.016 | 10 | 237 |
| Average | 29 | 7.8 | 1.2 | 3.6 | 2.28 | 118 | 11.0 | 0.018 | 11 | 253 |
| Average expressed as epm | 1.45 | 0.64 | 0.03 | 0.16 | 2.28 | 1.93 | 0.31 | - | 0.23 | - |
| World average freshwater as epm[2] | 1.49 | 0.42 | 0.08 | 0.36 | 2.35 | 1.71 | 0.23 | - | 0.37 | - |

[1] Determined from total alkalinity measurements.

[2] Gorham, 1957.

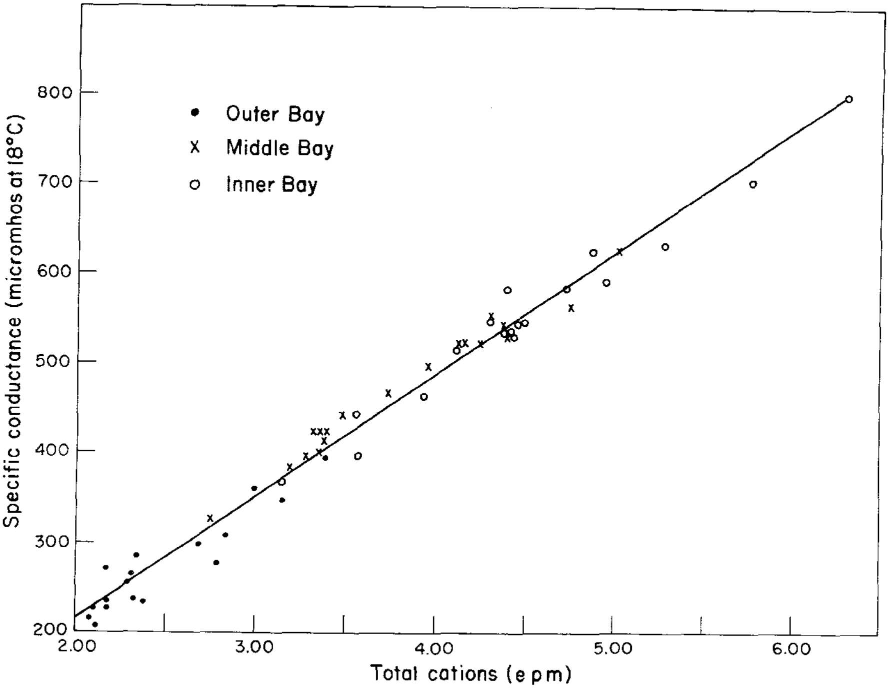


Figure 5. Relationship between specific conductance and total cation concentrations in three areas of Saginaw Bay, June 7, 1956.

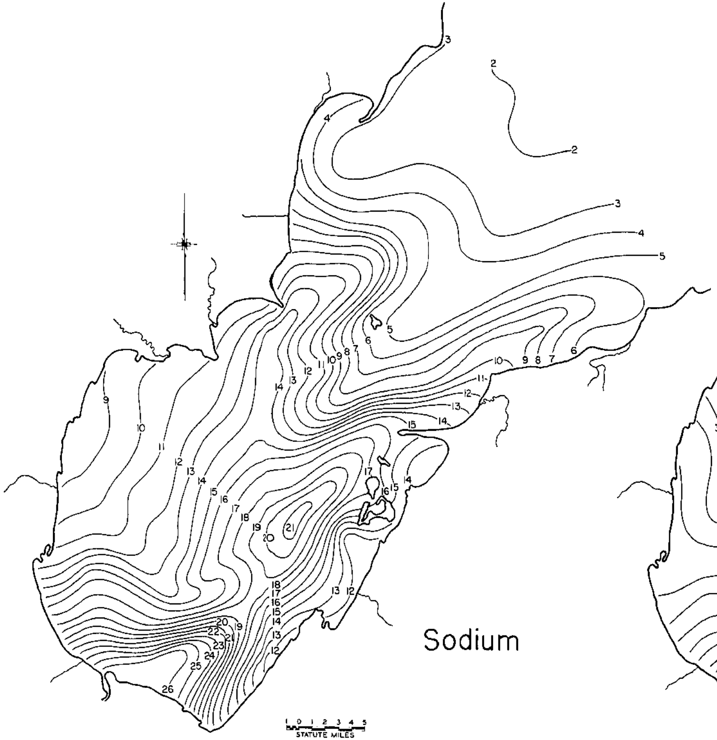
the accuracy of chemical analyses or subjective contouring. Consequently, emphasis has been placed on major patterns in the distributions and not on minor details.

Synoptic survey I, June 7. - Water with a high sodium content extended along Coryeon Reef from the Saginaw River mouth (26 ppm) to the vicinity of Sand Point (15 ppm, Fig. 6). Part of this water mass extended well beyond Sand Point to Flat Rock Point, but dilution was considerable in the outer bay and the sodium content had decreased to 6 ppm at Flat Rock Point. Some of the water with high sodium content extended north to Point Lookout and into the outer bay. Water low in sodium occupied much of the outer bay and extended into the inner bay near Charity Island. Sodium concentrations were relatively low in the inner bay along the northwest shore (9 ppm) and the southeast shore (12 ppm). This condition may have resulted from isolation of Lake Huron water that entered the bay earlier, or from dilution by the inflow from tributaries or surface runoff. The survey was made shortly after the period of maximum discharge from tributaries that have a lower sodium content than the inner bay (Appendix Table A-5).

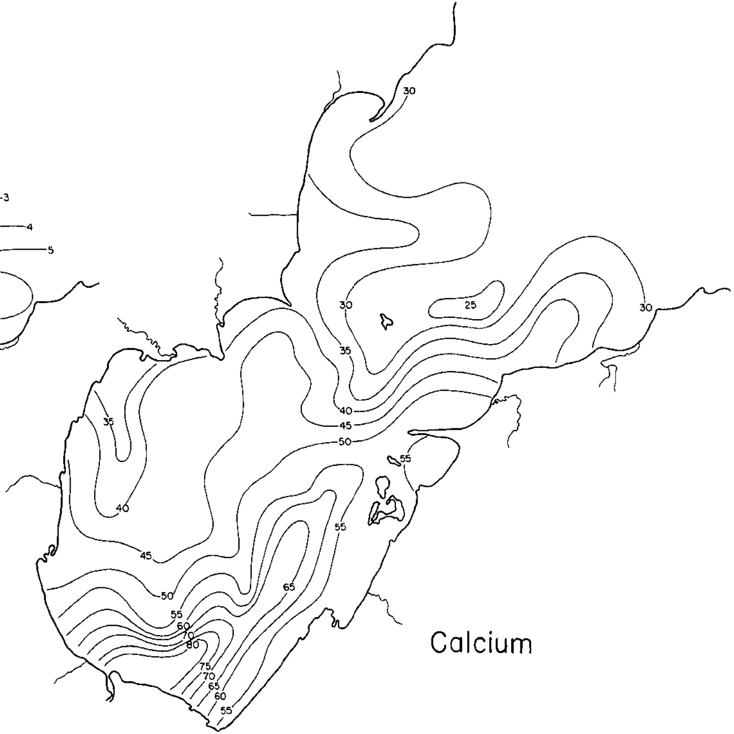
The distributions of calcium, sulfate, conductivity, potassium, and magnesium were similar to that of sodium (Figs. 6 and 7). Values for all were relatively low along the northwest and southeast shore of the inner bay. The low concentrations of calcium and sulfate in the northwest area strengthen the assumption that these areas of dilution resulted from entrapment of Lake Huron water. Although the Rifle River, which flows into the northwest area, is low in calcium, its sulfate content is high (Appendix Table A-5). The dilutions in these areas reflect more closely the characteristics of lake water.

The distribution of alkalinity (Fig. 7) agreed generally with that of sodium. The highest alkalinity values were in areas affected by Saginaw River outflow and extended toward Sand Point. A pronounced deflection of this high alkalinity water toward the north shore was a major feature of the distribution. The mass of water of low alkalinity extending into the inner bay near Charity Island, appeared to penetrate farther toward the southeast shore than shown by other measures.

The distribution of phosphorus showed the least agreement with the distribution of sodium, except for high concentrations in areas influenced by Saginaw River outflow (Fig. 7). Phosphorus concentrations in this area were 70 parts per billion (ppb), but two-thirds of the bay had concentrations of 20 ppb or less. The decrease in phosphorus content of the water between the Saginaw River mouth and Sand Point (72%) was greater than for other measures. All of the other ions and conductivity decreased 35 to 40%.



Sodium



Calcium

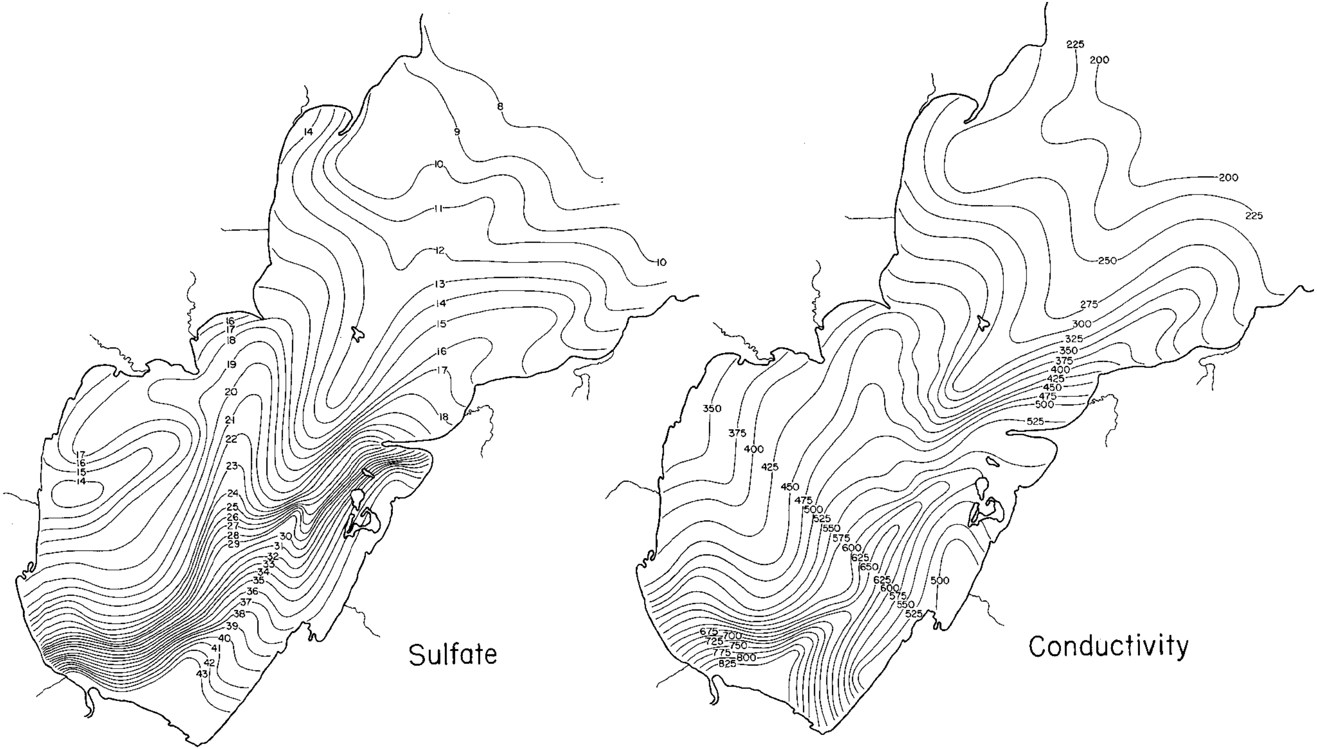
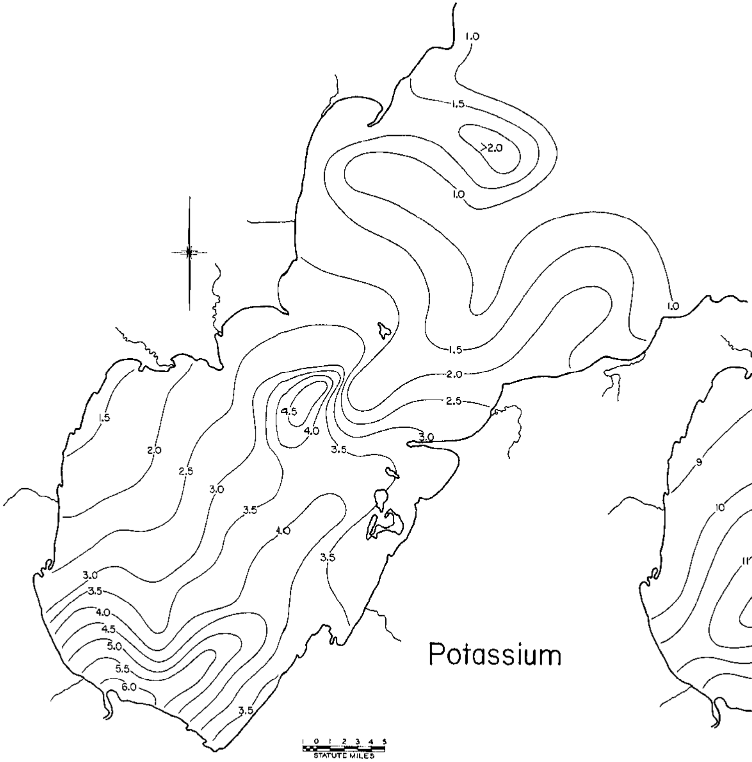
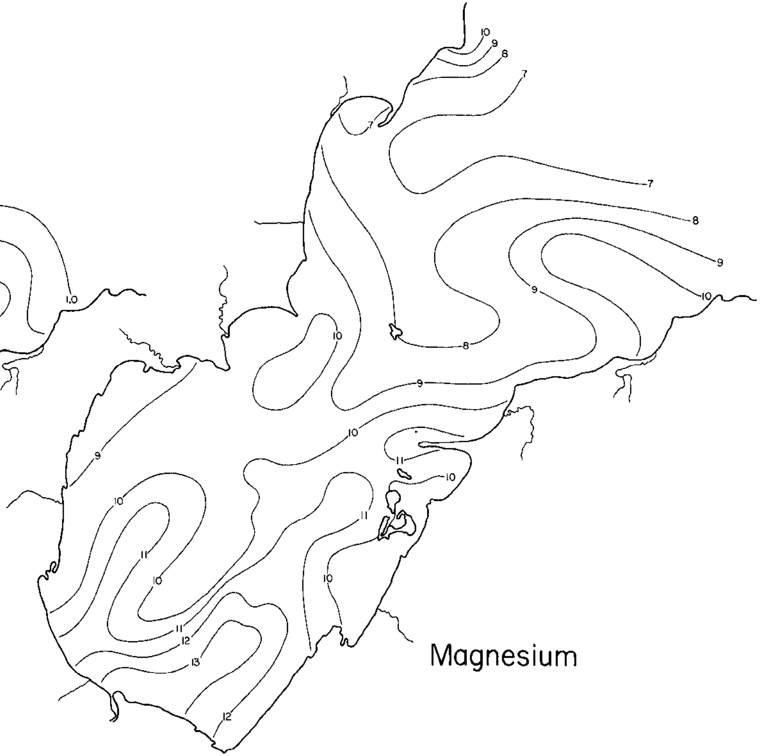


Figure 6. Distribution of sodium, calcium and sulfate (ppm), and conductivity (μmhos at 18 °C) in Saginaw Bay, June 7, 1956.



Potassium



Magnesium

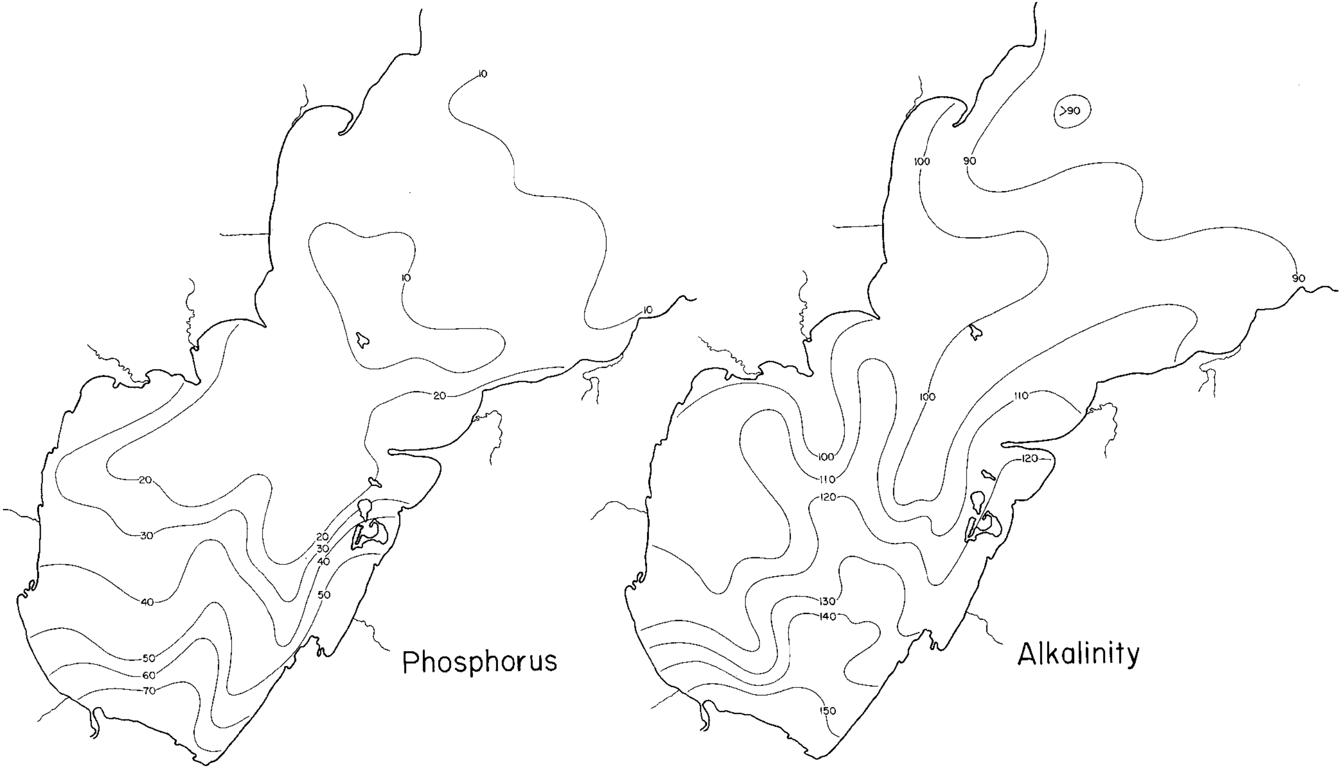


Figure 7. Distribution of potassium and magnesium (ppm), phosphorus (ppb), and alkalinity (ppm $CaCO_3$) in Saginaw Bay, June 7, 1956.

The distribution of the various constituents Suggests a deflection of the Saginaw River outflow to the southeast as it entered the bay, and a flow of river water along the Coryeon Reef. The predominant circulation was probably counterclockwise in the inner bay and some of the diluted river water was deflected toward Point Lookout where it was influenced by a general counterclockwise circulation in the outer bay. The main outflow of river water from the inner bay was probably around Sand Point where it was diluted as it mixed with outer bay water. Lake Huron water was dominant in the outer bay and was obviously flowing into the bay in the northern half of its mouth. The outflow from the bay through the southern half of the mouth would have consisted of a mixture of lake and bay water. These proposed currents agree closely with current trajectories based on returns from drift bottles released on June 7 and 10, 1956 (Johnson, 1958).

*Distribution of chloride June 21-22.* -The distribution of chloride during the survey by Dow Chemical Company on June 21-22 (Fig. 8) was similar in several aspects to the distribution of other constituents on June 7 (Fig. 6 and 7). The high chloride concentration near shore in the southeast corner of the bay suggests a southeast deflection of Saginaw River water similar to that on June 7. A partly isolated mass of water high in chloride northeast of the river mouth indicated, however, that the river water must have been deflected northwestward sometime between June 7 and June 21-22. A diluted mass of water high in chloride extended northward across the inner bay and into the outer bay, and low chloride water extended southeasterly from the northwest shore into the inner bay. The difference in distribution of chloride on June 21-22 from the other ions on June 7 indicates a greater influx of lake water into the inner bay had occurred, since dilution gradients were not great, except near the Saginaw River mouth. In the outer bay the greatest difference from the June 7 survey was the northerly extension (almost to Tawas Point) of water of high concentration from the inner bay; concentrations were higher in the northern half of the bay mouth than in the southern half.

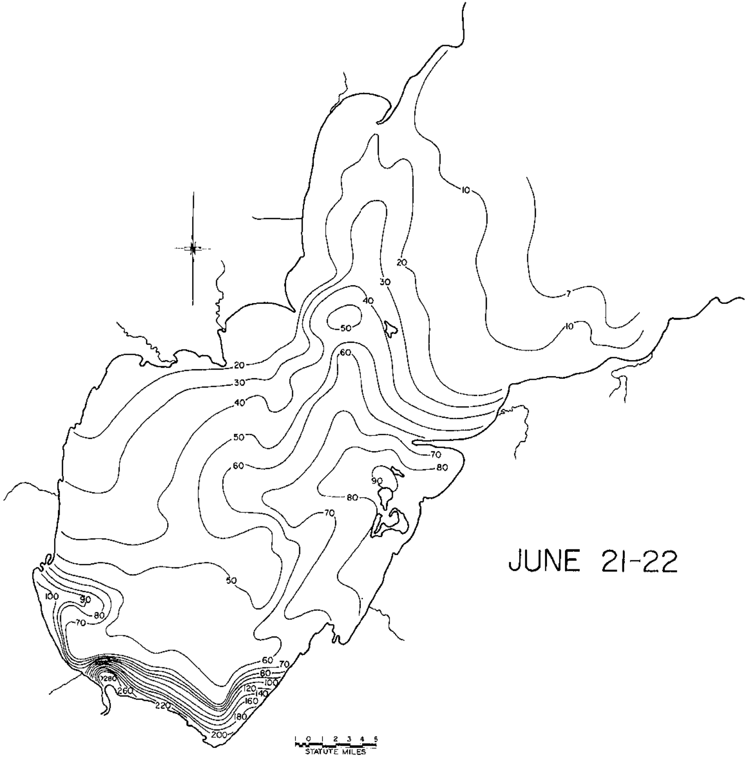
The distribution of chloride on June 21-22 indicates that circulation had changed since the June 7 survey. Circulation in the inner bay may have shifted from counterclockwise on June *7 to* clockwise and back to counterclockwise in response to winds that were from the southwest shortly after June 7 but shifted abruptly to the northeast during June 15-18 (Johnson, 1958). The protrusion of inner bay water between Point Lookout and Charity Island into the outer bay and the occurrence of water with a low chloride Content in the southern part of the bay mouth suggest a clockwise circulation in the outer bay. Lake Huron water was probably entering the mouth of the bay along the southern shore and inner bay water was probably flowing into the lake along the northwest shore of the outer bay.

Recoveries of drift bottles released on June 20 and 21 offer additional evidence for a clockwise circulation in the outer bay (Johnson, 1958). Most of the bottles released 5 miles (8 km) southwest of Tawas Point moved northeasterly and were recovered along Tawas Point; recoveries of bottles released elsewhere also suggest a clockwise circulation.

*Distribution of chloride July* 20-21. --High chloride concentration on July 20-21 extended from the mouth of the Saginaw River along the southeast shore of the bay to Sand Point as on June 21-22, but the high chloride water from the inner bay protruded into the outer bay around Charity Island instead of between Point Lookout and the island (Fig. 8). An isolated mass of water with high chloride content north of the river was similar to that of June 21-22. The low chloride water from the lake entered the bay between Point Lookout and Charity Island and extended almost 20 miles (32 km) southward into the southern corner of the bay. Chloride concentrations were not low enough to draw the 7 ppm isopleth in the outer bay. Water with the lowest chloride content occurred along the north and south shores of the outer bay.

The high chloride water along the west shore as well as the southeast shore of the inner bay and the isolated area of high chloride northwest of the Saginaw River provide additional evidence of frequently shifting circulation in the bay. The direction of circulation in the inner bay must have changed at least twice since the June 21-22 survey. The intrusion of low chloride water into the inner bay between Point Lookout and Charity Island suggests a counterclockwise circulation in the outer bay that brought Lake Huron water into the bay shortly before the July 20-21 survey. Recoveries of drift bottles released on July 12, indicated a counterclockwise circulation in the outer bay (Johnson, 1958); winds were predominantly from the southwest during July 7-14.

*Synoptic survey II, August 10.-* Water of high sodium content extended from the Saginaw River mouth along both the southeast and northwest shores of the inner bay on August 10 (Fig. 9). The distribution of this water along the southeast shore was similar to that in June (Fig. 6), although the sodium content was less and the water mass did not extend as far beyond Sand Point. The presence of a large mass of high sodium water to the north of the river mouth on August 10 was a major difference between the distribution of sodium in June and August. This water mass occupied much of the area where the sodium content was low along the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JUNE 21-22

Chloride

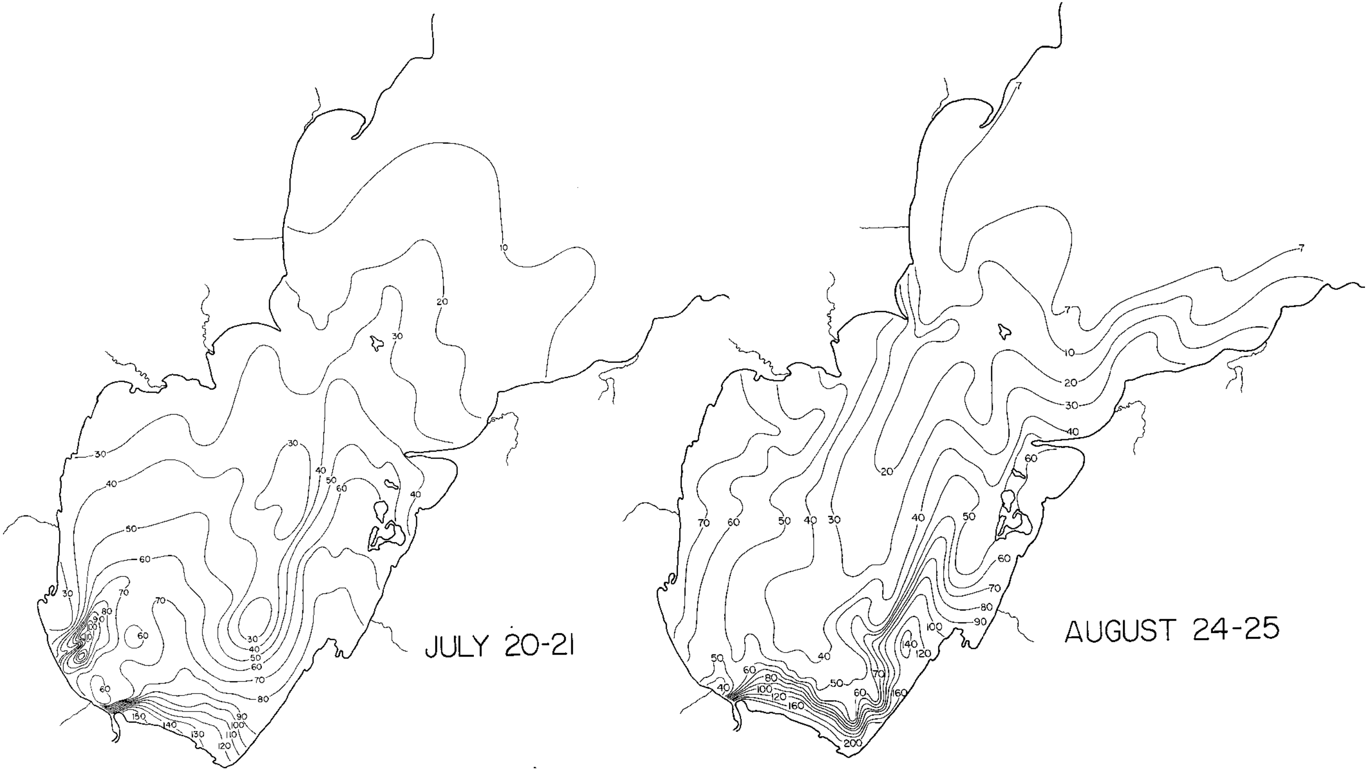
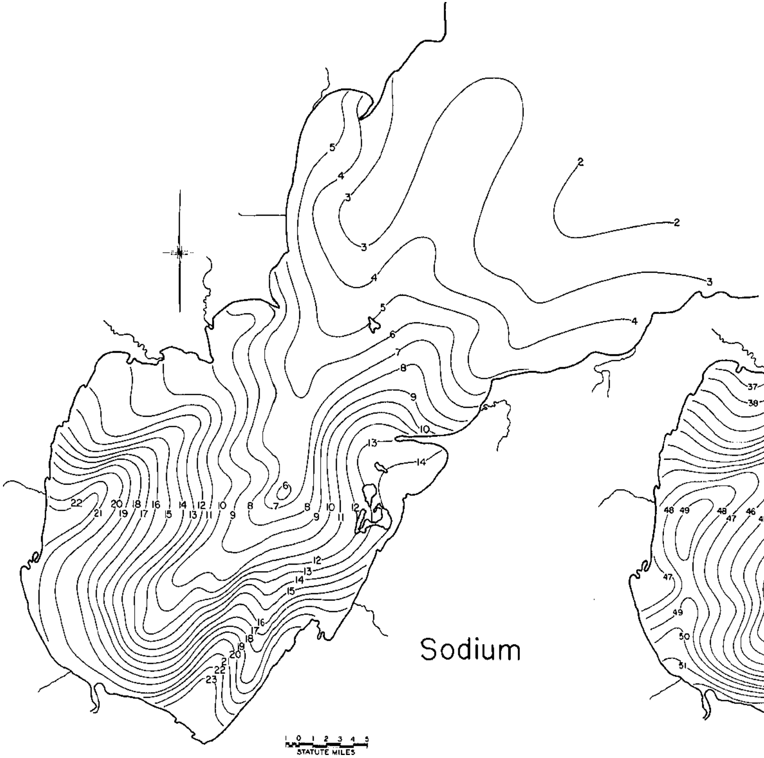
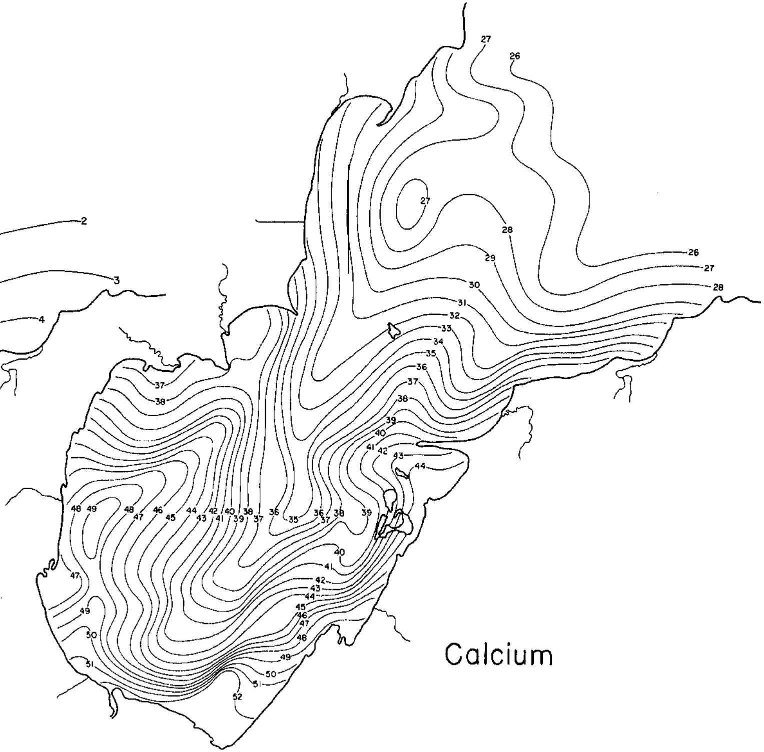


Figure 8. Distribution of chloride (ppm) June 21-22, July 20-21, and August 24-25.



Sodium



Calcium

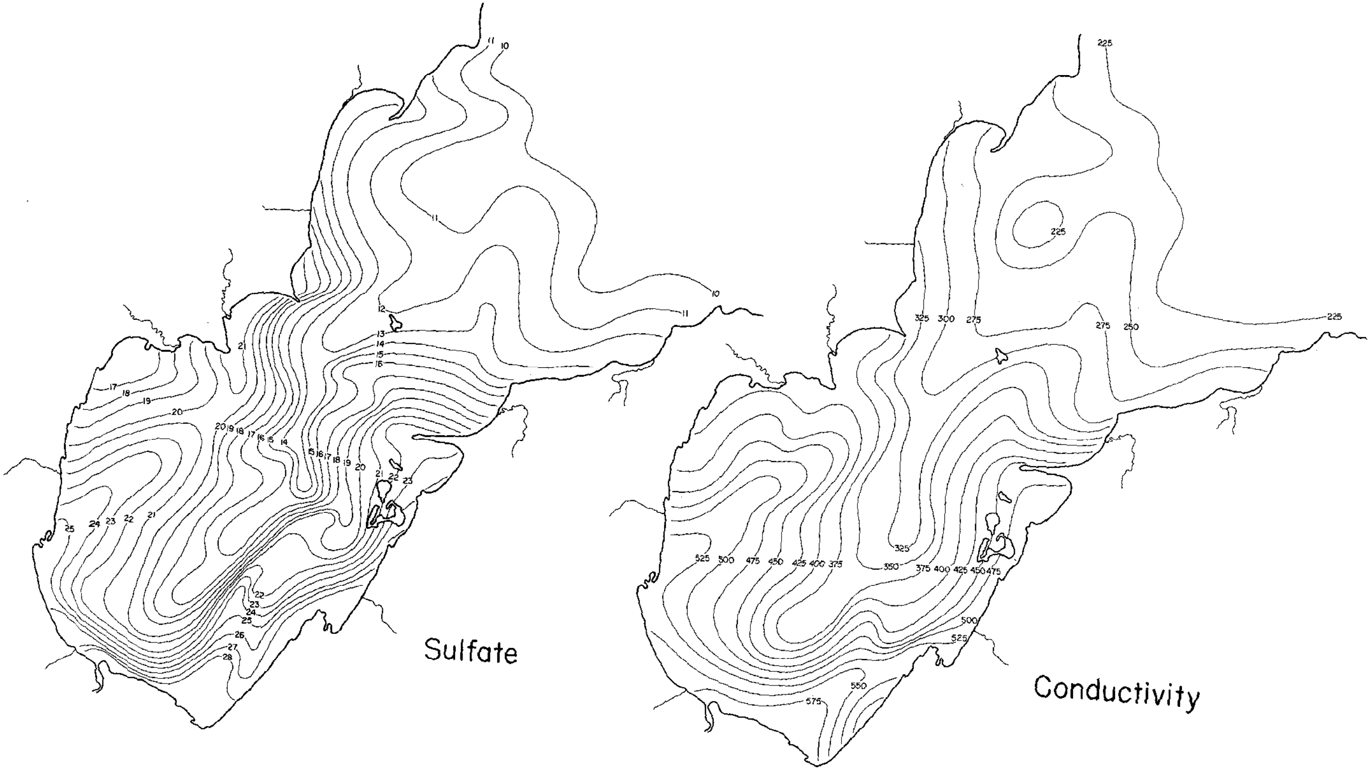


Figure 9. Distribution of sodium, calcium and sulfate (ppm), and conductivity (μmhos at 18° C) in Saginaw Bay, August 10, 1956.

northwest shore in June. Low sodium water which extended into the inner bay east of Charity Island in June was west of the island in August and had penetrated much farther into the inner bay; the 7 ppm isopleth extended about 12 miles (19.3 km) farther into the inner bay. Only one small area of the outer bay, between Sand Point and Charity Island, had sodium concentrations greater than 5 ppm. Sodium concentrations were lower on August 10 than on June 7 throughout the outer bay. Concentrations of sodium were lowest in the southern half of the bay mouth.

Distributions of calcium, sulfate, and conductivity were similar to that of sodium (Fig. 9). Slight differences in the distribution of sodium compared to calcium and sulfate appeared in the vicinity of the Au Gres and Rifle Rivers. The slightly lower calcium content near the mouth of the Rifle River may represent dilution by river water of a lower calcium content. Sulfate concentrations were slightly higher near the mouth of the Au Gres River which has a higher sulfate content than adjacent streams (Appendix Table A-5). Sulfate content of bay water west of the Rifle River mouth was lower than in any of the rivers analyzed. Other rivers entering the bay have such low discharges, especially during August, that they probably have little influence on the ion content of bay water.

The distribution of alkalinity, magnesium, phosphorus, and potassium (Fig. 10) agreed less well with sodium. Highest concentrations were north and east of the Saginaw River mouth. The higher magnesium values of the inner bay and the low magnesium concentrations at the bay mouth corresponded with sodium. Other features of the magnesium distribution were not like those of sodium. Penetration of low magnesium water into the bay was not clearly indicated as with sodium, Alkalinity was high at the mouth of the Saginaw River and in the southern corner of the bay, but high values did not extend to the north and northeast as did those of sodium. Water of low alkalinity occurred throughout the outer bay and a tongue of low alkalinity water penetrated the inner bay west of Charity Island; but unlike sodium, this intrusion extended southward to Katechay and Stony Islands.

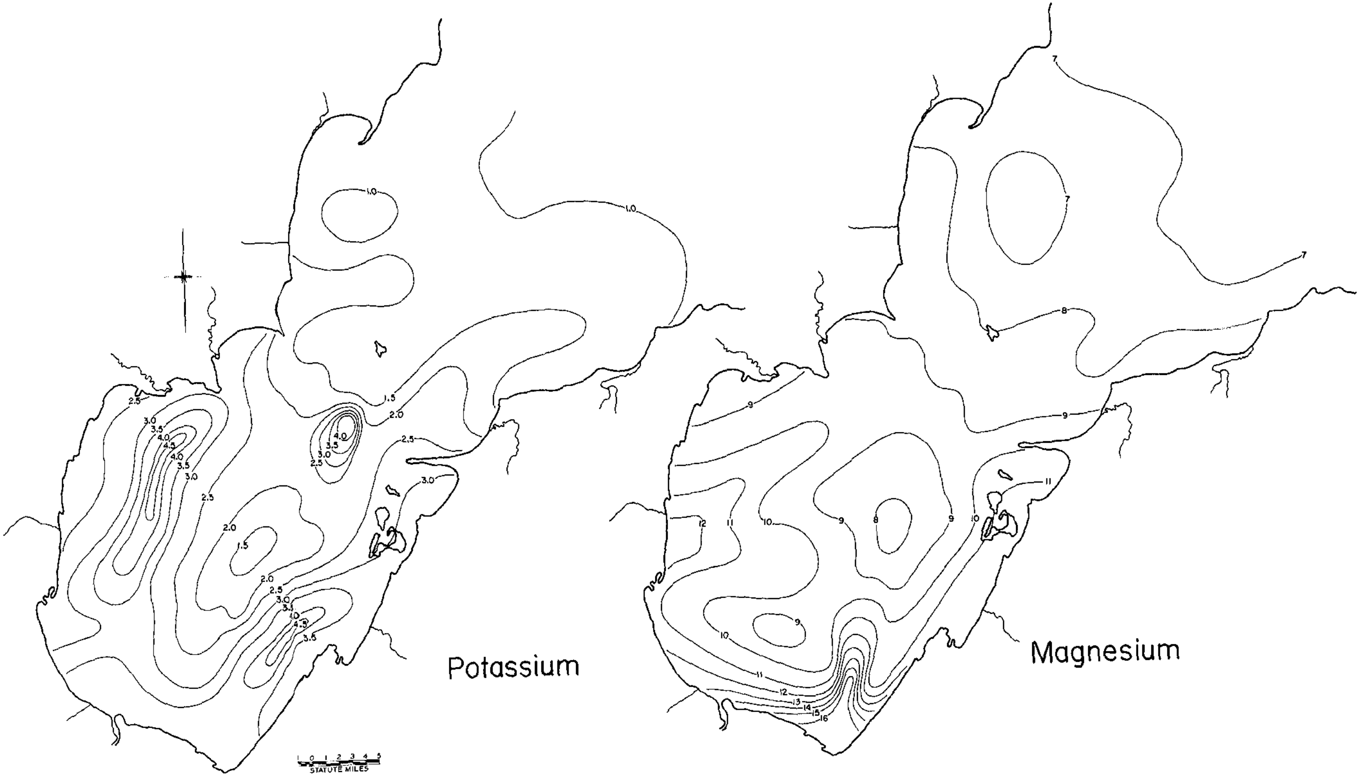
Concentrations of phosphorus were high on both sides of the river mouth and along the southeast shore to Sand Point; phosphorus content was low in the outer bay. Low phosphorus water extended through the middle of the outer bay and into the center of the inner bay instead of penetrating the inner bay west of Charity Island as for most ions including sodium. Water along both shores of the outer bay had high phosphorus concentrations. The highest concentration (70 ppb) was in Tawas Bay near Tawas City. An isolated mass of water high in phosphorus appeared off Point Au Gres.

Distribution of potassium differed most from that of other ions. Highest concentrations were at three isolated locations within the inner bay: near the southeast shore, near the northwest shore, and near the middle of the bay between Sand Point and Point Lookout (Fig. 10). Except for a small area near Sand Point influenced by outflow from the inner bay, potassium concentrations *in* the outer bay did not exceed 1.5 ppm.

The two masses of water of high ion content along the north and southeast shore on both sides of the Saginaw River mouth suggest that the August 10 survey was made during a period when the current pattern of the bay was changing. A counterclockwise circulation of the inner and outer zones, similar to the one described for the June 7 survey, appears to have been developing after a period of clockwise circulation. The earlier clockwise movement is indicated by the high ion content of the water north of the river mouth and by the low ion content of the water in the south half of the bay mouth. Clockwise movement within the inner bay seems to have moved river water along the northwest shore and around Point Lookout into the outer bay. Winds from the northeast, east, and southeast from July 15 to August 6 would have created such a circulation. The higher ion concentrations and higher conductivity of water in the southern corner and along the southeast shore, as well as the penetration of low ion water into the inner bay on the west side of Charity Island, suggest a more recent counterclockwise circulation. This movement was probably established between August 6 and 10 by winds from the southwest and west. This current pattern agrees with the trajectories plotted from returns of drift bottles (Johnson, 1958).

*Distribution of chloride August* 24-25. - Water of high chloride content extended from the mouth of the Saginaw River to the southeastern corner of the bay and northeastward toward Sand Point along the south side of Coryeon Reef (Fig. 8). Chloride content was high around Sand Point and along the southeast shore of the outer bay. An isolated mass of water of high chloride content occurred along the west shore of the inner bay. Low chloride concentrations (40-50 ppm) near the mouth of the Kawkawlin River may represent the outflow of this river (Appendix Table A-4), Most of the outer bay had low chloride concentrations-7 ppm or less. A tongue of low chloride water extended almost 20 miles (32 km) into the inner bay between Point Lookout and Charity Island.

The deflection of Saginaw River water to the right as it entered the bay, the presence of water of high chloride content along the southeast shore, and the penetration of outer bay water into the inner bay between Point Lookout and Charity Island indicate a counterclockwise circulation. Lake Huron water apparently was


Potassium
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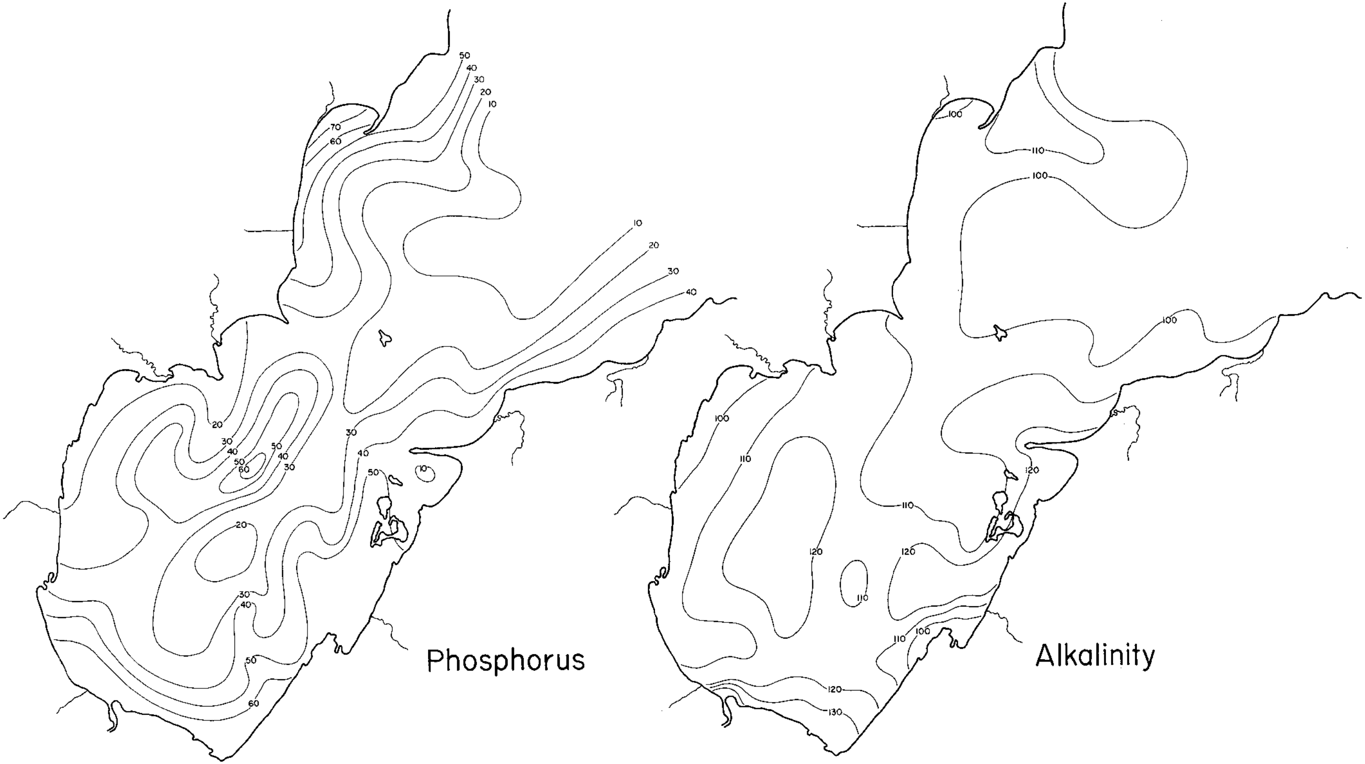


Figure 10. Distribution of potassium and magnesium (ppm), phosphorus (ppb), and alkalinity (ppm $CaCO_3$) in Saginaw Bay, August 10, 1956.

moving into the bay along the northwest shore and occupied most of the bay mouth.

Recoveries of drift bottles released on August 22 also suggest a counterclockwise circulation (Johnson, 1958). Between August 6 and 26 winds were from the northwest, west, and southwest.

Synoptic Survey III, *October* 30. - The distribution of sodium during the October 30 survey (Fig. 11) was similar to the sodium distribution on August 10 (Fig. 9). Water with a high sodium content extended from the Saginaw River mouth along the southeast and northwest shores of the inner bay. Low sodium water occupied the center of the bay between these masses. The high sodium water along the southeast shore continued around Sand Point into the outer bay. Sodium concentrations were low off the mouth of the Rifle River. The southern half of the outer bay had sodium concentrations less than 3 ppm and the lowest (2 ppm) were at the southernmost corner of the bay mouth. Sodium concentrations were generally lower throughout the bay in October than in August.

The distributions of calcium, sulfate, and conductivity agreed more closely with that of sodium than during the two previous surveys (Figs. 6, 9, and 11). Conductivity showed a movement of outer bay water into the inner bay between Charity Island and Point Lookout.

The distributions of alkalinity, magnesium, phosphorus, and potassium (Fig. 12) were similar to that of sodium. Potassium and magnesium values in water near the Saginaw River were only slightly higher than concentrations at other points within the inner bay. Consequently, these ions did not show clearly the distribution of river water. An isolated mass of water with a high potassium content occurred halfway between Sand Point and Point Lookout. This area had high concentrations of potassium on June 7 and August 10. The distribution of alkalinity in the inner bay was very similar to that of sodium. Most of the outer bay waters had alkalinity concentrations of less than 100 ppm; distribution differed somewhat from that of sodium.

The distribution of phosphorus differed strongly from that of other properties. The Saginaw River outflow extended northward as a tongue of high phosphorus water (Fig. 12). Water with high phosphorus content also occurred along the west and southeast shores of the inner bay, but this water appeared to be separated from the river outflow by water with a lower phosphorus content. A distinct mass of water with low phosphorus lay along the west shore north of the mouth of the Saginaw River. Low phosphorus water also occupied the center of the inner bay and continued to the outer bay between Charity Island and Point Lookout-similar to the distribution of sodium, sulfate, and conductivity in that area.

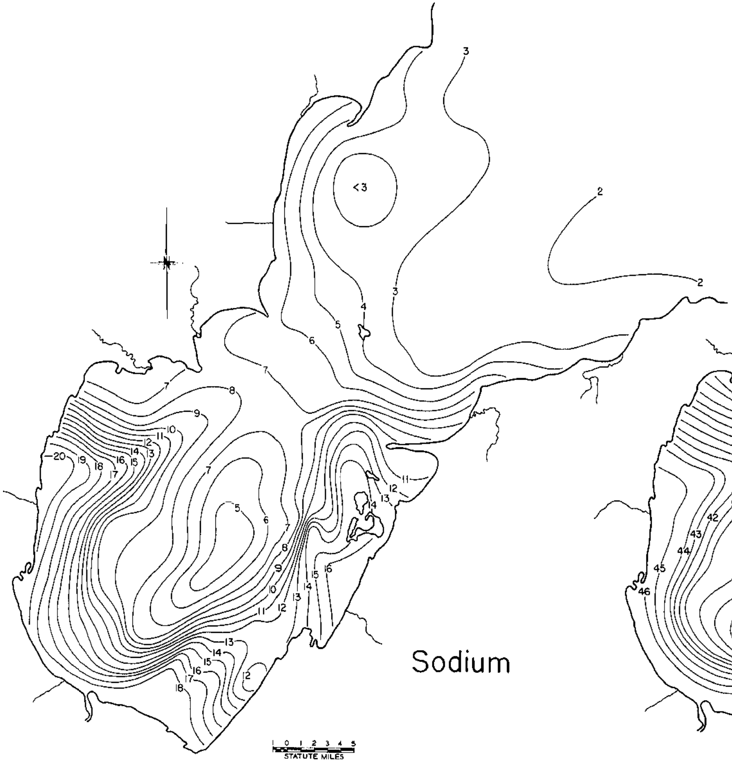
The existence of two masses of water with high ion content along the west and southeast shores suggests that at the time of the October 30 survey the distribution of various properties in the inner bay was determined by a strong injection of Lake Huron water down the center of the inner bay from a point near Charity Island. This intrusion effectively divided the inner bay water into masses along the two shorelines. Clockwise and counterclockwise movements resulting from wind stresses may have been superimposed on this basic pattern.

*Summary of the physical and chemical characteristics.* -Comparisons of the distribution charts indicate that from June through October concentrations of all chemicals except phosphorus decreased progressively. Also, the sizes of areas of high concentration decreased. Phosphorus concentrations were higher in June and October than in August but water with high phosphorus content occupied a greater area of the bay in August than in June or October. The distribution of phosphorus probably was determined in part by local conditions, especially biological activity.

The large mass of water of high ion content in June may reflect the accumulation of Saginaw River water under the ice during the winter, when wind-induced circulation is minimal. This accumulation of river water is well illustrated by the distribution of chlorides in early surveys of the Michigan Stream Control Commission (1937) which indicated a flow of river water under the ice along the bottom into the deeper part of the inner bay. The direction of this flow was northeasterly, along the west side of Coryeon Reef. On the surveys of March 2-4 and 6-7, 1936, river water appeared as a mass of high chloride water (100-300 ppm), about 2 to 3 miles (3.2 to 4.8 km) wide, which extended at least 20 miles (32 km) from the river mouth. Much higher chloride concentrations were detected throughout the inner bay in the spring of 1936 after the ice had disappeared than in October of 1935.

Currents in the bay were strongly affected by winds. Johnson (1958) concluded from his analysis of drift bottle data: “It appears that the dynamics of the bay are closely related to the highly variable meteorological conditions of this area and that the surface currents are in a continuous state of change. For this reason, we must state specifically under what conditions any particular surface-current pattern was found.” Evidence from the present study and from earlier studies by the Michigan Stream Control Commission (1937) suggests that northeast, east, and southeast winds produce a clockwise circulation, and west and southwest winds a counterclockwise circulation.

Surveys by the Michigan Stream Control Commission in 1935 and 1936 provide good examples of the circulation established by



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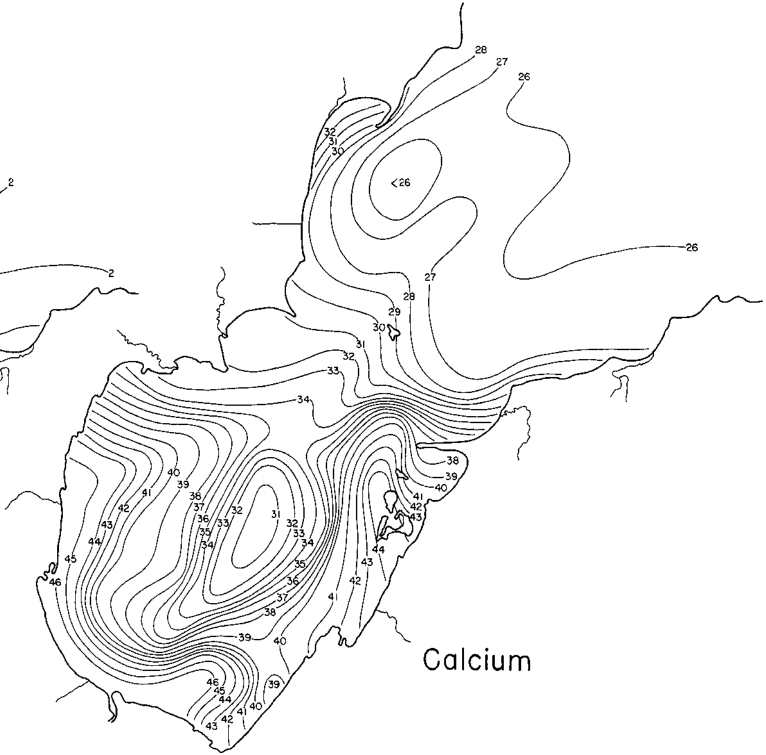


Calcium

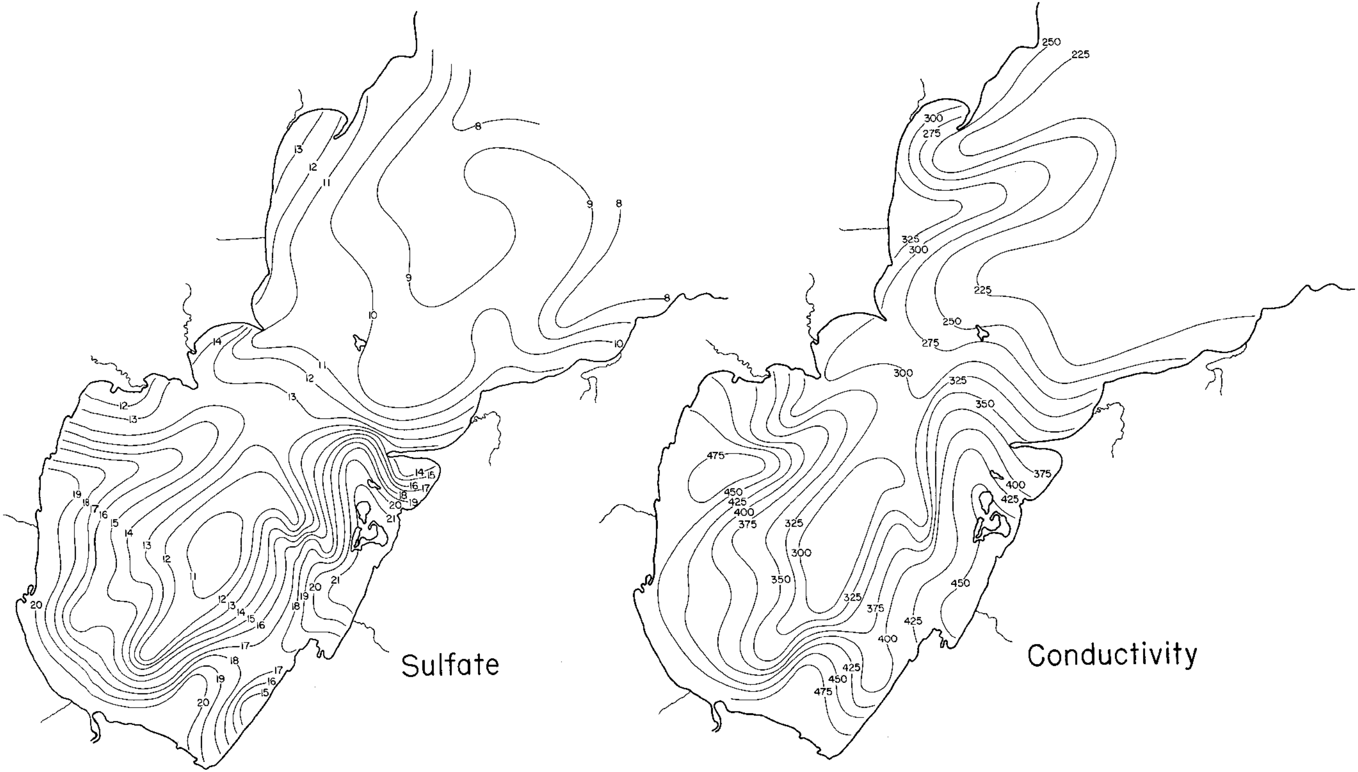
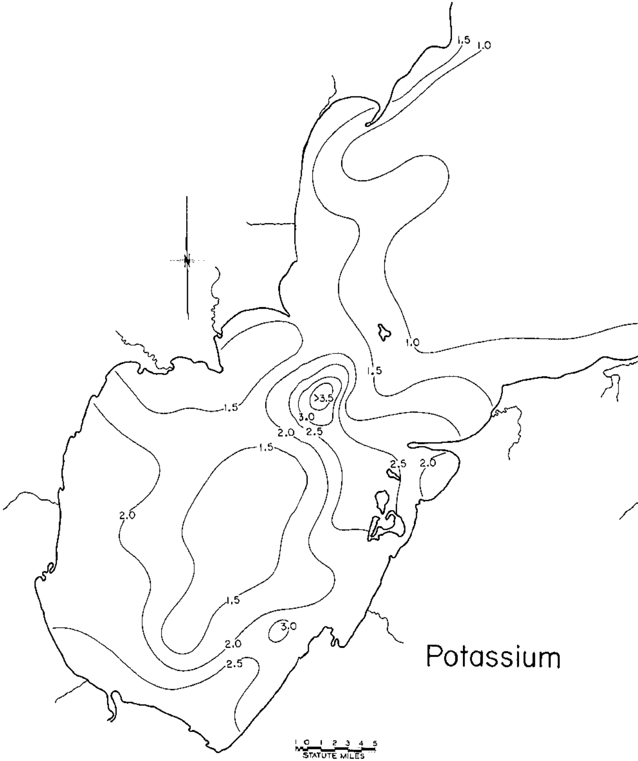
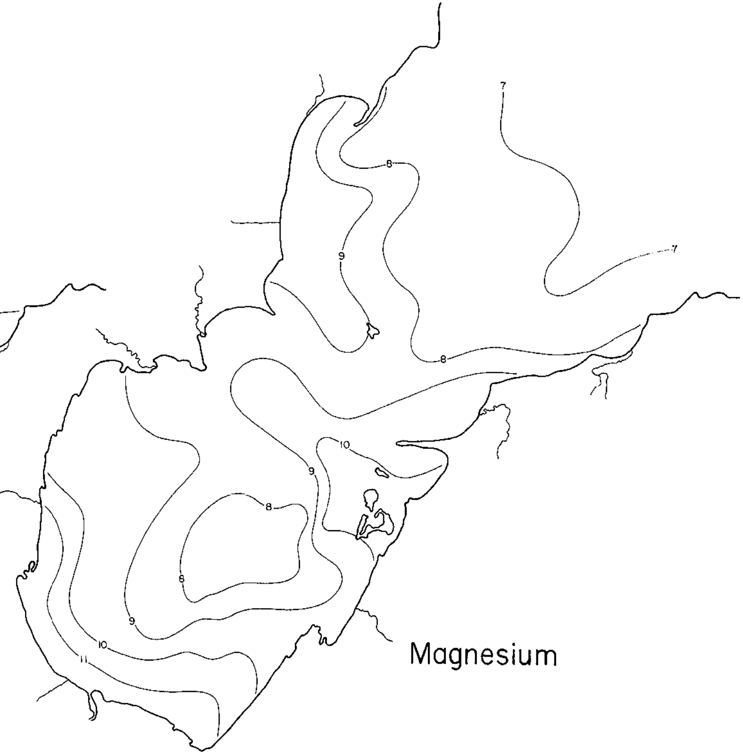


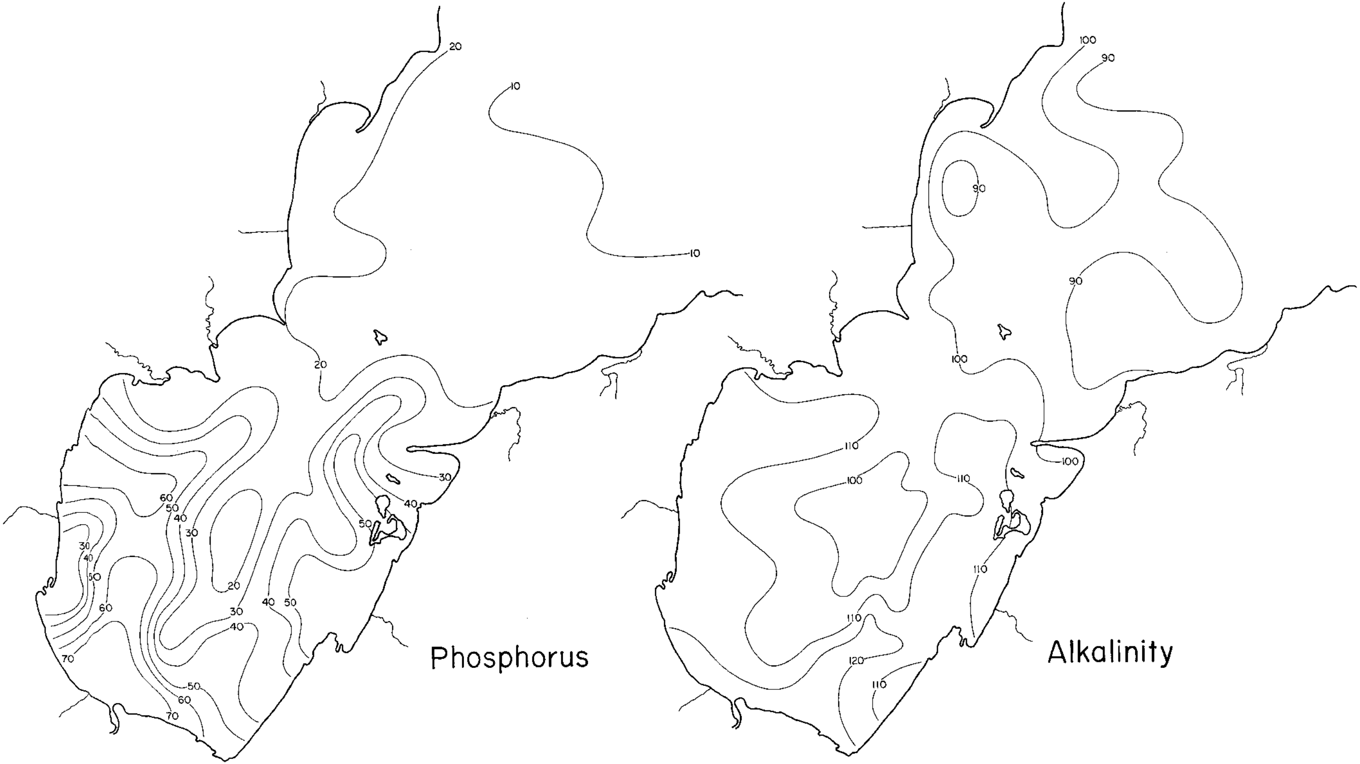
Figure 11. Distribution of sodium, calcium and sulfate (ppm), and conductivity (μmhos at 18° C) in Saginaw Bay, October 30, 1956.



Potassium



Magnesium



Phosphorus

Alkalinity

Figure 12. Distribution of potassium and magnesium (ppm), phosphorus (ppb), and alkalinity (ppm $CaCO_3$) in Saginaw Bay, October 30, 1956.

different winds. Winds predominantly from the northeast on May 12-24, 1935, were followed by a pronounced clockwise circulation indicated by the results of the surveys on May 13-18 and May 20-24, 1935. Saginaw River water extended from the river mouth along the west and northwest shore of the inner bay and entered the outer bay between Point Lookout and Charity Island. Low chloride water of the outer bay protruded into the inner bay around Sand Point and extended along the southeast shore. Winds from the north, northeast, and southeast during June 7-21, 1936, also produced a clockwise circulation as shown by the survey on June 22-25. A counterclockwise circulation that resulted from southwest and northwest winds during June 19-28, 1935, was evident from the distribution of chlorides in the surveys of June 24-28 and July 1-4. Saginaw River water extended from the river mouth along the southeast shore of the inner bay. Outer bay water penetrated the inner bay between Point Lookout and Charity Island. Winds from the northwest October 18-31, 1935, and from the southwest May 17-27, 1936, also produced a counterclockwise circulation as shown by surveys of October 28-30, 1935, and May 25-27, 1936.

It appears that circulation of bay water can be changed from clockwise to counterclockwise by a shift in wind direction in as short a time as 4 days. The survey of August 10, 1956, suggests that a clockwise circulation existed earlier although counterclockwise circulation was being established by August 10. Winds had been from the northeast, east, and southeast July 15-August 5, but had shifted to southwest and west August 6-10. Similar examples can be found in data of the Michigan Stream Control Commission (1937); the chloride distribution during the survey of June 10-14, 1935, suggests establishment of a counterclockwise circulation after an earlier period of clockwise circulation. Moderate to strong winds were from the southwest and west June 2-8, 1935.

Although it seems clear that the local winds over Saginaw Bay have a strong influence, the relationship of the circulation of the bay to the larger circulation of Lake Huron has not been explored. It cannot be assumed that the larger and presumably stronger inertial current system of Lake Huron does not at times upset or modify the local water movement of Saginaw Bay, particularly when bay currents are weak compared with currents of Lake Huron. This situation is suggested by occasional injections of lake water into the deeper portion of the inner bay through the deep channel between Point Lookout and Charity Island.

The evidence of deflection of the Saginaw River to the right after it enters the bay in every period of this study reflects the effect of the Coriolis influence on a river entering an estuary. The more usual occurrence of higher concentrations of the various ions along the Coryeon Reef or the southeast shore of the inner bay and the south shore of the outer bay indicate clearly that the Coriolis force has a strong influence on the general circulation of the bay. The frequent modification of this influence by wind or injection of Lake Huron water which cause deflection and isolation of river water in various directions are major factors of mixing within the bay. The surveys show that the degree of mixing of Saginaw River water is highly variable particularly in the outer bay where it usually moves into Lake Huron along the south shore around Point Aux Barques under the Coriolis influence of the open lake.

Little similarity existed between the distribution of temperatures (Fig. 2) and other water properties (Figs. 6-12) within the inner bay. The distribution of temperature was similar to other properties on June 7 and August 10 in the outer bay, when the outer bay water with its low ion content also had low temperatures and the warm water of the inner bay had a high ion content. By October 30, however, temperatures were too uniform throughout the bay for any similarity with the distribution of other properties to persist.

## Exchange of Saginaw River and Lake Huron Waters in Saginaw Bay

Circulation in marine estuaries has been studied from data on the rate of inflow of freshwater and its distribution in the estuary. From these data estimates can be made of the net seaward transport of river water, the time required for river water to move through the estuary, and the magnitude of the counter current moving into the estuary (Ketchum, 1950, 1953). Low salinity or some other characteristic of river water serves as a tracer. Consequently, it is necessary to have reasonably accurate estimates of the average concentration of the tracer to differentiate river water from sea water. This method assumes that without the river inflow the embayment would have the same salinity as the open sea and that any decrease in salinity can be attributed to river water.

Synoptic surveys of the Saginaw Bay in 1956 provided information on the distribution of river water for estimates of flushing rate, lakeward transport of river water, and exchange between lake and river water. As in marine estuaries, the river water can be used as a tracer, but the salinity relation is reversed; the water of high salinity from the Saginaw River flows out of the bay and the low salinity water from Lake Huron enters the bay. The situation in Saginaw Bay is somewhat more complex than that in the marine estuary because the salt content of the diluting water (Lake Huron), as well as that of the Saginaw Bay and River, must be considered. Furthermore the salt content and the volume of river discharge varied seasonally. Despite these complications the methods used by Tully (1949), Ketchum (1950), and Ketchum, Redfield, and Ayers (1951) can be used to evaluate the circulation of this freshwater bay.

The average salt content of Saginaw Bay was much lower than the river, and was closer to that of Lake Huron. This condition indicated that an appreciable exchange of Saginaw River and Lake Huron water must take place.

The volume of Saginaw River flow and its chemical content varied throughout the year. Although the discharge of the river and its ion content appeared to vary inversely, this relationship was unpredictable. Chloride varied more than 200 ppm in a week. Consequently, records of salt content, as well as river flow, were required.

A gaging station was not maintained on the Saginaw River proper, but discharge records were available for all of the main tributaries. The flow of the Saginaw River, as used in this study, is the combined flow of the Shiawassee, Bad, Flint, Cass, and Tittabawassee Rivers. Data used were those recorded at Fergus, Brant, Fosters, Frankenmuth, and Midland, Michigan (U.S. Geological Survey, 1958, 1959). From these data the average daily discharge of the Saginaw River was calculated for the 30-day period preceding the 2nd day of each synoptic survey (Appendix Table A-6). The average daily flow before the first survey in June (993 million cubic feet or 28 million cubic meters) was 5 to 11 times higher than in August or October. This greater discharge was due to the spring thaw and May rains. Stream flow declined from the end of May to October; the average daily flow before the third survey on October 30 was 86 million cubic feet (2.4 million m3). The annual average discharge was 292 million cubic feet (8.3 million $m^3$) per day.

Fourteen small rivers and a number of creeks flow into Saginaw Bay, but most of the larger rivers, except for the Rifle and Au Gres, have a mean discharge of less than 60 cubic feet (1.7 cubic meters) per second during most of the year. The combined average daily flow of the Rifle, Au Gres, and Kawkawlin Rivers for the 30 days preceding the first survey, which included their flood periods, was about 8% of the flow of the Saginaw River. These rivers have a lower ion content than the Saginaw River (Appendix Table A-5) and therefore have a diluting influence.

Sodium was selected as the best tracer for study of the distribution of Saginaw River water in the bay, because it is least likely to be removed by chemical precipitation or by biological uptake. The concentration of sodium in the Saginaw River was not determined during our surveys and evidently had not been measured in the past. The chloride content of the river, however, had been determined routinely for many years by the Dow Chemical Company and data were available for a period preceding each survey.

To determine the relationship between sodium and chloride for the Saginaw River, the sodium content was measured for weekly water samples from the Saginaw River from November 1959 to March 1960. These values were plotted against weekly chloride determinations made by the Dow Chemical Company over the same period. The relationship was described by $\mathrm{Na} = 17.7 + 0.187\ \mathrm{Cl}$. Subsequently the sodium concentrations of river water were calculated from the average chloride concentration measured by the Dow Chemical Company for the 30-day period before each survey of 1956. The average chloride ranged from 152 ppm before the first survey to 346 ppm before the third survey. Corresponding sodium values were 46 ppm and 82 ppm (Appendix Table A-6).

The average sodium content of the bay during each survey was estimated by superimposing a transparent plastic grid on charts[4] on which isopleths of sodium were drawn. The grid consisted of l-inch squares (6.45 cm2); hence, each square represented a surface area unit of 100 x 106 square feet (9.29 x 106 m2). The volume of each unit was determined by placing the grid on a chart of depth contours. Calculations were made of the quantity of sodium within the volume of each unit for each of the three surveys. From these data water volumes, total sodium, and the average sodium content (ppm) were calculated for each of three zones delineated by the transects A-B, C-D, and E-F (Fig. 1). Zone 1 is closest to the Saginaw River mouth, zone 2 is the area that lies between lines A-B and C-D, and zone 3 is the outer bay. The area of bay cross-sections at each transect and the corresponding average sodium content of water across the transect were calculated also from the values of grid units or fractions thereof bisected by the transects (Table 3).

The proportion of Saginaw River water in any sample, water column, or in the entire bay can be calculated from the average sodium content. It can be assumed that Saginaw River and Lake Huron water were mixing in the bay during the surveys. Vertical differences in the distribution of the major ions were slight. Consequently, the surface concentration of sodium was considered representative of the sodium content of an entire water column. The volumes of river water $(V_r)$ and lake water $(V_h)$ were derived from the relationship:

$$V_r\ S_r + V_h\ S_h = (V_r + V_h)\ S_o$$

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[4] These charts were drawn from Corps of Engineers, U.S. Army, Lake Survey Chart No. 52, revised 1955; scale 1 inch = 10,000 feet.

where So is the observed sodium content, $S_h$ the sodium content of Lake Huron water, and $S_r$ the average concentration of sodium in the Saginaw River. The sodium values selected as representative of the lake and the river obviously were critical in the computations. A sodium concentration of 2.0 ppm was taken as representative of Lake Huron water, although the lowest sodium value reported by Allen (1964) was 2.21 ppm.

Table 3. Volume of zones and areas of cross-sections

[See Fig. 1 for boundaries of zones and locations of cross-sections1

| Zone and section | Volume of zone (billion cu. ft.) | Area of cross-section (million sq. ft.) |
|---|---|---|
| Zone 1, A-B | 122.8 | 2.051 |
| Zone 2, C-D | 136.1 | 1.155 |
| Zone 3, E-F | 694.7 | 12.259 |
| Total | 953.6 | |

The time required for the daily discharge of a river to move through an estuary is the flushing time. It is the ratio of the volume of accumulated river water in the estuary to the volume introduced daily. The flushing times for zones 1, 2, and 3 of Saginaw Bay were calculated from data of each survey (Table 4). During the period of peak river discharge, the 30 days preceding the June 7 survey, 114 days would be required for a l-day accumulation of river water to move through the bay. Flushing time increased as river discharge decreased in August and October. The average river discharge in October was about one-tenth that of May 9 - June 7 (Appendix Table A-6) but the October flushing time was only about three times longer than that for June.

Two factors influence calculations of the flushing rates-the morphology of the bay and the varying sodium content of the river. Point Lookout, Sand Point, and the shoal area extending from the southeast shore to Charity Island (Fig. 1) evidently limit exchange between the inner and outer bay. The effect of decrease in river flow on flushing time is more pronounced in the inner bay (zones 1 and 2) than in the outer bay (Table 4). The flushing time in the inner bay increased by a factor of 3.8 between June and October but it increasedonly 2.4 times in the outer bay. The sodium concentration of the river increased as the discharge decreased. This relationship causes the fraction of river water in the bay to decrease as the sodium content of the river increases and results in underestimation of the flushing time as river flow decreases.

Table 4. Average sodium content, percentage of river water in zones, and flushing times for the three zones of Saginaw Bay, 1956

| Date and zone | Average sodium (ppm) | Percentage of river water | Flushing time (days) |
|---|---|---|---|
| June 7 | | | |
| 1 | 15.0 | 29.5 | 37 |
| 2 | 13.8 | 26.8 | 37 |
| 3 | 4.5 | 5.7 | 40 |
| Total | | | 114 |
| August 10 | | | |
| 1 | 15.6 | 19.9 | 131 |
| 2 | 9.3 | 10.7 | 78 |
| 3 | 3.3 | 1.9 | 71 |
| Total | | | 280 |
| October 30 | | | |
| 1 | 11.2 | 11.4 | 162 |
| 2 | 8.0 | 7.5 | 118 |
| 3 | 3.0 | 1.2 | 96 |
| Total | | | 376 |
| Annual average[1] entire bay | 5.9 | 5.7 | 186 |

1 Based on the average sodium concentration in the entire bay during the three surveys and the average annual discharge of the Saginaw River.

The rate of lakeward transport of Saginaw River water at transects A-B, C-D, and E-F of Saginaw Bay (Fig. 1) was calculated for each survey (Table 5). Calculations were based on the average daily river flow; consequently transport rates are expressed in feet per day.

Although lakeward transport decreased with decreasing river discharge, change in lakeward transport was not of the same magnitude as the change in river flow. Transport ranged from 619 to 2,294 feet (188.7 to 699.2 m) per day for section A-B, and from 1,410 to 3,000 feet (429.8 to 914.4 m) per day for section E-F. The corresponding river discharge ranged from 86 to 993 million cubic feet (2.4 to 28 million m3) per day. The discrepancy is due to the greater percentages of river water in the areas of the cross

Table 5. Lakeward transport of Saginaw River water and entrained lake water for three sections of Saginaw Bay, 1956

| | Section A-B | | | Section C-D | | | Section E-F | | |
|---|---|---|---|---|---|---|---|---|---|
| | June 7 | Aug. 10 | Oct. 30 | June 7 | Aug. 10 | Oct. 30 | June 7 | Aug. 10 | Oct. 30 |
| Percentage of river water | 21.1 | 11.6 | 6.8 | 23.0 | 7.5 | 5.8 | 2.7 | 1.0 | 0.5 |
| Lakeward transport (ft. per day) | 2,294 | 782 | 619 | 3,737 | 2,147 | 1,290 | 3,000 | 1,517 | 1,410 |
| Total volume moving lakeward (million cu. ft. per day) | 4,705 | 1,604 | 1,270 | 4,317 | 2,480 | 1,490 | 21,954 | 10,510 | 9,839 |
| Transport ratio (total volume to river volume) | 4.7 | 8.6 | 14.7 | 4.3 | 13.3 | 17.2 | 22.1 | 56.5 | 113.9 |

sections during the first survey (Table 5). Change in river discharge had the greatest influence on the rate of lakeward transport in the innermost part of the bay. This situation has been observed in marine estuaries (Ketchum, 1953).

The lakeward transport through section C-D was greater than that for transects A-B in all surveys and greater than transect E-F except on October 30 (Table 5). This transport through section C-D was to be expected since the area of this transect is only 56.3% of section A-B and only 9.4% of section E-F. The transport through section E-F in October was greater than during earlier surveys because the river water made up a smaller fraction of the area of the cross section.

The decrease in the ion concentrations from the river to the bay mouth was caused by mixing of river water with progressively greater amounts of water from Lake Huron. Consequently, the river flow entrained an increasing amount of lake water as it moved through the bay. The exchange of lake and bay water must be extensive since the average sodium content of the bay was low and decreased from 7.2 ppm in June to 4.7 ppm in October (Table 4) even though the ion content of river water remained high.

## Acknowledgments

The assistance of many employees of the Michigan Department of Conservation and the U.S. Bureau of Commercial Fisheries is gratefully acknowledged. Dr. Glenn Flittner drew the contoured distributions of temperature, conductivity, and chemical constituents. Mr. William Cristanelli prepared most of the figures.

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# APPENDIX

Table A-l. Thermal and chemical data for various stations in Saginaw Bay, 1956

| Station and date | Time (EST) | Depth (meters) | Temperature (°C) | Dissolved oxygen | | pH |
|---|---|---|---|---|---|---|
| | | | | ppm | percentage saturation | |
| Station 42 | | | | | | |
| June 29 | 14:00 | 0 | 19.1 | 10.1 | 112 | 8.3 |
| | | 5 | 19.1 | 8.4 | 94 | 8.3 |
| | | 8 | 16.9 | 6.4 | 93 | 8.3 |
| July 18 | 11:00 | 0 | 20.1 | 9.1 | 103 | 8.4 |
| | | 5 | 20.1 | 9.1 | 103 | 8.4 |
| | | 9 | 18.3 | 8.9 | 97 | 8.3 |
| August 10 | 11:00 | 0 | 21.0 | 8.5 | 98 | 8.3 |
| | | 5 | 21.0 | 8.6 | 99 | 8.3 |
| | | 9 | 20.9 | 8.5 | 98 | 8.3 |
| August 30 | 11:00 | 0 | 20.1 | 8.7 | 98 | 8.3 |
| | | 5 | 20.0 | 8.8 | 100 | 8.3 |
| | | 9 | 19.8 | 8.5 | 96 | 8.2 |
| September 21 | 10:30 | 0 | 13.9 | 9.3 | 93 | 8.1 |
| | | 5 | 13.9 | 9.0 | 90 | 8.0 |
| | | 9 | 13.9 | 8.6 | 86 | 8.0 |
| October 12 | 12:20 | 0 | 12.0 | 10.2 | 97 | 8.0 |
| | | 5 | 11.9 | 10.0 | 95 | 8.0 |
| | | 9 | 11.8 | 10.1 | 96 | 8.0 |
| October 30 | 11:30 | 0 | 10.5 | 9.5 | 88 | 7.9 |
| | | 5 | 10.5 | 9.7 | so | 8.0 |
| | | 10 | 9.5 | 9.7 | 88 | 7.9 |
| Station 45 | | | | | | |
| June 29 | 11:50 | 0 | 15.6 | 9.7 | 100 | 8.3 |
| | | 7 | 12.4 | 10.4 | 101 | 8.3 |
| | | 15 | 9.3 | 11.2 | 101 | 8.1 |
| July 18 | 9:00 | 0 | 17.0 | 9.2 | 98 | 8.3 |
| | | 5 | 17.0 | 9.2 | 98 | 8.3 |
| | | 15 | 13.4 | 10.1 | 100 | 8.3 |
| August 10 | 9:00 | 0 | 18.8 | 9.0 | 100 | 8.1 |
| | | 9 | 18.8 | 8.9 | 99 | 8.0 |
| | | 14 | 14.6 | 10.1 | 103 | 8.0 |
| August 30 | 9:00 | 0 | 19.1 | 8.9 | 99 | 8.3 |
| | | 5 | 19.1 | 9.0 | 100 | 8.3 |
| | | 14 | 15.2 | 9.6 | 98 | 8.1 |
| September 21 | 8:35 | 0 | 14.2 | 9.2 | 93 | 8.0 |
| | | 5 | 14.2 | 9.2 | 93 | 8.0 |
| | | 14 | 14.2 | 9.2 | 93 | 8.0 |
| October 12 | 10:15 | 0 | 11.5 | 9.9 | 94 | 7.9 |
| | | 5 | 11.6 | 10.0 | 95 | 7.8 |
| | | 17 | 11.6 | 10.1 | 96 | 1.8 |
| October 30 | 9:40 | 0 | 10.7 | 8.4 | 78 | 8.0 |
| | | 5 | 10.7 | 7.9 | 73 | 8.1 |
| | | 15 | 10.4 | 8.5 | 78 | 7.8 |
| Station 60 | | | | | | |
| June | 11:00 | 0 | 18.3 | 9.1 | 99 | 8.1 |
| | | 5 | 16.2 | 8.8 | 92 | 8.1 |
| | | 10 | 13.3 | 1.3 | 72 | 7.9 |
| June 20 | 13:30 | 0 | 19.9 | 7.8 | 86 | 8.1 |
| | | 4 | 19.8 | 7.1 | 86 | 8.1 |
| | | 9 | 16.0 | 6.3 | 66 | 7.9 |
| July 1 | 10:45 | 0 | 19.5 | 9.5 | 106 | 8.3 |
| | | 5 | 18.8 | 8.6 | 95 | 8.3 |
| | | 9 | 15.8 | 9.5 | 98 | 6.3 |
| July 12 | 15:15 | 0 | 19.2 | 9.1 | 102 | 8.4 |
| | | 5 | 18.6 | 8.9 | 98 | 8.4 |
| | | 9 | 11.8 | 8.4 | 92 | 8.3 |
| July 22 | 11:00 | 0 | 20.6 | 8.6 | 99 | 6.2 |
| | | 5 | 20.6 | 8.5 | 97 | 8.2 |
| | | 10 | 19.1 | 8.2 | 92 | 8.0 |

Continued

Table 1. (Continued)

| Station and date | Time (EST) | Depth (meters) | Temperature (°C) | Dissolved oxygen ppm | Dissolved oxygen percentage saturation | pH |
|---|---|---|---|---|---|---|
| August 1 | 10:20 | 0 | 21.1 | 8.0 | 92 | 8.2 |
| | | 5 | 20.9 | 8.0 | 92 | 8.2 |
| | | 10 | 20.8 | 7.8 | 89 | 8.2 |
| August 12 | 11:30 | 0 | 22.0 | 8.3 | 98 | 8.3 |
| | | 5 | 21.4 | 8.6 | 100 | 8.3 |
| | | 10 | 21.3 | 8.3 | 97 | 8.2 |
| August 22 | 12:10 | 0 | 20.3 | 8.5 | 97 | 8.3 |
| | | 5 | 20.3 | 8.3 | 95 | 8.3 |
| | | 9 | 20.2 | 8.3 | 95 | 8.3 |
| September 1 | 11:20 | 0 | 20.3 | 8.7 | 100 | 8.3 |
| | | 5 | 20.3 | 8.7 | 100 | 8.3 |
| | | 9 | 18.1 | 1.2 | 80 | 8.1 |
| September 12 | 12:00 | 0 | 19.0 | 8.6 | 96 | 8.1 |
| | | 5 | 18.7 | 8.6 | 95 | 8.1 |
| | | 10 | 18.5 | 8.3 | 92 | 8.1 |
| September 23 | 11:30 | 0 | 15.0 | 8.9 | 92 | 8.1 |
| | | 4 | 15.0 | 8.5 | 87 | 8.1 |
| | | 9 | 15.0 | 8.9 | 92 | 8.1 |
| October 3 | 12:35 | 0 | 15.0 | 9.2 | 94 | 8.2 |
| | | 5 | 14.7 | 9.6 | 98 | 8.1 |
| | | 9 | 14.6 | 9.3 | 94 | 8.1 |
| October 13 | 12:30 | 0 | 12.5 | 9.4 | 91 | 8.0 |
| | | | 12.4 | 9.4 | 91 | 8.0 |
| | | 10 | 12.0 | 8.8 | 84 | 8.0 |
| November 3 | 13:50 | 0 | 12.2 | 8.6 | 83 | 8.0 |
| | | 5 | 12.1 | 8.5 | 82 | 7.9 |
| | | 10 | 12.0 | 8.6 | 82 | 7.9 |
| November 14 | 12:15 | 0 | 8.3 | 10.4 | 92 | 8.0 |
| | | 5 | 8.2 | 10.6 | 93 | 8.0 |
| | | 9 | 7.9 | 10.3 | 89 | 8.0 |
| Station 61 | | | | | | |
| June 10 | 9:00 | 0 | 15.2 | 10.4 | 106 | 8.1 |
| | | 5 | 10.4 | 11.3 | 104 | 8.1 |
| | | 10 | 8.2 | 11.7 | 103 | 8.0 |
| June 20 | 16:15 | 0 | 17.4 | 9.2 | 98 | 8.3 |
| | | 5 | 17.3 | 9.2 | 98 | 8.3 |
| | | 14 | 13.8 | 9.3 | 93 | 8.3 |
| July 1 | 9:00 | 0 | 16.0 | 9.7 | 102 | 8.3 |
| | | 5 | 15.6 | 9.8 | 102 | 8.3 |
| | | 14 | 8.2 | 11.4 | 100 | 8.1 |
| July 12 | 17:20 | 0 | 16.9 | 9.4 | 99 | 8.3 |
| | | 5 | 16.8 | 9.5 | 100 | 8.3 |
| | | 14 | 1.7 | 11.0 | 96 | 8.1 |
| July 22 | 9:00 | 0 | 19.2 | 8.8 | 98 | 8.3 |
| | | 9 | 18.8 | 9.1 | 100 | 8.3 |
| | | 14 | 16.2 | 9.3 | 97 | 8.0 |
| August 1 | 12:30 | 0 | 19.3 | 9.1 | 101 | 8.2 |
| | | 5 | 19.3 | 9.1 | 101 | 8.1 |
| | | 14 | 18.8 | 9.0 | 100 | 8.1 |
| August 12 | 9:00 | 0 | 19.9 | 8.9 | 101 | 8.2 |
| | | 5 | 19.1 | 8.9 | 99 | 8.1 |
| | | 14 | 11.1 | 10.9 | 102 | 8.0 |
| August 22 | 14:10 | 0 | 19.4 | 9.0 | 101 | 8.3 |
| | | 5 | 19.4 | 9.0 | 101 | 8.3 |
| | | 14 | 16.6 | 9.4 | 100 | 8.3 |
| September 1 | 9:30 | 0 | 19.8 | 8.9 | 100 | 8.1 |
| | | 5 | 19.6 | 8.7 | 98 | 8.1 |
| | | 10 | 16.4 | 9.1 | 97 | 8.1 |
| September 12 | 14:00 | 0 | 17.7 | 9.1 | 98 | 8.2 |
| | | 5 | 17.2 | 9.3 | 99 | 8.2 |
| | | 15 | 14.3 | 9.8 | 98 | 8.1 |

Continued

Table 1. (Continued)

| Station and date | Time (EST) | Depth (meters) | Temperature (°C) | Dissolved Oxygen ppm | Dissolved Oxygen percentage saturation | pH |
|---|---|---|---|---|---|---|
| September 23 | 9:40 | 0 | 14.4 | 8.6 | 87 | 8.1 |
| | | 5 | 14.4 | 8.7 | 88 | 8.1 |
| | | 14 | 14.4 | 9.0 | 92 | 8.1 |
| October 3 | 14:45 | 0 | 14.2 | 9.8 | 98 | 8.0 |
| | | 5 | 14.0 | 10.2 | 101 | 8.1 |
| | | 14 | 14.2 | 9.9 | 100 | 8.0 |
| October 13 | 10:15 | 0 | 11.8 | 10.3 | 98 | 7.9 |
| | | 5 | 11.8 | 10.3 | 98 | 7.8 |
| | | 16 | 11.7 | 10.3 | 98 | 7.8 |
| November 3 | 9:30 | 0 | 11.5 | 9.8 | 93 | 8.0 |
| | | 5 | 11.4 | 9.7 | 92 | 8.0 |
| | | 14 | 11.4 | 9.4 | 89 | 8.0 |
| November 14 | 15:10 | 0 | 7.8 | 10.0 | 87 | 8.0 |
| | | 5 | 7.1 | 10.0 | 87 | 8.0 |
| | | 15 | 7.6 | 10.3 | 88 | 8.0 |
| Station 62 | | | | | | |
| June | 17:00 | 0 | 9.2 | 11.5 | 103 | 7.9 |
| | | 15 | 7.1 | 11.9 | 102 | 7.9 |
| | | 30 | 6.9 | 11.9 | 102 | 7.9 |
| June 21 | 9:30 | 0 | 17.7 | 9.1 | 98 | 8.1 |
| | | 15 | 8.2 | 12.1 | 107 | 8.1 |
| | | 30 | 5.8 | 11.7 | 97 | 1.9 |
| July 13 | 9:40 | 0 | 16.2 | 9.5 | 100 | 8.3 |
| | | 15 | 10.3 | 11.0 | 102 | 8.3 |
| | | 30 | 5.4 | 11.3 | 93 | 7.9 |
| August 2 | 9:40 | 0 | 17.5 | 9.4 | 102 | 7.9 |
| | | 15 | 16.3 | 9.7 | 102 | 7.9 |
| | | 30 | 10.8 | 11.6 | 108 | 7.8 |
| August 24 | 10:40 | 0 | 18.2 | 9.1 | 99 | 8.2 |
| | | 15 | 18.1 | 9.1 | 99 | 8.2 |
| | | 30 | 9.6 | 11.0 | 100 | 1.9 |
| September 13 | 9:20 | 0 | 17.1 | 9.1 | 98 | 8.1 |
| | | 15 | 15.6 | 9.4 | 91 | 8.1 |
| | | 30 | 7.8 | 11.0 | 96 | 7.6 |
| October 5 | 9:30 | 0 | 13.2 | 10.0 | 98 | 8.1 |
| | | 15 | 13.2 | 10.0 | 98 | 8.1 |
| | | 30 | 13.2 | 9.8 | 96 | 8.0 |
| October 27 | 9:30 | 0 | 11.4 | 9.6 | 91 | 8.0 |
| | | 15 | 11.4 | 9.6 | 91 | 8.0 |
| | | 30 | 11.4 | 9.7 | 91 | 8.0 |

Table A-2. Chemical characteristics of Saginaw Bay, June 1, 1956

| Station | Depth (meters) | Calcium (ppm) | Magnesium (ppm) | Potassium (ppm) | Sodium (ppm) | Total alkalinity (ppm CaCO$_3$) | Phosphorus (ppm) | Sulfate (ppm) | Specific conductance (μmhos 18°C) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 56 | 11.1 | 3.5 | 14.0 | 142 | 0.054 | 41 | 530 |
| 2 | 0 | 59 | 12.5 | 4.3 | 18.6 | 142 | 0.050 | 41 | 629 |
| 3 | 0 | 71 | 13.0 | 5.1 | 23.8 | 144 | 0.066 | 43 | 702 |
| 4 | 0 | 80 | 13.3 | 5.5 | 25.0 | 144 | 0.068 | 42 | 800 |
| 5 | 0 | 54 | 11.1 | 3.6 | 11.0 | 120 | 0.049 | 27 | 536 |
| 6 | 0 | 55 | 10.1 | 3.1 | 11.0 | 118 | 0.045 | 23 | 537 |
| 1 | 0 | 55 | 11.1 | 3.8 | 16.7 | 118 | 0.045 | 23 | 546 |
| 8 | 0 | 49 | 9.9 | 2.9 | 13.8 | 116 | 0.047 | 21 | 462 |
| 9 | 0 | 54 | 11.3 | 3.8 | 13.5 | 131 | 0.039 | 37 | 550 |
| 10 | 0 | 63 | 12.0 | 4.2 | 16.2 | 140 | 0.041 | 38 | 591 |
| 11 | 0 | 68 | 12.4 | 4.4 | 18.2 | 135 | 0.046 | 37 | 632 |
| 12 | 0 | 52 | 11.8 | 4.2 | 16.8 | 137 | 0.044 | 36 | 585 |
| 13 | 0 | 59 | 12.3 | 3.7 | 15.9 | 130 | 0.052 | 31 | 587 |
| 14 | 0 | 56 | 11.2 | 3.1 | 16.4 | 130 | 0.043 | 28 | 549 |
| 15 | 0 | 52 | 9.1 | 3.1 | 16.1 | 129 | 0.042 | 23 | 517 |
| 16 | 0 | 43 | 9.9 | 2.6 | 12.6 | 110 | 0.038 | 19 | 443 |
| 17 | 0 | 42 | 11.1 | 2.5 | 11.5 | 106 | 0.028 | 17 | 396 |
| 18 | 0 | 38 | 9.7 | 1.9 | 9.7 | 106 | 0.021 | 14 | 367 |
| 19 | 0 | 39 | 9.2 | 1.8 | 8.1 | 106 | 0.024 | 17 |  |
| 21 | 0 | 52 | 10.1 | 3.4 | 14.5 | 113 | 0.043 | 33 | 520 |
| 22 | 0 | 58 | 11.4 | 4.0 | 19.0 | 109 | 0.019 | 28 | 561 |
| 23 | 0 | 61 | 11.6 | 4.3 | 21.3 | 112 | 0.016 | 29 | 629 |
| 24 | 0 | 53 | 10.3 | 3.8 | 18.0 | 98 | 0.014 | 21 | 542 |
| 25 | 0 | 51 | 10.6 | 3.5 | 11.2 | 109 | 0.022 | 21 | 523 |
| 26 | 0 | 48 | 10.1 | 3.1 | 15.0 | 112 | 0.019 | 24 | 491 |
| 27 | 0 | 43 | 9.5 | 2.6 | 12.0 | 91 | 0.018 | 17 | 442 |
| 28 | 0 | 41 | 9.4 | 2.2 | 11.2 | 111 | 0.019 | 18 | 413 |
| 29 | 0 | 41 | 9.2 | 2.0 | 10.7 | 106 | 0.033 | 18 | 400 |
| 30 | 0 | 52 | 10.3 | 3.1 | 18.0 | 113 | 0.019 | 24 | 553 |
| 31 | 0 | 58 | 10.3 | 3.2 | 14.3 | 122 | 0.020 | 36 | 532 |
| 32 | 0 | 50 | 11.0 | 3.1 | 15.1 | 115 | 0.021 | 21 | 520 |
| 33 | 0 | 38 | 9.8 | 2.1 | 10.1 | 99 | 0.018 | 15 | 383 |
| 34 | 0 | 34 | 8.5 | 1.6 | 7.6 | 94 | 0.016 | 13 | 328 |
| 35 | 0 | 41 | 8.6 | 4.2 | 11.2 | 100 | 0.016 | 15 | 426 |
| 36 | 0 | 41 | 10.6 | 2.4 | 11.2 | 104 | 0.015 | 11 | 422 |
| 37 | 0 | 45 | 9.9 | 2.8 | 14.6 | 108 | 0.018 | 19 | 464 |
| 38 | 0 | 40 | 9.6 | 2.4 | 11.6 | 101 | 0.018 | 18 | 421 |
| 39 | 0 | 40 | 9.7 | 2.1 | 10.4 | 99 | 0.019 | 16 | 396 |
| 41 | 0 | 43 | 9.0 | 2.3 | 10.1 | 103 | 0.018 | 16 | 394 |
| 42 | 0 | 36 | 8.9 | 1.8 | 9.1 | 102 | 0.009 | 11 | 358 |
| 42a | 0 | 25 | 1.4 | 1.1 | 4.6 | 98 | 0.010 | 15 | 211 |
| 43 | 0 | 29 | 8.2 | 1.3 | 5.1 | 100 | 0.011 | 13 | 288 |
| 44 | 0 | 35 | 1.1 | 1.4 | 5.8 | 100 | 0.009 | 13 | 299 |
| 45 | 0 | 30 | 1.3 | 1.0 | 3.8 | 93 | 0.014 | 11 | 255 |
|  | 16 | 21 | 7.3 | 1.8 | 3.3 | 91 | 0.018 | 11 | 226 |
| 46 | 0 | 29 | 1.3 | 0.9 | 2.4 | 93 | 0.011 | 10 | 231 |
|  | 14 | 27 | 7.1 | 0.8 | 2.7 | 95 | 0.016 | 8 | 237 |
| 47 | 0 | 31 | 6.9 | 1.8 | 3.8 | 100 | 0.012 | 13 | 265 |
| 48 | 0 | 35 | 9.2 | 1.1 | 6.4 | 100 | 0.016 | 14 | 308 |
| 49 | 0 | 40 | 9.2 | 2.4 | 8.1 | 100 | 0.012 | 15 | 347 |
| 49a | 0 | 34 | 10.6 | 1.1 | 4.8 | 94 | 0.016 | 13 | 218 |
| 50 | 0 | 28 | 10.2 | 1.3 | 3.0 | so | 0.013 | 11 | 234 |
|  | 28 | 32 | 1.2 | 2.5 | 2.1 | 96 | 0.019 | 8 | 224 |
| 50a | 0 | 27 | 7.3 | 0.9 | 2.6 | 94 | 0.014 | 11 | 206 |
| 51 | 0 | 21 | 7.0 | 2.1 | 2.3 | 92 | 0.015 | 9 | 221 |
|  | 26 | 26 | 6.8 | 0.8 | 2.4 | 91 | 0.010 | 9 | 227 |
| 51a | 0 | 21 | 7.0 | 1.5 | 2.4 | 100 | 0.010 | 9 | 217 |
| 52 | 0 | 28 | 8.0 | 0.9 | 2.4 | 94 | 0.012 | 9 | 233 |
| 53 | 0 | 29 | 9.6 | 1.1 | 2.7 | 92 | 0.009 | 9 | 238 |

Table A-3. Chemical characteristics of Saginaw Bay, August 10,1956

| Station | Depth (meters) | Calcium (ppm) | Magnesium (ppm) | Potassium (ppm) | Sodium (ppm) | Total alkalinity (ppm $CaCO_3$) | Phospohrus (ppm) | Sulfate (ppm) | Specific conductance (μmhos 18°C) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 51 | 11.1 | 3.5 | 18.8 | 120 | 0.060 | 21 | 510 |
| 2 | 0 | 51 | 16.1 | 3.6 | 21.8 | 119 | 0.049 | 28 | 557 |
| 3 | 0 | 52 | 10.9 | 3.6 | 21.8 | 113 | 0.038 | 27 | 559 |
| 5 | 0 | 42 | 9.0 | 2.4 | 11.1 | 119 | 0.030 | 18 | 411 |
| 6 | 0 | 46 | 9.8 | 3.2 | 14.6 | 110 | 0.032 | 21 | 456 |
| 1 | 0 | 49 | 10.0 | 3.0 | 18.8 | 111 | 0.048 | 23 | 482 |
| 8 | 0 | 41 | 10.4 | 3.0 | 19.9 | 112 | 0.040 | 24 | 512 |
| 9 | 0 | 48 | 10.6 | 3.4 | 19.0 | 100 | 0.045 | 21 | 525 |
| 10 | 0 | 44 | 10.0 | 4.5 | 15.2 | 118 | 0.046 | 23 | 448 |
| 11 | 0 | 44 | 10.4 | 3.5 | 16.0 | 117 | 0.039 | 22 | 456 |
| 12 | 0 | 43 | 10.5 | 2.6 | 15.2 | 113 | 0.044 | 24 | 440 |
| 13 | 0 | 38 | 9.3 | 1.8 | 10.4 | 110 | 0.029 | 17 | 369 |
| 14 | 0 | 38 | 9.6 | 2.1 | 10.6 | 115 | 0.028 | 11 | 313 |
| 15 | 0 | 38 | 9.8 | 1.9 | 10.0 | 115 | 0.024 | 17 | 373 |
| 16 | 0 | 43 | 10.5 | 2.4 | 14.2 | 124 | 0.029 | 19 | 433 |
| 11 | 0 | 47 | 10.1 | 4.4 | 18.4 | 123 | 0.029 | 23 | 486 |
| 18 | 0 | 48 | 11.4 | 3.0 | 20.3 | 113 | 0.032 | 23 | 510 |
| 19 | 0 | 44 | 10.0 | 2.5 | 14.3 | 108 | 0.025 | 20 | 433 |
| 21 | 0 | 39 | 9.9 | 2.1 | 10.9 | 109 | 0.050 | 19 | 394 |
| 22 | 0 | 40 | 8.6 | 2.1 | 9.5 | 112 | 0.034 | 20 | 383 |
| 23 | 0 | 37 | 8.5 | 2.0 | 1.8 | 110 | 0.040 | 16 | 333 |
| 24 | 0 | 35 | 8.2 | 2.0 | 6.0 | 110 | 0.034 | 14 | 315 |
| 25 | 0 | 36 | 8.5 | 1.9 | 8.3 | 101 | 0.025 | 17 | 339 |
| 26 | 0 | 31 | 8.8 | 2.3 | 8.3 | 108 | 0.084 | 16 | 348 |
|  | 10 | 36 | 9.2 | 1.6 | 8.0 | 99 | 0.022 | 15 | 349 |
| 21 | 0 | 44 | 10.4 | 2.9 | 13.1 | 118 | 0.023 | 21 | 450 |
|  | 7 | 41 | 9.6 | 2.8 | 12.0 | 109 | 0.035 | 21 | 433 |
| 28 | 0 | 40 | 9.1 | 4.5 | 11.1 | 114 | 0.037 | 19 | 416 |
| 29 | 0 | 38 | 9.3 | 3.1 | 11.2 | 109 | 0.027 | 18 | 421 |
| 30 | 0 | 42 | 10.0 | 2.5 | 13.1 | 108 | 0.050 | 21 | 441 |
| 31 | 0 | 44 | 10.4 | 3.0 | 13.9 | 121 | 0.014 | 23 | 483 |
| 32 | 0 | 41 | 9.1 | 2.5 | 12.2 | 115 | 0.038 | 22 | 420 |
| 33 | 0 | 37 | 8.5 | 2.1 | 10.0 | 112 | 0.037 | 17 | 311 |
| 34 | 0 | 35 | 9.1 | 4.0 | 1.1 | 110 | 0.015 | 16 | 352 |
| 35 | 0 | 32 | 8.5 | 1.5 | 6.4 | 101 | 0.031 | 16 | 310 |
| 36 | 0 | 31 | 9.0 | 1.6 | 5.4 | 104 | 0.039 | 13 | 292 |
|  | 8 | 32 | 1.5 | 1.6 | 5.6 | 99 | 0.015 | 14 | 298 |
| 37 | 0 | 34 | 9.0 | 1.5 | 6.5 | 110 | 0.026 | 15 | 310 |
|  | 9 | 30 | 8.8 | 1.4 | 5.4 | 97 | 0.017 | 13 | 290 |
| 38 | 0 | 38 | 9.1 | 2.0 | 8.6 | 111 | 0.025 | 11 | 361 |
| 39 | 0 | 39 | 8.8 | 2.9 | 8.2 | 111 | 0.023 | 21 | 311 |
| 41 | 0 | 35 | 1.8 | 1.5 | 5.0 | 102 | 0.032 | 14 | 280 |
| 42 | 0 | 31 | 1.6 | 1.5 | 4.9 | 99 | 0.019 | 13 | 280 |
|  | 5 | 31 | 8.3 | 1.5 | 4.8 | 99 | 0.017 | 13 | 282 |
|  | 9 | 31 | 8.5 | 1.4 | 5.5 | 100 | 0.014 | 13 | 280 |
| 42a | 0 | 32 | 8.3 | 1.6 | 5.3 | 101 | 0.016 | 13 | 293 |
| 43 | 0 | 31 | 1.5 | 1.2 | 4.5 | 96 | 0.012 | 12 | 272 |
| 44 | 0 | 28 | 6.9 | 1.5 | 3.9 | 96 | 0.009 | 12 | 253 |
| 45 | 0 | 28 | 1.0 | 0.9 | 2.8 | 96 | 0.014 | 11 | 232 |
|  | 9 | 27 | 7.3 | 0.8 | 2.8 | 100 | 0.015 | 10 | 233 |
|  | 14 | 26 | 1.0 | 1.0 | 2.6 | 95 | 0.051 | 10 | 220 |
| 46 | 0 | 30 | 7.8 | 1.1 | 4.2 | 108 | 0.031 | 13 | 214 |
| 41 | 0 | 32 | 7.3 | 1.2 | 4.8 | 113 | 0.069 | 14 | 280 |
| 48 | 0 | 32 | 8.1 | 1.2 | 4.7 | 100 | 0.041 | 13 | 280 |
| 49 | 0 | 29 | 1.6 | 1.5 | 3.6 | 100 | 0.028 | 11 | 256 |
| 49a | 0 | 27 | 7.6 | 1.1 | 2.6 | 98 | 0.009 | 10 | 228 |
| 50 | 0 | 27 | 7.1 | 1.2 | 2.3 | 98 | 0.008 | 11 | 223 |
|  | 24 | 21 | 7.1 | 0.9 | 2.2 |  | 0.012 | 10 | 217 |
| 50a | 0 | 21 | 1.4 | 1.0 | 3.0 | 106 | 0.010 | 11 | 246 |
| 51 | 0 | 21 | 1.6 | 1.0 | 3.1 | 109 | 0.009 | 10 | 243 |
|  | 23 | 26 | 7.4 | 1.0 | 2.1 | 111 | 0.012 | 9 | 222 |
| 51a | 0 | 29 | 1.8 | 1.2 | 3.3 | 100 | 0.011 | 11 | 252 |
| 52 | 0 | 21 | 1.0 | 1.6 | 2.1 | 98 | 0.051 | 10 | 239 |
| 53 | 0 | 21 | 1.0 | 1.3 | 2.7 | 99 | 0.053 | 11 | 232 |

Table A-4. Chemical characteristics of Saginaw Bay, October 30, 1956

| Station | Depth (meters) | Calcium (ppm) | Magnesium (Ppm) | Potassium (ppm) | Sodium (Ppm) | Total alkalinity (Ppm Ca $CO_3$) | Phosphorus (Ppm) | Sulfate (ppm) | Specific conductance (µmhos 18°C) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 39 | 10.1 | 2.3 | 13.1 | 107 | 0.031 | 15 | 402 |
| 2 | 0 | 43 | 10.5 | 2.7 | 16.1 | 115 | 0.037 | 19 | 440 |
|  | 3 | 41 | 9.7 | 2.4 | 16.1 | 115 | 0.045 | 19 |  |
| 3 | 0 | 46 | 10.1 | 2.7 | 15.7 | 112 | 0.043 | 20 | 452 |
| 4 | 0 | 45 | 10.1 | 1.5 | 16.7 | 122 | 0.044 | 19 | 475 |
| 5 | 0 | 36 | 8.8 | 1.5 | 7.2 | 102 | 0.031 | 12 | 320 |
|  | 4 | 34 | 9.0 | 1.4 | 7.5 | 104 | 0.025 | 11 |  |
| 6 | 0 | 37 | 9.5 | 2.1 | 11.6 | 108 | 0.068 | 16 | 393 |
| 7 | 0 | 39 | 9.7 | 2.3 | 14.5 | 113 | 0.052 | 16 | 410 |
|  | 6 | 42 | 10.0 | 2.2 | 15.0 | 111 | 0.057 | 17 |  |
| 8 | 0 | 44 | 10.4 | 2.2 | 16.8 | 113 | 0.029 | 19 | 429 |
| 9 | 0 | 41 | 9.2 | 2.3 | 12.3 | 116 | 0.051 | 18 | 421 |
| 10 | 0 | 40 | 9.5 | 3.0 | 12.2 | 116 | 0.035 | 17 | 400 |
| 11 | 0 | 38 | 9.2 | 1.9 | 10.4 | 115 | 0.039 | 17 | 369 |
| 12 | 0 | 31 | 8.7 | 1.6 | 9.1 | 123 | 0.040 | 15 | 355 |
| 13 | 0 | 33 | 8.1 | 1.5 | 6.3 | 102 | 0.028 | 13 | 305 |
| 14 | 0 | 32 | 7.6 | 1.3 | 5.1 | 103 | 0.024 | 12 | 284 |
| 15 | 0 | 33 | 8.5 | 1.4 | 5.7 | 103 | 0.023 | 12 | 304 |
|  | 7 | 33 | 8.7 | 1.4 | 6.3 | 101 | 0.029 | 13 |  |
| 16 | 0 | 38 | 8.7 | 1.8 | 8.6 | 108 | 0.054 | 15 | 360 |
|  | 7 | 38 | 9.1 | 1.7 | 8.4 | 112 | 0.054 | 15 |  |
| 17 | 0 | 39 | 9.4 | 1.9 | 9.7 | 109 | 0.053 | 15 | 375 |
|  | 6 | 39 | 9.8 | 2.6 | 10.0 | 110 | 0.051 | 15 |  |
| 18 | 0 | 44 | 9.9 | 2.2 | 17.0 | 109 | 0.049 | 18 | 451 |
| 19 | 0 | 45 | 9.5 | 2.3 | 19.0 | 112 | 0.064 | 19 | 475 |
| 21 | 0 | 41 | 9.8 | 2.4 | 13.1 | 112 | 0.037 | 17 | 421 |
| 22 | 0 | 40 | 10.0 | 2.5 | 14.2 | 112 | 0.036 | 18 | 401 |
| 23 | 0 | 34 | 7.8 | 2.0 | 7.3 | 111 | 0.034 | 13 | 315 |
| 24 | 0 | 34 | 8.1 | 1.5 | 6.9 | 99 | 0.031 | 14 | 315 |
| 25 | 0 | 32 | 8.3 | 1.4 | 6.0 | 100 | 0.027 | 12 | 295 |
| 26 | 0 | 32 | 8.3 | 1.3 | 6.0 | 100 | 0.025 | 12 | 295 |
| 27 | 0 | 38 | 8.9 | 1.7 | 9.5 | 113 | 0.043 | 16 | 369 |
| 28 | 0 | 35 | 8.6 | 1.6 | 8.1 | 114 | 0.027 | 14 | 327 |
| 29 | 0 | 34 | 8.8 | 1.2 | 6.5 | 110 | 0.026 | 13 | 395 |
| 30 | 0 | 44 | 10.2 | 2.8 | 14.5 | 112 | 0.039 | 21 | 438 |
| 31 | 0 | 39 | 9.8 | 2.0 | 10.9 | 103 | 0.029 | 15 | 378 |
| 32 | 0 | 41 | 9.7 | 2.1 | 12.6 | 114 | 0.026 | 19 | 401 |
| 33 | 0 | 39 | 9.0 | 2.0 | 10.8 | 107 | 0.049 | 15 | 383 |
| 34 | 0 | 32 | 8.6 | 1.8 | 6.3 | 108 | 0.026 | 13 | 368 |
| 35 | 0 | 33 | 8.8 | 3.6 | 6.5 | 103 | 0.017 | 13 | 294 |
| 36 | 0 | 33 | 8.8 | 2.2 | 6.5 | 106 | 0.026 | 13 | 295 |
|  | 9 | 33 | 8.3 | 1.5 | 1.1 | 103 | 0.021 | 12 |  |
| 37 | 0 | 31 | 8.8 | 1.2 | 6.3 | 104 | 0.016 | 12 | 285 |
|  | 10 | 31 | 8.1 | 1.5 | 5.3 | 97 | 0.022 | 10 |  |
| 38 | 0 | 31 | 8.3 | 1.2 | 6.2 | 106 | 0.021 | 11 | 285 |
| 39 | 0 | 31 | 8.6 | 1.8 | 7.1 | 108 | 0.025 | 15 | 305 |
| 41 | 0 | 29 | 9.5 | 1.2 | 5.2 | 92 | 0.019 | 11 | 249 |
| 42 | 0 | 26 | 8.1 | 1.3 | 2.5 | 84 | 0.015 | 10 | 216 |
|  | 5 | 26 | 7.9 | 0.8 | 2.6 | 92 | 0.012 | 9 |  |
|  | 10 | 26 | 10.5 | 0.8 | 2.5 | 88 | 0.013 | 8 |  |
| 42a | 0 | 26 | 7.7 | 0.9 | 2.3 | 84 | 0.013 | 10 | 216 |
| 43 | 0 | 26 | 7.9 | 0.8 | 2.5 | 92 | 0.015 | 9 | 218 |
| 44 | 0 | 28 | 7.8 | 0.9 | 3.4 | 95 | 0.018 | 10 | 239 |
| 45 | 0 | 25 | 9.0 | 1.3 | 2.4 | 93 | 0.015 | 10 | 317 |
|  | 5 | 26 | 7.7 | 0.9 | 2.6 | 93 | 0.014 | 9 |  |
|  | 15 | 25 | 7.9 | 0.9 | 2.7 | 99 | 0.016 | 9 |  |
| 46 | 0 | 26 | 7.7 | 0.9 | 3.2 | 92 | 0.025 | 11 | 221 |
| 47 | 0 | 32 | 9.3 | 1.8 | 6.1 | 102 | 0.028 | 13 | 296 |
| 48 | 0 | 27 | 1.1 | 1.0 | 2.9 | 86 | 0.013 | 10 | 227 |
| 49 | 0 | 26 | 7.7 | 0.9 | 2.3 | 92 | 0.013 | 8 | 215 |
| 49a | 0 | 26 | 6.8 | 0.9 | 2.0 | 93 | 0.014 | 10 | 217 |
| 50 | 0 | 26 | 7.4 | 0.9 | 2.2 | 93 | 0.012 | 9 | 216 |
|  | 26 | 26 | 6.9 | 0.8 | 2.3 | 90 | 0.013 | 9 |  |
| 50a | 0 | 26 | 7.6 | 0.8 | 2.6 | 92 | 0.013 | 9 | 216 |
| 51 | 0 | 27 | 1.2 | 0.9 | 3.2 | 98 | 0.015 | 9 | 260 |
|  | 25 | 26 | 7.6 | 1.2 | 2.6 | 92 | 0.012 | 9 |  |
| 51a | 0 | 26 | 7.4 | 0.8 | 2.6 | 92 | 0.011 | 8 | 222 |
| 52 | 0 | 27 | 1.7 | 0.8 | 3.4 | 93 | 0.018 | 10 | 227 |
| 53 | 0 | 28 | 7.6 | 1.7 | 3.7 | 101 | 0.020 | 10 | 248 |

Table A-5. Mean discharge and chemical composition of three of the larger secondary tributaries to Saginaw Bay

[Discharge is for the water year Oct. 1955 through Sept. 19561

| River | Calcium (ppm) | Sodium (ppm) | Chloride (ppm) | Sulfate (ppm) | Silica (ppm) | Specific conductance (µmhos 18°C) | Mean flow (cfs) |
|---|---|---|---|---|---|---|---|
| Au Gres | 51 | 3.6 | 7.3 | 100 | 5.8 | 315 | 146 |
| Kawkawlin | 53 | 8.7 | 22.2 | 73 | 3.8 | 332 | 53 |
| Rifle | 34 | 4.5 | 10.0 | 36 | 7.0 | 230 | 230 |

Table A-6. Saginaw River flow and average sodium content, 1956

| Date | Average discharge (million cu. ft. Per day) | Average sodium [1] (ppm) | Average chloride [2] (ppm) |
|---|---|---|---|
| May O-June 7 | 993 | 46 | 152 |
| July 12-August 10 | 186 | 70 | 280 |
| October 1-31 | 86 | 82 | 346 |
| Annual average | 292 | 70 | 280 |

[1] Calculated from chloride values.

[2] Average chloride, Dow Chemical Co. data, 1956.

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