CHANGES IN CHLORIDE CONCENTRATIONS, MIXING PATTERNS, AND STRATIFICATION CHARACTERISTICS OF IRONDEQUOIT BAY, MONROE COUNTY, NEW YORK, AFTER DECREASED USE OF ROAD-DEICING SALTS, 1974-1984.

By Robert C. Bubeck and Richard S. Burton

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 87-4223

Prepared in cooperation with the

MONROE COUNTY DEPARTMENT OF HEALTH

Albany, New York

1989

DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR. Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

U.S. Geological Survey
P.O. Box 1669
Albany, New York 12201

Copies of this report may be purchased from:

U.S. Geological Survey
Books and Open-File Reports
Federal Center, Bldg. 41
Box 25425
Denver, Colorado 80225

CONTENTS

	Page
Abstract	1
Introduction	3
Deicing salts	3
Previous studies	3
Effects of deicing salts on Irondequoit Bay	4
Purpose and scope	4
Acknowledgments	5
Irondequoit drainage basin	5
Physiography and geology	5
Land use	6
Climate	6
Hydrology of Irondequoit Creek	7
Streamflow	7
Water quality	7
Limnology of Irondequoit Bay	9
Geomorphic features	9
Morphometry	10
Water quality	11
Stratification and mixing	13
Methods of study	17
Sampling sites	17
Field methods	17
Analytical methods	18
Changes resulting from decreased use of road-deicing salts	18
Chloride concentrations in the creek and bay	20
Irondequoit Creek	20
Irondequoit Bay	22
Mixing patterns of the bay	23
Spring mixing	23
Fall mixing	23
Stratification characteristics of the bay	26
Water temperature	26
Specific conductance	27
Dissolved oxygen	27
Chloride	28
Return of spring meromixis in 1984	44
Suggestions for further study	44
Summary and conclusions	45
References cited	48

ILLUSTRATIONS

Figure 1.--Map showing location and major geographic features of Irondequoit Bay drainage basin 2

2.--Photograph of Irondequoit Bay showing sediment plumes from Irondquoit Creek into bay and from bay into Lake Ontario, April 6, 1968 16

ILLUSTRATIONS (CONTINUED)

Page

Figures 3-7.--Graphs showing:

3.--Annual use of deicing salt in Irondequoit Creek basin, 1956-84. 18

4.--Total annual snowfall and annual use of deicing salt in Monroe County, 1965-84. 19

5.--Annual basin population, annual basin salt application, and chloride concentration during June-August in Irondequoit Creek, Irondequoit Bay, and Lake Ontario from the early 1900's through 1984. 21

6.--Vertical distribution of temperature, specific conductance, and chloride concentration in Irondequoit Bay, station 1: A. on August 9, 1971. B. on August 18, 1982 . . 28

7.--The vertical distribution of water temperature, specific conductance, dissolved oxygen, and chloride concentration in Irondequoit Bay at station 1, through calendar years 1978-84. 30

TABLES

Page

Table 1.--Chemical characteristics of composite water samples from Irondequoit Creek at Blossom Road, 1981 8

2.--Morphometric characteristics of Irondequoit Bay. 9

3.--Chemical quality of water at surface (0.5 meter) and at 22.5-meter depth in Irondequoit Bay, station 1, 1982. . . 12

4. Total snowfall and amount of deicing salt used in Monroe County and Irondequoit Bay drainage basin, 1965-84. 20

5.--Summary of the fall and spring mixing characteristics of Irondequoit Bay, including the chloride concentrations and amount of NaCl in the water column 24

PLATE

(in pocket)

Plate 1.--Bathymetric map of Irondequoit Bay showing locations of sampling stations and major geographic features.

CONVERSION FACTORS AND ABBREVIATIONS

For readers who prefer inch-pound units rather than the metric (International System) units used in this report, conversion factors are given below:

Multiply SI unit	by	To obtain inch-pound units
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter per second (m/s)	3.281	foot per second (ft/s)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
	1.196	square yard (yd^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
	1.308	cubic yard (yd^3)
liter (L)	1.057	quart (qt)
	Flow	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
milligram (mg)	0.0000353	ounce (oz)
gram (g)	0.0353	ounce (oz)
	0.0022	pound (lb)
kilogram (kg)	2.205	pound (lb)
metric ton	1.102	ton, short
	Temperature	
degree Celsius (°C)	(1.8 x °C) + 32°	degree Fahrenheit (°F)

Concentration

Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (μg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand μg/L is equivalent to 1 mg/L. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

National Geodetic Vertical Datum of 1929 (NGVD of 1929):

A Geodetic datum derived from a general adjustment of the first-order level nets of both the Unites States and Canada, formerly called "Mean Sea Level."

CHANGES IN CHLORIDE CONCENTRATIONS, MIXING PATTERNS, AND STRATIFICATION CHARACTERISTICS OF IRONDEQUOIT BAY, MONROE COUNTY, NEW YORK, AFTER DECREASED USE OF ROAD-DEICING SALTS, 1974-1984

By Robert C. Bubeck and Richard S. Burton*

Abstract

Extensive use of road-deicing salts in the drainage basin of Irondequoit Bay on the southern shore of Lake Ontario, changed the bay's chemical and thermal stratification and mixing patterns. The bay's 438-square-kilometer drainage basin contains urban, suburban, and rural land and is intersected by highways and roads that were heavily treated with deicing salts in the late 1960's and early 1970's. Irondequoit Creek, the major stream in the bay's drainage basin, receives most of the runoff containing these salts and discharges directly to the bay.

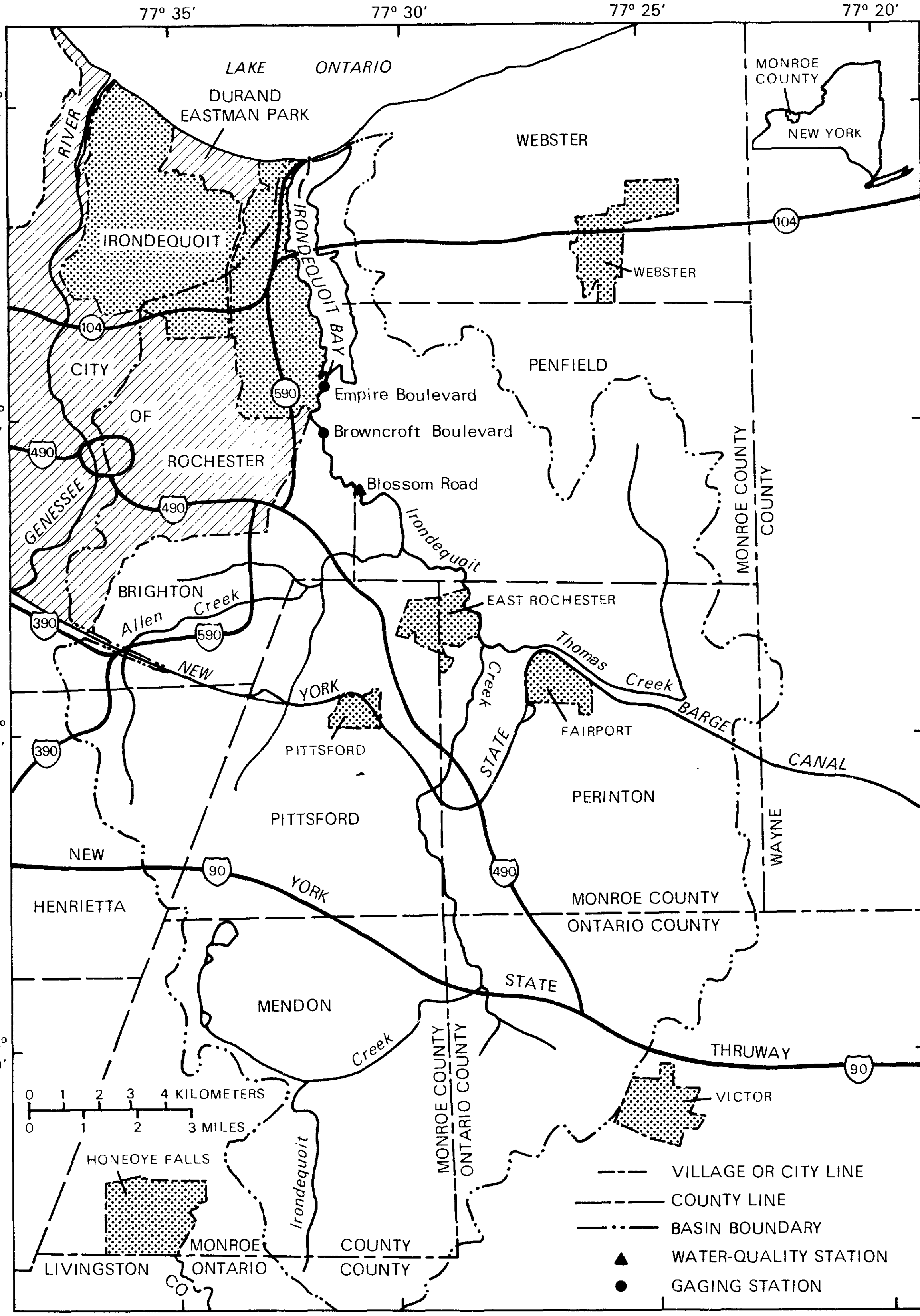
Studies in the early 1970's showed that summer chloride concentrations in Irondequoit Creek and in the surface water of the bay had increased fourfold since the 1950's and that winter concentrations in the creek reached 600 milligrams per liter. Runoff containing these elevated concentrations accumulated in the bottom water of the bay and caused a density gradient that prevented complete mixing each spring of 1970-73. As the chloride content increased, summer stratification and anoxic conditions in the bottom water continued later each fall.

The greatest amount of salt used in the basin was 76,600 metric tons during winter 1969-70. In the mid-1970's, Monroe County began a cooperative effort with towns in the county to decrease this amount. By winter 1974-75, the amount used had decreased by 54 percent and, in 1979-80, by 70 percent.

As a result of the decrease in salt application within the basin, the bay mixed completely in spring 1975 and did so each spring until 1984. The amount of chloride remaining in the bay after each spring mix decreased yearly until 1980-81, and fall mixing occurred earlier as the summer salt load in the bay decreased. By spring 1980, the salt load in the bay had decreased 53 percent below its greatest (spring 1972) load, and the bay continued its pre-1969 dimictic condition until spring 1984, when it failed to mix completely.

The amount of salt used annually in the basin increased during 1980-84 to 37,800 metric tons. Although this still represented a 51-percent net decrease from 1969-70, the salt load to the bay also increased during 1980-84, and some remained in the bay after each spring and fall mix. Salt entered the bay throughout the 1983-84 winter, but a larger-than-usual amount entered in late winter and caused a density gradient in the bay's bottom water that prevented complete spring mixing in 1984. Thus, incomplete spring mixing in 1984 was less a result of the amount of salt that entered the bay than of the time at which it entered. The bay remains susceptible to incomplete mixing in the spring and will continue to require prudent management of deicing-salt distribution in its drainage basin.

* Environmental Health Laboratory,
Monroe County Department of Health, Rochester, N.Y.



Base from U.S. Geological Survey
State base map, 1974

Figure 1.--Location and major geographic features of the Irondequoit Bay drainage basin.

INTRODUCTION

Irondequoit Bay, surrounded by the eastern suburbs of Rochester, N.Y., lies on the southern shore of Lake Ontario and is an important esthetic and recreational water resource for Monroe County (fig. 1). The principal tributary to the bay is Irondequoit Creek, which drains a 438-km^2 (square-kilometer) drainage basin that is characterized by urban and suburban areas, farms, and woodlands. The drainage basin is intersected by an expanding network of highways and roads. The bay has been culturally eutrophic for decades (primarily from sewage) and also is adversely affected by the accumulation of deicing salts used on roads since the 1950's.

Deicing Salts

Use of sodium and calcium chloride on highways and roads as deicing agents in winter is a common practice in the Great Lakes and northeastern regions of the United States. Chloride salts have been in use in this country since the early 1900's (Gupta and others, 1981), and their use has increased greatly in the latter half of this century. This use of salts has had a major effect on the chemical quality of streams, lakes, and ground water. The environmental, economic, and social effects of the use of deicing salts are discussed in Highway Research Board (1967, 1973) and U.S. Environmental Protection Agency (1971). The effects of deicing salts on water quality and biota are given by Westing (1969); Hanes and others (1970); Field and others, (1973); Hanes and others (1976); Crowther and Hynes (1977); and Molles (1980).

Adverse effects of deicing salts on water resources have been noted since the mid-1960's in many areas (Hutchinson, 1970). The effects on rivers and streams have been studied in urban basins near Chicago (Wulkowicz and Saleem, 1974) and Toronto (Scott, 1976; 1980); in the central Sierra Nevada Mountains in California (Hoffman and others, 1981); and the Mohawk River basin in upstate New York (Peters and Turk, 1981). Infiltration and percolation of road runoff containing deicing salt to ground water has been studied in Massachusetts (Huling and Hollocher, 1972; Pollock and Toler, 1973; Frost and others, 1981); near Indianapolis, Ind. (Dennis, 1973); in a northwestern Indiana peatland (Wilcox, 1986), and in western New York State (Davis, 1978). Adverse effects on the water quality and stratification of small lakes have been reported in Michigan (Judd, 1970); Wisconsin (Cherkauer and Ostenso, 1976); Ontario (Free and Mulamoottil, 1983); and to a minor extent in small lakes in the central Sierra Nevada, Calif. (Hoffman and others, 1981).

Previous Studies

The first year-round study of the limnology of Irondequoit Bay was done during 1939-40 (Tressler and others, 1953). That study entailed a monthly measurement of a few physical, chemical, and biological (plankton) constituents. The first major study of the mixing and chemical characteristics of the bay was conducted from spring 1969 through winter 1971 (Bubeck, 1972). In that study, detailed temperature, optical, and chemical profiles of the water column were made at least monthly but usually more frequently to document seasonal change. The most comprehensive limnological study of the bay to date (1987) documents the hydrologic, physical, chemical, and biological characteristics of the bay and its drainage basin, including a review of all known past studies (Bannister and Bubeck, 1978).

Effects of Deicing Salts on Irondequoit Bay

The accumulation of deicing salt in the bay and changes in its mixing characteristics were first observed in 1969-70 (Bubeck and others, 1971). Subsequent studies addressed the effect of extensive use of deicing salts on streams of the bay's drainage basin (Bubeck, 1972; Diment and others, 1973) and the fate of dissolved salts remaining in the drainage basin, accumulating in the bay, and discharging to Lake Ontario (Diment and others, 1974). The results of these studies showed that (1) summer chloride concentrations of Irondequoit Creek and the surface layer of the bay had increased fourfold since the 1950's; (2) maximum winter concentrations of chloride in the creek reached 600 mg/L (milligrams per liter); maximum winter chloride concentrations in 10 smaller streams that discharge to the bay ranged from 260 to 46,000 mg/L; (4) chloride in runoff to the bay caused a density gradient in the bottom water sufficient to prevent complete mixing in each spring of 1970-73; (5) summer stratification was prolonged later each fall as the net amount of chloride in the bay increased each year; and (6) approximately half the salt used for deicing in winter was removed from the drainage basin by surface runoff; the remainder was stored in the soil and may have entered the ground water. Chloride concentration was used as an indicator of the NaCl (sodium chloride) entering the system as a result of deicing-salt application.

In the mid-1970's, Monroe County began a cooperative effort with towns in the county to decrease their use of deicing salts through more efficient distribution measures. This was intended to decrease the chloride loading to the bay and led to a gradual improvement of the bay's mixing patterns to that of a completely mixing dimictic lake. About this time, Monroe County, through the New York State Department of Environmental Conservation, also began a long-term study of the water quality of the Irondequoit Bay drainage basin as part of the U.S. Environmental Protection Agency's National Urban Runoff Program. Coincidental with this, the Monroe County Pure Waters Agency began an extensive program to divert sewage from the Irondequoit Creek basin and therefore from the bay. At the same time, the Monroe County Department of Health, Environmental Health Laboratory, started a comprehensive water-quality-monitoring program on the bay. Together these efforts created an ideal setting within which to document the limnological changes in the bay after the decrease in salt applications and the diversion of sewage from the basin.

Purpose and Scope

In 1984, the U.S. Geological Survey, in cooperation with the Monroe County Department of Health, began a study to determine whether the chloride concentration, mixing pattern, and stratification of the bay had changed since the decreased use of road deicing salts. This report (1) documents the decrease in use of deicing salts in the Irondequoit drainage basin and the subsequent decrease in chloride concentration in Irondequoit bay during 1974-84; (2) documents the vertical distribution of water temperature, specific conductance, dissolved oxygen, and chloride at the deepest part of the bay for each year during 1978-84; (3) describes the time and extent of seasonal mixing and stratification; and (4) compares the latter observations with those made at the same location in 1970-73. It also includes several suggestions for additional study of Irondequoit Bay.

Acknowledgments

Field and laboratory staff of the Environmental Health Laboratory, Monroe County Department of Health, maintained field equipment, collected, prepared, and analyzed water samples, and verified the data used in this report. Special appreciation is extended to Eric Baker, who was in charge of the field collection and analyses of samples from the bay, and to Robin Evans, who compiled most of the data relating to salt use and loads from Irondequoit Creek.

IRONDEQUOIT DRAINAGE BASIN

The Irondequoit drainage basin is a 438-km^2 subbasin of the Lake Ontario drainage basin (Wagner, 1982) in the Erie-Ontario Lowlands physiographic province of New York State (Cressey, 1966). It is east of the Genesee River and lies mostly within Monroe County (fig. 1). The northwestern part of the basin includes the east side of the city of Rochester; the southeastern part includes parts of Ontario and Wayne Counties (fig. 1).

Physiography and Geology

The major physiographic features of the basin are Irondequoit Creek, its tributaries, and Irondequoit Bay. Irondequoit Creek, the major stream in the bay's watershed, drains an area of about 391 km^2 (Wagner, 1982) and discharges directly to the south end of the bay near Empire Boulevard (fig. 1). The remaining 47 km^2 of the bay's drainage basin consists of the bay itself plus the basins of its minor tributaries, which originate inland beyond the steep slopes of its eastern and western shores. The bay discharges to Lake Ontario through a dredged outlet in a sandbar that blocks its northern end (fig. 1).

The surficial geology of the basin, including the bay, is the product of several glacial advances and retreats. Moraines, drumlins, till plains, and small lake plains are prevalent in the southern and midsections of the basin, and beach ridges and plains are common in the northern part near Lake Ontario (Fairchild, 1935; Young, 1983). Major surficial geologic features of the basin are described in Yager and others (1985). Soils of the basin are derived from glacial debris, lacustrine sediments, and alluvial deposits. Sand, silt, and clay mixtures are abundant (Hennigan, 1970).

The geohydrology of Monroe County is described by Leggette and others (1935) and Grossman and Yarger (1953). An important geohydrologic feature of the drainage basin is a preglacial buried valley known as the Irondogenesee

River valley (Fairchild, 1935), which underlies the drainage basin and the bay (Waller and others, 1982). The buried-valley aquifer is a major ground-water resource of Monroe County and is vulnerable to contamination from surface-water sources (Waller and Finch, 1982).

Land Use

The northern and central parts of the basin are mostly urban and suburban, with light industry and commerce in the Rochester area and along the creek in the northern and central part; to the east are suburbs. The southern part of the basin is largely agricultural and rural residential, although suburban communities and commercial development have increased in this area since the late 1960's. The New York State Barge Canal and the New York State Thruway traverse the basin east to west (fig. 1). Waller and others (1982) present a recent land-use map of the areas surrounding the bay and the central part of the basin.

The population within the basin increased only slightly during 1970-80 to about 243,000 (Sherwood, 1981), although a population shift from the city of Rochester and outside the county to towns east of the city and north of the canal has occurred (O'Brien and Gere, 1983). The State and Interstate highway systems within the county have been expanded since the mid-1960's to meet the transportation needs of the shift in population and of businesses. Expansion of the major road system may necessitate a wider distribution and increased use of deicing salts throughout the basin in the future.

Climate

Precipitation in the Rochester area averages about 83.1 cm/yr (centimeter per year) and falls at a rate of about 6.9 centimeters per month. (National Oceanic and Atmospheric Administration, 1984.) The precipitation and temperature at a given location are strongly influenced by proximity to Lake Ontario. In summer, the lake's cooling effect keeps the air temperatures in the low to mid-30's (°C). In winter, the lake prevents temperatures nearby from falling much below -26°C, whereas temperatures in areas more than 24 km inland may reach -34°C. The first frost usually occurs in late September and the last in mid-May. The growing season averages 150 to 180 days.

The average snowfall in the Rochester area for the period of record (1944-84) is 228 cm (centimeters), but the distribution is strongly influenced by Lake Ontario. Winter snowfalls in the northern part of the county, near the lake, range from 254 to 508 cm annually as a result of the "lake effect"; farther inland, they range from 203 to 254 cm. The area also receives repeated short periods of light and moderate snowfall or snow squalls. Measurable snow occurs from November through April, with frequent snow traces in October and May. Continuous snow cover usually lasts from December through March. The high frequency and varying intensity of snowstorms and the long snow season result in extensive use of deicing salts on the highways and roads of the drainage basin.

Hydrology of Irondequoit Creek

The headwaters of Irondequoit Creek originate in the northern part of Ontario County, south of the Monroe County line (fig. 1). The main stream has a total length of about 60 km (kilometers) and drops from an elevation of 235 m (meters) at its headwaters in Ontario County to 75 m (mean level of Lake Ontario) in Irondequoit Bay (Monroe County Planning Council, 1964). The stream flows northward along the path of the buried preglacial river valley and passes through culverts under the New York State Barge Canal, from which it intermittently receives water during the canal's operating season. The stream is joined by Thomas Creek (its main tributary from the east) near the village of East Rochester, then continues northwestward to Allen Creek, its western tributary, near the village of Penfield. From there it meanders through Ellison Park (between Blossom Road and Browncroft Boulevard) and flows to the wetland area north of the boulevard. Below the wetlands, it enters Irondequoit Bay at Empire Boulevard (fig. 1).

Streamflow

No continuous study of the streamflow of Irondequoit Creek near its mouth or along its mainstem was made before 1971, but results of the short-term studies before 1971 are summarized by Bubeck (1972). A gaging station was established on Irondequoit Creek at Browncroft Boulevard (Bubeck, 1972) and operated from November 1970 through December 1972. Mean annual discharge for that period was 3.7 m^3/s (cubic meters per second) (Bannister and Bubeck, 1978).

In the mid-1970's, the Geological Survey, in cooperation with Monroe County, began a gaging program to provide discharge data for calculations of chemical loads from the creek to the bay. The program was expanded in the late 1970's, when the Irondequoit Creek basin was designated as a study area under the U.S. Environmental Protection Agency's National Urban Runoff Program. A network of nine continuous-record sites and seven partial-record sites was established at selected subbasins for the duration of that study (Zarriello and others, 1985; Kappel and others, 1986). The Monroe County Environmental Health Laboratory has continued to operate selected gaging and water-quality stations in the drainage basin. The site nearest the mouth of the creek, Irondequoit Creek at Blossom Road (fig. 1), was used in this study. Its drainage area is 370 km^2 or 95 percent of the creek's basin at its mouth. The average discharge for the period of record December 1980 through November 1984 was about 3.4 m^3/s. A description of the subbasin upstream of the Blossom Road site is given in Kappel and others (1986).

Water Quality

Domestic and industrial wastes were discharged to Irondequoit Creek and its tributaries for decades. Historical water-quality surveys showed that sewage and industrial waste from within the basin produced elevated biochemical oxygen demand, decreased oxygen levels, and sludge deposits in some reaches of the creek as early as the late 1930's (Bannister and Bubeck, 1978). As residential and commercial development increased in the 1950's and 60's, 12 town or village sewage-treatment plants, combined sewer overflows from the city of Rochester, and several industrial plants made major discharges to the creek or directly to the bay. The major chemical constituents besides chloride were nitrogen, phosphorus, sulfur, trace metals, and organic compounds.

In 1978, Monroe County implemented a plan to divert all sewage within the basin to a new treatment facility outside the basin and to close the unused plants. It also began to divert out of the basin the discharge of Rochester's combined sewer overflows, which had been channeled to the creek's wetlands and the bay. During the 3 years before this diversion (1975-77), Irondequoit Creek at Browncroft Boulevard transported an average of 1,600 kg/d (kilograms per day) total nitrogen, 220 kg/d total phosphorus, and 135 kg/d orthophosphorus (Bannister and Burton, 1980, p. 1). During the first 12 months after the diversions began (May 1978 through April 1979), the total nitrogen load from the creek decreased by about 54 percent, and the total phosphorus load decreased by about 64 percent (Bannister and Burton, 1980, p. 10). By 1980, the effluents from most treatment plants had been diverted from the basin and from the bay, and diversion of combined sewer overflows was well underway. The general chemical characteristics of Irondequoit Creek during 1981 are given in table 1.

Table 1.--Chemical characteristics of composite water samples from Irondequoit Creek at Blossom Road, 1981.

[Data from Zarriello and others, 1985. All units in milligrams per liter unless otherwise noted. A dash indicates no data.]

	Date and time		
	Feb 11 (0900-1700)	May 6-7 (1020-0945)	Aug 11 (0615-0915)
Discharge (m^3/s)	6.2	2.5	2.7
Specific conductance (µS/cm at 25° C)	1,128	1,056	871
pH (units)	8.0	8.2	7.8
Alkalinity (field), as $CaCO_3$	150	222	162
Nitrogen, ammonia, dissolved as N	.110	.010	.050
Nitrogen, ammonia + organic dissolved, as N	--	1.1	.80
Nitrogen, ammonia + organic total, as N	2.10	1.4	1.80
Nitrogen, NO_2 + NO_3, dissolved, as N	1.3	.70	.80
Phosphorus, total, as P	.528	.064	.135
Phosphorus, ortho, dissolved, as P	.013	<.005	.008
Calcium, dissolved, as Ca	40	93	103
Magnesium, dissolved, as Mg	17	31	21
Sodium, dissolved, as Na	120	61	50
Potassium, dissolved, as K	3.0	2.9	3.3
Chloride, dissolved, as Cl	220	110	90
Sulfate, dissolved, as SO_4	87	86	150
Organic carbon, total, as C	13	--	--

Chloride concentrations as high as 360 mg/L were first noted in the creek in 1969-70 (Bubeck and others, 1971). Subsequent studies of the chloride loads at Browncroft Boulevard from November 1970 through December 1972 were made by Diment and others (1974). Base-flow concentrations of chloride during summer and fall of these years were 100 mg/L--a tenfold increase since 1913 and a fourfold increase since the beginning of widespread use of deicing salts in the basin in the 1950's. Concentrations reached 600 mg/L during the thaws in winter and early spring of 1970-72. Diment and others (1974) calculated that Irondequoit Creek discharged 28,500 metric tons of NaCl in 1970-71 and 39,100 tons in 1971-72. Thus, the creek began to load the bay with relatively high salt concentrations from the late 1960's to the early 1970's while contributing a steady long-term loading of nutrients, trace metals, and organic compounds.

Limnology of Irondequooit Bay

The physical, chemical, and biological characteristics of a lake result from the morphometry, or shape of that part of its basin that holds water, in addition to the nature of its drainage area and climate (Goldman and Horne, 1983). The morphometry of a lake's or bay's basin greatly influences physical and biochemical processes that determine thermal and chemical stratification, the distribution of organisms and their productivity, and the trophic level. The geomorphic features of the shore and the morphometry of the basin also determine the effects that elevated concentrations of deicing salts have on the bay.

Geomorphic Features

Irondequoit Bay is a coastal bay on the southern shore of Lake Ontario and lies near the point of maximum curvature of a coastline depression known as the Rochester embayment. It is the third largest bay in terms of surface area (6.78 km^2), second largest in volume (45.95 x 10^6 m^3), and deepest (23.8 m) of the State's coastal bays (table 2.)

Table 2.--Morphometric characteristics of Irondequoit Bay.

[Data from Bubeck (1972);
[km, kilometer; m, meter]

Latitude	43°13'N
Longitude	77°32'W
Length (maximum)	6.6 km
Width (maximum)	1.2 km
Surface area	6.78 km^2
Maximum depth	23.8 m
Mean depth	6.8 m
Volume	45.9 x 10^6 m^3
Hydraulic retention time*	116 days

* Calculated from bay volume divided by mean tributary inflow of 4.6 meter per second (Bannister and Bubeck, 1978).

The bay is about 6.6 km long and about 1.2 km wide; its long axis trends roughly north-south (pl. 1). It is bounded on the west and east by steep, wooded hillsides that rise 30 to 45 m above the water surface. In some places the vertical bluffs are exposed to erosion by wave action and have little or no vegetation. In general, the western shore is relatively linear, whereas the eastern shore has well-developed concave features or cusplike indentations, especially to the north. Neither side has well-developed beaches. Both sides have major coves near the midsection. Of particular interest is Ides Cove, on the western shore just south of Point Pleasant (pl. 1). It is the deepest cove of the bay (8.8 m) and is separated from it by a submerged sill whose top is 1 m below the water surface. This cove was found to be marginally meromictic (Bubeck, 1972), probably as a result of the addition of deicing salt to the already elevated concentration of dissolved solids of biological origin in its deep basin. "Pesacreta and Makarewitz (1982) discuss the causes and possible recovery of the Cove from meromixis. A report on the physical and chemical limnology of Ides Cove, 1970-1982, is in preparation."

A major manmade feature of the bay is the Irondequoit Bay Bridge (Rt. 104), which crosses the bay from east to west near its narrowest part (pl. 1). The bridge, opened in February 1970, is about 46 m above water and is supported by eight concrete platforms. This multilane bridge and its approach lanes are point sources of deicing salts to the bay.

The shoreline cliffs from the midsection of the bay southward are incised by small intermittent and perennial streams. The largest of these minor tributaries, Densmore Creek, enters the bay from the west shore and has formed a delta (pl. 1). Other smaller streams entering the bay have basins of less than 16 km2 but are capable of transporting small loads of deicing salts in high concentrations to the southern bay (Diment and others, 1974). Irondequoit Creek enters the extreme southern end of the bay at Empire Boulevard (pl. 1) after meandering through extensive wetlands.

The northern end of the bay is separated from Lake Ontario by a sandbar about 2 km long and about 150 m wide (pl. 1). The outlet to the lake was a narrow channel, about 30 m wide and 2 m deep, just west of the center of the sandbar. Winds over Lake Ontario periodically raise its water level at the outlet and occasionally cause reverse flow of lake water into the north arm of the bay. Recently the channel was artifically widened and deepened, and breakwaters were constructed on the Lake Ontario side to form a navigable channel for pleasure craft.

Morphometry

The general morphometric characteristics of the bay are summarized in table 2. The values are from Bubeck (1972), who calculated them from a bathymetric map of the bay drawn in 1931 by Odell (1940). Bannister and others (1982) surveyed the bay 50 years later during the winters of 1981 and 1982 and prepared a new map to verify the bay's bathmetry (pl. 1). Bannister's values agree with those in table 2 except that they indicate the volumes of the meta- and hypolimnia to be slightly larger, and the volume of the epilimnion slightly smaller, than those calculated by Bubeck (1972) from the Odell map. Thus, Bannister and others (1982) estimate the total bay volume to be 47.0 x 106 m3, about 2 percent larger than Bubeck's value of 45.9 x 106 m3.

Differences between the two maps are attributed to improvements in instrumentation and field techniques since the 1930's.

The general bathymetry of the bay has changed little since 1931. The following discussion is based upon the map of Bannister and others (1982), who divide the bay into five major segments--north shallows, north basin, middle basin, south basin, and south shallows (pl. 1)--described below.

North shallows.--The northern end of the bay consists of a shallow (1 to 1.5 m deep) northeast-tending arm about 2.0 km long that is bounded by the sandbar to the north and steep cliffs to the west, east, and southeast. Rooted aquatic plants that extend to within 0.5 m of the surface grow in the spring, summer, and early fall. A marsh occupies the extreme northeastern end of this arm of the bay. Small intermittent streams and roadside drainages discharge around its shore. Its shallow depth makes it one of the first areas of the bay to freeze in winter.

North basin.--The moderate constriction at Stony Point (pl. 1), where the water quickly deepens from 4 m to 22 m, defines the beginning of the north basin, which extends 1.6 km south to the Irondequoit Bay bridge. This is the deepest part of the bay; much of it is 22 to 23 m deep, and it attains a maximum depth of 23.8 m off Point Pleasant. The bottom is relatively flat but has steep slopes. The north basin gradually becomes shallower near the bay bridge and is about 20 m deep beneath the center span of the bridge.

Middle basin.--The narrowest part of the bay, about 0.42 km wide, is just south of the bridge. The depth decreases more abruptly here, from 20 m to 14 m, and the bay widens to form the broad and more shallow middle basin, which extends south to the Densmore Creek delta at about 11 m depth (pl. 1).

South basin.--The south basin extends from Densmore Creek to about the 1.5-m depth contour and is the widest and shallowest part of the bay's basins. The south half of middle basin (south of Held's Cove) and all of the south basin seem to be structurally offset to the east in relation to the north basin. Both basins provide an extensive north-south fetch. The bottom configuration of this part of the bay has a major control on the direction of currents, which transport water and suspended matter to the deeper north basin.

South shallows.--The south shallows extend from about the 1.5-m contour to the southern shore of the bay; here rooted aquatic plants are abundant during the spring, summer, and early autumn (pl. 1). The bottom of this area consists of sediment from Irondequoit Creek, organic debris from rooted aquatic plants, and several shoal areas. Most of the deicing salt that enters the bay comes from Irondequoit Creek through the south shallows.

Water Quality

Irondequoit Bay is a hard-water lake that showed advanced stages of cultural eutrophication through the late 1970's. Its primary source of water is Irondequoit Creek; thus, the creek water is the major influence on the water quality of the bay. The second most influential factor is the chemical composition of the bottom sediments of the bay. Schroeder (1985) describes the sedimentation rates and abundance of trace elements in the bay's sediments. Water in contact with sediments, either during mixing or during stratification under anoxic conditions, or moving downslope as a density current, will dissolve soluble nutrients, trace elements, and gases and redistribute them to the water column.

The seasonal concentrations of selected chemical constituents at the surface of the water column and at 22.5-m depth during February, April, August, and November 1982 are summarized in table 3. Comparison of these values with those of Bannister and Bubeck (1978) shows a decrease in concentrations of nitrogen, phosphorus, alkalinity, and silica, as well as in chloride and sodium, but little or no change in sulfate, calcium, magnesium, or potassium. The decrease in the nutrient (nitrogen and phosphorus) concentrations is consistent with the diversion of sewage from the basin and the subsequent decrease in the loads of these constituents from the creek.

Table 3.--Chemical quality of water at surface (0.5 meter) and at 22.5-meter depth in Irondequoit Bay, station 1, 1982.

[Location is shown on pl. 1. All units in milligrams per liter unless otherwise noted. A dash indicates no data available.]

Constituent	Date and depth: February 23, 0.5 m	February 23, 22.5 m	April 14 (end of spring mix), 0.5 m	April 14 (end of spring mix), 22.5 m	August 18, 0.5 m	August 18, 22.5 m	November 30 (end of fall mix), 0.5 m	November 30 (end of fall mix), 22.5 m
Secchi disk (m)	3.9		1.6		1.5		1.5	
Temperature (°C)	0.6	1.0	3.0	2.7	22.8	6.2	7.0	6.2
Specific conductance (µS/cm)	855	1255	970	1004	937	1091	906	926
pH (units)	7.8	7.6	8.0	8.0	8.4	7.4	7.8	7.9
Alkalinity, as $CaCO_3$	201	242	200	201	145	244	166	171
Dissolved oxygen	10.9	7.8	17.5	13.4	8.3	0.0	9.1	9.6
Nitrogen, NH_3, dissolved as N	0.36	0.71	0.09	0.11	0.02	3.1	0.46	0.45
Nitrogen, NH_3 + organic, dissolved as N	0.8	0.9	1.20	1.10	0.90	3.7	1.5	1.1
Nitrogen, NH_3 + organic, total as N	0.9	1.3	1.40	1.30	0.91	4.4	1.8	1.1
Nitrogen, NO_2 + NO_3, dissolved as N	1.0	1.1	1.3	1.4	0.01	0.02	0.6	0.2
Phosphorus, total as P	0.085	0.140	0.120	0.093	0.03	0.62	0.14	0.14
Phosphorus, ortho, dissolved as P	0.046	0.084	0.04	0.03	<0.005	0.56	0.08	0.08
Silica as SiO_2	5.3	7.9	5.5	5.8	0.8	7.6	0.2	0.7
Chloride	120	230	150	150	130	140	120	130
Sulfate	100	130	100	100	120	83	120	140
Calcium	90	120	--	105	--	--	87	89
Magnesium	26	28	29	28	--	--	28	28
Sodium	71	140	--	77	85	92	72	70
Potassium	3.9	4.0	3.6	3.9	3.3	3.4	3.1	3.2

Stratification and Mixing

Thermal stratification is the most important physical event in a lake's annual cycle and is a direct result of heating by the sun (Goldman and Horne, 1983). Because Irondequoit Bay is in the northern temperate zone, it experiences strong seasonal contrasts in temperature and winds, and these, in turn, influence its stratification. The bay's seasonal stratification and subsequent mixing characteristics are described in the paragraphs that follow.

Spring.--Ice cover normally lasts from late December through the end of March. As air temperatures warm in the early spring, the ice cover weakens and melts in shallow areas. The weakened ice over the deep basins then is usually cleared in a few hours by the strong spring winds blowing along the bay's north-south fetch. In addition, water at the surface quickly warms to its temperature of maximum density (a few tenths of a degree below 4°C, depending on salinity and pressure) and gradually sinks. This sinking, combined with the work of the wind, causes rapid mixing of the entire water column in all parts of the bay within a few days, and chemical constituents are mixed nearly uniformly from surface to bottom. (Lakes that mix completely to the bottom are called holomictic. If the bottom water of the bay contains high concentrations of dissolved ions, however, its density may be great enough to resist the mixing with the water circulating above it. In this case, the water column will not mix completely to the bottom. Such lakes are termed meromictic.)

As spring air temperatures warm the surface layers above the temperature of maximum density, the water column in the bay tends to stratify thermally and chemically. An upper, warmer and lighter layer, the epilimnion, develops above a deeper, cooler, and denser layer, the hypolimnion. The epilimnion is a relatively isothermal, well-oxygenated, circulating layer of water that becomes warmer through the spring and summer and is subject to turbulence by wind. Its depth depends on how much heat the bay receives in the spring and summer and the duration and strength of the wind.

Summer.--As summer stratification begins, oxygen is consumed, and reducing gases are produced in the hypolimnion. The hypolimnion then becomes anoxic, and dissolved constituents such as ammonium, orthophosphate, carbonate, sulfide, and trace elements accumulate through (1) biochemical interactions with suspended and bottom material, (2) the action of microorganisms, and (3) the addition of constituents from tributary streams. The initial temperature of the hypolimnion is determined by the final water temperature during spring mixing. Its temperature changes relatively little during the summer.

Between the epilimnion and the hypolimnion is a transition zone or thermal discontinuity called the metalimnion. It is characterized by a steep thermal gradient, or thermocline. This zone is well developed by June, and the gradient is greatest in midsummer. The lower part of the metalimnion often becomes anoxic or nearly so as the biochemical oxygen demand of the hypolimnion increases through the summer. Marked changes in concentrations of other chemical constituents that are produced or consumed in the epilimnion or hypolimnion are found in the metalimnion.

The depth range of the epilimnion in Irondequoit Bay is 0 to 6 m; that of the metalimnion 6 to 12 m, and that of the hypolimnion is 12 to 23.8 m (Bannister and others, 1982). This division indicates that 50 percent of the total volume of the bay is epilimnion, 30 percent is metalimnion, and 20 percent is hypolimnion. Nearly all the hypolimnion (90 percent) and about half the metalimnion (46 percent) are within the north basin; the south basin has no hypolimnion (Bannister and others, 1982).

Fall.--The metalimnetic thermocline begins to descend in late summer and early fall as cooling air temperatures and wind-induced mixing slowly deepen the epilimnion. As the air temperatures decrease, the water of the bay loses heat. Fall mixing begins with the increased density of the cooling surface water and the work of the wind. Circulation continues through late fall as the water column continues to cool and increases in density. The bay mixes completely to the bottom in its deepest part by late October or early November. The rate and duration of the mixing are dependent upon the rate of heat loss from the surface, the wind conditions during the fall, and the chemical density of the bottom waters.

Lakes that mix completely in the spring and fall are called dimictic lakes. They stratify directly in the summer (warm water lies over cold water) and inversely in winter (cold water lies over warm water) under ice cover (Wetzel, 1983). Irondequoit Bay is dimictic. Complete mixing (holomixis) or "turnover" in the spring and fall is desirable because it allows dissolved nutrients and oxygen to be uniformly distributed through the water column and excess constituents, such as chloride, to be flushed from the bay.

When autumnal circulation is completed, the water column is isothermal and continues to cool and mix as the water approaches its temperature of maximum density (about 4°C). As the water at the surface cools below 4°C, it becomes slightly lighter than warmer water just below it. This stable condition is easily disrupted by the strong winds, and the bay is continually mixed as the water column cools to 1°C before the surface freezes.

Winter.--When ice cover forms, the mixing effect of the wind is lost, and an inverse thermal stratification begins wherein the bottom water is slightly warmer than the surface water. As the winter continues, the bottom water (below 20 m) absorbs heat through several processes, including (1) solar radiation through the ice, which generates density currents in the shallow areas that flow to the deeper basins; (2) low-level heat and solute flux from biochemical reactions in the sediment and at the interface between sediment and water; and (3) heat from the constant geothermal heating of the sediment.

As winter progresses, the bottom water usually becomes anoxic or nearly so, and dissolved chemicals accumulate near the bottom as they do under direct stratification in summer. The inflow of deicing salts during winter is especially significant because the chloride salts accumulate in the deep part of the bay under ice cover. The concentration of chloride in the deep water at this time, together with the chloride remaining in the water column after the fall turnover, are the primary factors that determine whether the bay will mix completely the following spring. If the mixing is incomplete, the anoxic condition and increasing concentrations of dissolved solids that developed during the winter will remain in the hypolimnion that forms during the spring and summer.

Irondequoit Bay has considerable water movement under the ice as a result of continuous inflow from streams. The discharge of Irondequoit Creek to the bay stratifies according to its density relative to bay water. Measurements of temperature, specific conductance, dissolved oxygen, and chloride through the water column under the ice at several stations along the longitudinal axis of the bay have verified the vertical stratification (Bubeck, 1972). Anomalous density currents of saline water also enter the bay from Densmore Creek and from smaller streams and drainage ditches that discharge directly to the bay under the ice during winter thaws.

Horizontal circulation.--The horizontal circulation patterns in the bay have not been thoroughly studied (Bannister and Bubeck, 1978), but measurements were made several times of the year through the water column at specific sites on the bay during the early 1970's and 1980's (Bubeck, 1972; Bubeck, unpublished data). Temperature, specific conductance, chloride, dissolved oxygen, secchi disk, and horizontal light-transmission data show a general horizontal homogeneity at a given depth from station to station in the north and middle basins. The southern parts of the bay, however, have slightly higher dissolved oxygen and turbidity and a less developed thermocline than the northern and middle parts. Specific conductance and chloride concentration were similar at the same depths throughout the three basins of the bay.

High discharge from Irondequoit Creek during periods of heavy precipitation and winter thaws causes a plume of turbid water to extend northward from the south shallows into the south and middle basins (fig. 2). Frequently these sediment-laden plumes concentrate along the eastern shore of the bay but can also move northward in a nearly linear front. The shape and path of a plume is controlled by the direction and force of the wind, the amount and duration of the discharge, and the bay's morphometry. The bay usually discharges a small plume of sediment-laden water to Lake Ontario within a few days of receiving turbid discharge from the creek (fig. 2).

Periodic strong north winds cause Lake Ontario water to flow intermittently into the north shallows of the bay, which temporarily reduces the specific conductance and chloride concentration of the water near the outlet (Bannister and Bubeck, 1978).

In summary, the bay mixes in spring and autumn and is naturally holomictic. It undergoes direct stratification in summer and inverse stratification in winter under ice cover. Its nutrient content has decreased since the diversion of sewage out of its drainage basin. Its chemical quality, stratification, and mixing are influenced by water from Irondequoit Creek and by the composition of its bottom sediments, its geomorphic features, its morphometry, and the regional weather conditions. Chloride from deicing salts makes it susceptible to incomplete mixing (meromixis).

Figure 2.--Sediment plumes from Irondequoit Creek into bay and from bay into Lake Ontario, April 6, 1968. (Photo by Lockwood Mapping, Rochester, N.Y.)

METHODS OF STUDY

Sampling Sites

Station 1, east of Point Pleasant at mid-bay, at a depth of about 23 m (pl. 1), is one of three monitoring sites used in the Monroe County Department of Health's long-term water-quality-monitoring program. The three sites were established by earlier investigators and provide historical data for evaluating long-term changes in water quality. Station 1, the major sampling site in this and previous studies, is in the north basin (deepest part) of the bay. It has been shown to be representative of the general thermal and chemical stratification of the bay, as discussed in the previous section on horizontal circulation within the bay. All data in this report are from this station. Station 2 is north of the center span of the bay bridge at 20-m depth, and station 3 is east of Densmore Creek, mid-bay, at 11-m depth (pl. 1). Both serve as field quality-control stations and are sampled intermittently as part of the Monroe County water-quality-monitoring program and for special studies. The county also maintains a water-quality station on Irondequoit Creek at Blossom Road (fig. 1; table 1), which is representative of the chemical characteristics of the water entering the bay from the creek (Zarriello and others, 1985; Kappel and others, 1986).

Field Methods

Field sampling was done by the Monroe County Environmental Health Laboratory from a Boston Whaler[1] or a specially designed pontoon boat. Temperature, specific conductance, dissolved oxygen, and pH were measured onsite with a Hydrolab Surveyor Model 6D. Before 1980, water samples were collected with a WILDCO Van Dorn sampler and a standard hand-lowered measured line with messenger; after 1980, Masterflex or ISCO peristaltic pumps were used. Tygon hose from the pump was attached to the Surveyor's sensor, and water for laboratory analysis was retrieved from a given depth after the field measurements were made. Dissolved oxygen samples were fixed in the field and analyzed onsite or in the laboratory[2]. They and other samples were chilled and transported to the laboratory on the day of collection. The laboratory uses field procedures that incorporate a quality-assurance program for field instrumentation and sampling. The procedures for collecting samples at Irondequoit Creek at Blossom Road are described in Zarriello and others (1985).

---

[1] Use of brand names herein is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

[2] Before 1980, all dissolved oxygen samples were collected with a Von Dorn sampler, fixed in the field, and analyzed by the Alsterberg azide modification of the Winkler method. After 1980, all dissolved oxygen data were obtained with the Hydrolab field instrument, but quality-assurance samples were taken by Van Dorn sampler and fixed and analyzed as above.

Analytical Methods

Preserved samples were filtered through 0.45-μ-(micrometer) filters and analyzed by the Monroe County Environmental Health Laboratory by methods of Skougstad and others (1979) and U.S. Environmental Protection Agency (1979). The laboratory uses an internal quality-assurance program and is annually certified by the New York State Department of Health. Also it holds U.S. Environmental Protection Agency certification and has had a continuing quality-assurance program with U.S. Geological Survey since 1980 as a cooperating laboratory in the National Urban Runoff Program (Zarriello and others, 1985).

CHANGES RESULTING FROM DECREASED USE OF ROAD-DEICING SALTS

The use of deicing salts in Monroe County and the Irondequoit Bay drainage basin reached a maximum in the late 1960's and early 1970's. The amounts used from 1966 through 1984 are plotted in figure 3. Annual use of salt by the town of Irondequoit from 1956 through 1984 is included to illustrate the pre-1966 trend for the county and towns in the drainage basin.

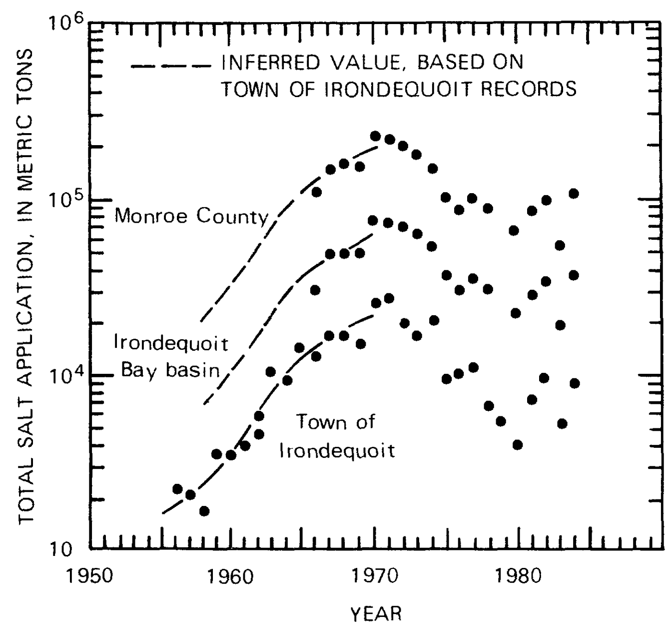


Figure 3.

Annual use of deicing salt in Irondequoit Creek basin, 1956-84. Town of Irondequoit data are the only accessible pre-1966 record and are the basis for extrapolation of the other curves. (Modified from Diment and others, 1974, p. 394. Post-1973 data from Monroe County Department of Health.)

Salt usage was highest in the winter of 1969-70, when about 224,000 metric tons were distributed in the county, of which about 76,600 were used within Irondequoit Creek basin. Relatively extensive use of salt continued for the next 4 years but at a slightly decreasing rate through 1973-74, when 152,600 metric tons were used in the county and about 53,400 in the basin.

The amounts of salt used in Monroe County and the Irondequoit drainage basin and the total snowfall for the winters of 1965-84 are given in table 4 (p. 20); salt use per winter in the county and the seasonal snowfall are plotted in figure 4. The trends in figure 4 and the data in table 4 indicate a 54-percent decrease in the use of salt in 1974-75 and a 60-percent reduction in 1975-76 from the 1969-70 maximum. This reduction is attributed to the cooperative effort by towns in the county to lower their use of salt through more efficient distribution measures. Despite a brief increase in 1976-77, by 1979-80, the amount used annually had decreased 70 percent from the 1969-70 amount.

Although the curves in figure 4 indicate some correlation between salt use and total snowfall during the winters of 1974-75 through 1983-84, none is evident for winters before 1974-75. In general, consistent correlation may not necessarily be expected because salt use tends to vary with frequency of storms during a given winter rather than with total snowfall. The winters of exceptionally low snowfall, 1979-80 and 1982-83, show the lowest amounts of salt used, as expected (fig. 4). This may also be a result of the effort to improve the efficiency of salt usage since about 1974-75 because salt use before that winter was exceptionally high, even during winters with low snowfall.

During the last 4 years of the study, salt use gradually increased 67 percent from the 64,700 metric tons for the county and 22,700 metric tons for the basin in 1979-80 to 108,000 and 37,800 metric tons, respectively, in 1983-84 (fig. 3 and table 4), which were the greatest amounts used since 1973-74. (The 1982-83 winter had unusually low snowfall and thus exceedingly low salt use.) Nevertheless, salt use in the basin in 1983-84 was 51 percent below the maximum amount used 14 years earlier (1969-70). If the average salt use of the last 4 years of the study is considered to represent current salt use in the basin (annual average = 30,075 metric tons), then salt use has declined 61 percent below the maximum amount used in 1969-70.

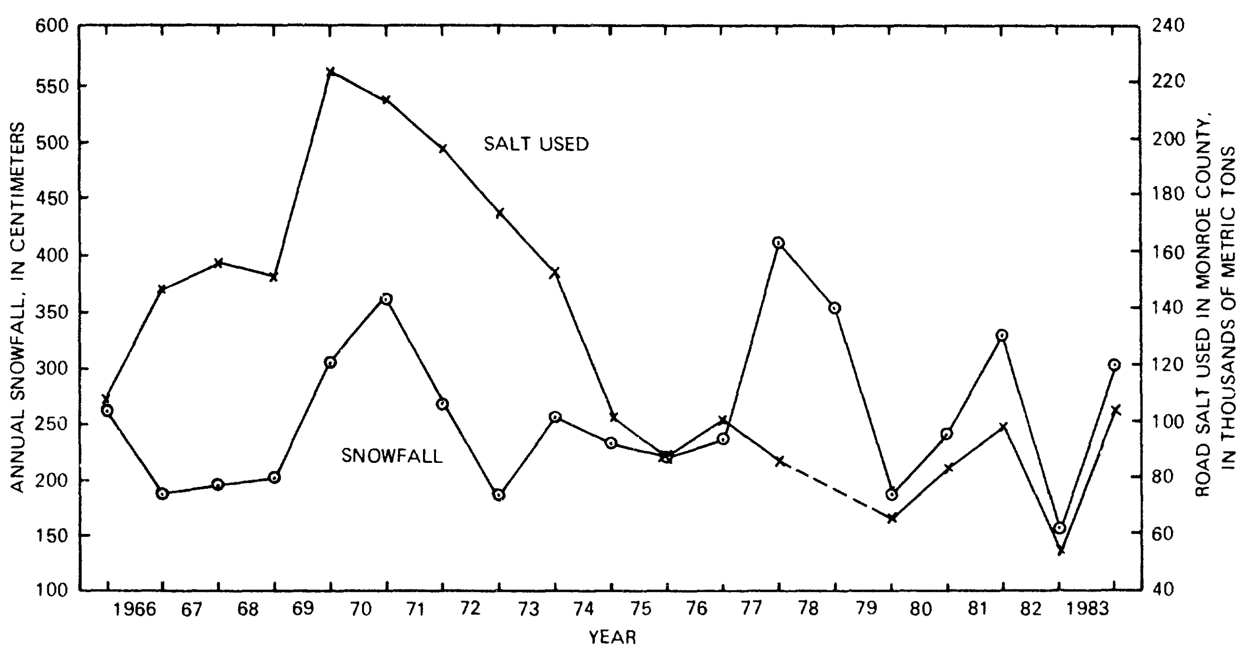


Figure 4.--Total annual snowfall and annual use of deicing salt in Monroe County, 1965-84.

Table 4.--Total snowfall and amount of deicing salt used in Monroe County and Irondequoit Bay drainage basin, 1965-84.*

[n = no data available.]

Winter	Monroe County (metric tons)	Irondequoit Bay drainage basin (metric tons)	Snowfall (centimeters)
1965-66	109,200	30,800	262
1966-67	148,400	47,400	188
1967-68	156,900	49,300	196
1968-69	151,500	49,600	203
1969-70	224,000	76,600	305
1970-71	214,600	73,500	363
1971-72	196,800	68,900	267
1972-73	173,900	64,000	185
1973-74	152,600	53,400	254
1974-75	102,300	35,800	232
1975-76	87,300	30,600	220
1976-77	100,100	35,000	235
1977-78	85,600	30,000	408
1978-79	n	n	350
1979-80	64,700	22,700	184
1980-81	83,000	29,000	240
1981-82	98,900	34,600	326
1982-83	53,900	18,900	153
1983-84	108,000	37,800	300

* 1965-73 data from Diment and others (1974).
1973-84 data from Monroe County Environmental Health Laboratory.

Chloride Concentrations in the Creek and Bay

The large salt loads that affect Irondequoit Bay enter primarily from Irondequoit Creek each winter and spring during periods of thaw and spring runoff (Bubeck and others, 1971; Diment and others, 1974; Kappel and others, 1986). Summertime chloride concentrations of the creek are considered to represent the residual amount of salt stored in the soil as the result of previous applications (Diment and others, 1974).

Irondequoit Creek

The historical trend of the average chloride concentration in the creek during summer (low flow) from 1912 to 1984 is plotted in figure 5 along with basin population and amount of salt applied to the basin. The concentrations peaked at about 123 mg/L in 1973, after years of heavy salt use in the late 1960's and early 1970's. Thereafter, as less deicing salt was used on the basin, the concentrations decreased to about 105 mg/L in the late 1970's.

During 1980-84, summer concentrations continued to fluctuate slightly from year to year, but the average of the low-flow concentration was about 97 mg/L. Thus, the average chloride concentration during base flow reflects the decrease in use of deicing salts since 1974-75 (fig. 5).

Chloride concentrations in Irondequoit Creek since 1980 may be more sensitive to the yearly changes in the amount of salt applied to the basin than those in previous years because (1) the amount of residual salt in the basin declined after 1970, which makes the yearly changes in salt use within the basin more readily detected in the creek, and (2) the county's monitoring program on the creek after 1980 provides storm sampling as well as daily chloride sampling, which enables detection of smaller changes in salt concentrations than could be determined in earlier years. The nearly continuous daily sampling of Irondequoit Creek at Blossom Road during 1980-84 indicated that chloride concentrations were 300 mg/L or greater on only 8 days, and were 400 to 490 mg/L on only 3 of these days. In contrast, a 2-year period of daily sampling of Irondequoit Creek at Browncroft Boulevard in 1971-72 showed that chloride concentrations exceeded 300 mg/L on more than 45 days, exceeded 400 mg/L on 7 days, exceeded 500 mg/L on 3 days, and exceeded 600 mg/L on 1 day. Although high concentrations alone do not always produce high loads, the decline in frequency of high concentrations is significant because it reflects the reduction in salt use in the basin since the early 1970's.

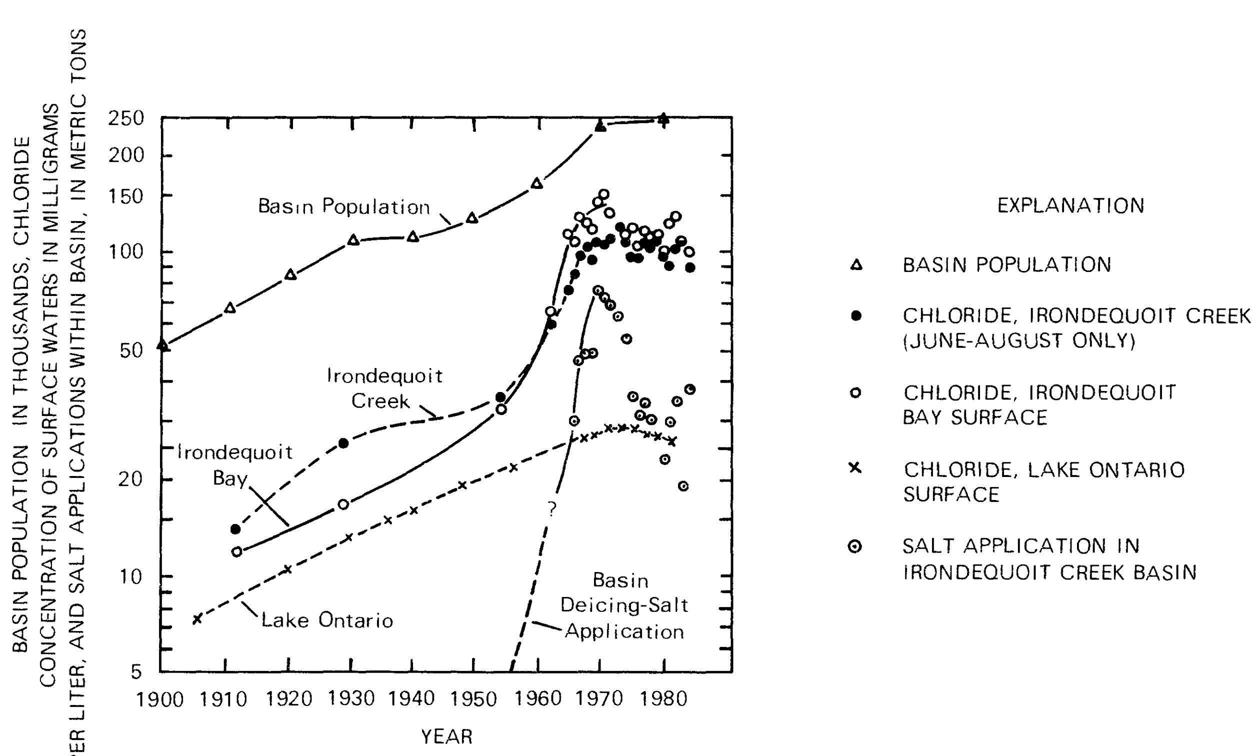


Figure 5.--Annual basin population, annual basin salt application, and the chloride concentration during June-August in Irondequoit Creek, Irondequoit Bay, and Lake Ontario from the early 1900's through 1984.

Kappel and others (1986) computed annual loads of selected constituents of Irondequoit Creek at Blossom Road from July 1980 through August 1981. The calculated loads of dissolved chloride at Blossom Road during 1980-81 represented a 40-percent reduction from the annual loads of 1970-71 and 1971-72 at Browncroft Boulevard (a short distance downstream) given by Diment and others (1974). This reduction of chloride in the stream is consistent with the 60-percent reduction of the amount of deicing salt applied in 1970-71 and 1971-72 (annual average = 71,200 metric tons) to the amount applied in 1980-81 (29,000 metric tons) (table 4).

In summary, the observed decrease in concentrations and loads of chloride in Irondequoit Creek reflects the decrease in use of deicing salts in the basin since the voluntary reduction in the mid-1970's and suggests that the amount of salt stored in the soils and ground water of the basin may also be decreasing. The net amount of salt accumulated in the soils and ground water of the basin is still unknown, however.

Irondequoit Bay

The average summer chloride concentrations at the water surface in the bay during 1912-84 are shown in figure 5. These concentrations peaked during the late 1960's and early 1970's, with a maximum average of 152 mg/L in 1971. The highest values were during three of the four summers that followed incomplete spring mixing (1970, 145 mg/L; 1971, 152 mg/L; 1972, 134 mg/L; 1973, no data). These concentrations represent the summer retention of salt in the bay after incomplete mixing during the previous spring plus the residual amount after the complete mixing of the previous fall. After 1973-74, average summer concentrations decreased slightly because the bay had begun to mix completely each spring as well as fall, which allowed more flushing, and because decreased use of deicing salts was continuing. During 1980-84, when the application of salt within the basin increased moderately, the average summer surface concentrations also increased. In general, however, the average summer chloride concentration at the bay's surface decreased in response to the reduction in use of salt in the drainage basin since 1974-75 (fig. 5).

The chloride concentrations, amount of NaCl salt, and mixing characteristics of the bay during fall and spring 1969-84 are summarized in table 5 (p. 24-25). During the years of incomplete spring mixing (1970-73), the salt content of the bay immediately after partial mixing ranged from 15,700 to 18,800 metric tons, and the deepest partial mix (in spring 1973) left about 11,700 metric tons. After 1974-75, the amount of salt remaining at time of the spring mix decreased and reached a low of about 8,800 metric tons in spring 1980 (a 53-percent reduction from spring 1972). In each year from 1981 through 1984, the amount of salt remaining after each spring mix increased to about 11,000 metric tons, but this nevertheless represents a 42-percent decrease from the maximum amount in spring 1972. This general decrease also is indicated by the mean chloride concentrations of the water column at time of spring mix. The mean chloride concentrations in spring 1970-72 ranged from 207 to 248 mg/L, whereas mean concentrations after the deepest partial mix (in spring 1973) was 154 mg/L (table 5). Subsequent complete spring mixes produced steadily decreasing mean concentrations through spring 1980. The mean concentrations from spring 1981 through 1984 increased slightly (reflecting the moderate increase in salt use during those years), but the trend after 1974-75 indicated a decrease in chloride content of the bay after spring mix.

The salt content of the bay at time of fall mixing increased from 8,500 to 12,600 metric tons during the fall of 1969 through 1971 (table 5). During fall 1972 (the fall before the last incomplete spring mix), the salt content had decreased to 11,800 metric tons and generally decreased thereafter as complete spring mixing resumed and the bay returned to a holomictic condition. The lowest salt content, 7,000 metric tons, was noted in fall 1980--a 45-percent reduction from the maximum amount in fall 1971. Even though the salt content during fall mixing increased moderately during 1981-84 to about 8,400 metric tons in fall 1984, it still represents a 33-percent reduction from the maximum content in fall 1971. As in the case of spring mixing, the chloride concentrations at the time of each fall mix decreased from 1974 through 1980. During 1981-84 the concentrations increased slightly, but the overall trend after 1974-75 reflects a decrease in chloride content of the bay at the time of fall mixing (see table 5). Yet, despite the decrease in chloride content of the bay through 1984, concentrations in the bay are still relatively high in relation to those in Lake Ontario (fig. 5) and in other natural lakes in Monroe County.

Mixing Patterns of the Bay

Spring Mixing

Changes in the chloride content of the bay cause changes in its mixing characteristics (table 5). Historical records show that the bay mixed completely to the bottom in the fall of 1939 and spring 1940 (Tressler and others, 1953). The first spring in which incomplete mixing was observed was 1970 (Bubeck and others, 1971). During 1970-72, the maximum depth of spring mixing decreased. In 1970 the bay mixed to 18 m; in 1971 to 15 m; and in 1972 to only 12 m. In 1973, however, the mix was complete to 20 m, about 3 m above the bottom of the deepest part of the bay. No data for spring 1974 are available, the but bay mixed completely to the bottom in the spring of 1975 for the first time in about 5 years and continued to mix every spring through 1983 (table 5). This change is attributed to an overall decrease in the chloride content of the bay. The bay's failure to mix completely in the spring of 1984 (table 5) was an unexpected response and is discussed in a later section.

Fall Mixing

Tressler and others (1953) showed that the bay mixed completely in early to mid-October 1939 at a temperature of about 12°C. During the years of high salt content (1969-73), complete fall mixing was never interrupted but occurred later in the year and at lower temperatures--for example, about November 13 in 1969, November 25 in 1970, December 10 in 1971, and December 1 in 1972 at 8-9°C, 7-8°C, 4-5°C, and 3-4°C, respectively (table 5). This prolonged the period of summer stratification and anoxia in the hypolimnion. Diment and others (1974) suggested that the continued increase in use of deicing salt may prevent the bay from mixing completely in the fall. If fall meromixis followed spring meromixis, a true meromictic condition could develop, and the deep part of the bay could become permanently anoxic. Salt use

Table 5.--Summary of the fall and spring mixing
chloride concentrations and amount

[m, meters; mg/L, milligrams per

Year (fall-spring)	Hypolimnion temperature and depth near end of September (°C) (m)	Completion of fall mix: Date of complete mixing	Completion of fall mix: Chloride concentration through water column (mg/L)	Completion of fall mix: Temperature through water column (°C)	Completion of fall mix: Amount of salt in water column (metric tons)	Ice Cover: Date complete cover forms	Ice Cover: Date complete cover melts
1939-40	7.6 22 on 9-24-39	early to mid-October 1939	n	11.7-12.8	n	12-28-39	4-11-40
1969-70	6.6 22.5 on 9-27-69	about 11-13-69	112	8-9	8,510	12-23 to 12-24-69	4- 6-70
1970-71	6.9 22.5 on 9-25-70	about 11-25-70	123	7-8	9,340	12-29 to 12-30-70	between 4- 9 and 4-10-71
1971-72	5.7 22.6 on 10-12-71	about 12-10-71	168	4-5	12,610	1-16 to 1-17-72	4-13-72
1972-73	5.0 22.5 on 9-27-72	about 12- 1-72	160	3-4	11,800	1-7 to 1-8-73	3- 9-73
1973-74	n	n	n	n	n	n	n
1974-75	8.4 22.5 on 10-10-74	between 10-28 and 11-25-74	123	6-7	9,300	n	before 3-27-75
1975-76	8.5 22.5 on 9-25-75	about 11-28-75	116	7-8	8,800	n	about 3- 8-76
1976-77	9.6 22.5 on 9-20-76	between 9-20 and 10-27-76	100	8-9	7,480	n	before 3-16-77
1977-78	8.9 22.0 on 10-13-77	after 10-28-77	98	9-10	7,460	unknown but before 2-23-78	between 3-29 and 4-13-78
1978-79	7.8 22.0 on 9-26-78	between 11-6 and 11-21-78	120	8-9	9,060	unknown but before 1-17-79	3-25-79
1979-80	6.5 22.0 on 9-26-79	between 11-7 and 11-20-79	106	6-7	8,050	unknown but before 2-18-80	3-30-80
1980-81	7.7 22.0 on 10-15-80	between 10-30 and 11-12-80	92	7-8	7,000	unknown but before 1-14-81	between 2-18 and 2-25-81
1981-82	9.1 22.0 on 9-22-81	between 10-20 and 10-27-81	110	9-10	8,340	between 1-9 and 1-16-82	4- 1-82
1982-83	6.5 22.0 on 9-21-82	between 11-23 and 11-30-82	124	6-7	9,370	1-21-83	3- 6-83
1983-84	7.9 22.0 on 9-20-83	between 11- 7 and 11-15-83	109	7-8	8,240	between 12-21 and 12-28-83	4- 3-84
1984-85	5.9 22.0 on 9-25-84	about 11-20-84	111	6-7	8,400		

* 1939-40 data from Tressler and others (1953).
1969-73 data from Diment and others (1974).
1973-84 data from Monroe County Environmental Health Laboratory.

*characteristics of Irondequoit Bay, including of NaCl salt in the water column.**

liter; n, no data available.]

Year (fall-spring)	Seasonal snowfall and salt application: Total snow (cm)	Salt applied to basin (metric tons)	Completion of spring mix: Date of maximum spring mix	Thickness of unmixed layer (m)	Chloride concentration through water column (3m)	(22m)	Amount of salt in water column (metric tons)	Mean chloride concentration in water column (mg/L)
1939-40	138	n	between 4-11 and 4-28-40	0	n	n	n	n
1969-70	305	76,600	between 4-27 and 4-28-70	5	200	360	15,710	207
1970-71	363	73,500	between 4-13 and 4-15-71	8	202	410	16,770	221
1971-72	267	68,900	between 4-25 and 4-26-72	11	228	395	18,840	248
1972-73	185	64,000	late 4-73	3	151	244	11,700	154
1973-74	254	53,400	n	n	n	n	n	n
1974-75	232	35,800	about 3-27-75	0	166	166	12,600	166
1975-76	220	30,600	about 3-22-76	0	158	163	12,000	159
1976-77	235	35,000	about 3-30-77	0	149	173	11,500	152
1977-78	408	30,000	between 4-13 and 5- 4-78	0	117	138	9,100	120
4978-79	350	n	between 3-28 and 5- 2-79	0	128	136	9,850	130
1979-80	84	22,700	between 4-17 and 4-30-80	0	116	122	8,830	116
1980-81	240	29,000	between 4- 8 and 4-24-81	0	130	130	9,860	130
1981-82	326	34,600	between 4- 1 and 4-14-82	0	150	150	11,400	150
1982-83	153	18,900	between 3- 9 and 3-15-83	0	140	150	10,700	141
1983-84	300	37,800	between 4-17 and 5- 2-84	10	140	216	11,200	147

was decreased after the mid-1970's, however, and the autumnal mixing characteristics returned to a more normal pattern. The data in table 5 show that, after 1975-76, fall mixing occurred 3 to 4 weeks earlier than it did during 1971 and 1972 and was completed at water-column temperatures 3°C to 5°C higher than in 1971 and 1972. Thus, the periods of summer stratification and hypolimnetic anoxia after 1975-76 were shorter than in the early 1970's until the summer of 1984.

The low temperatures of the bottom water of the hypolimnion at the end of September suggest the potential for a resistance to mixing, especially when salt concentrations are high. Bottom temperatures in the fall of 1971 and 1972, when fall mixing was delayed, were between 5°C and 6°C (table 5); those from then until September 1983 were 1.5°C to 3.5°C higher, which suggests less resistance to mixing during the time of fall turnover. Hypolimnetic temperatures after the spring 1984 meromixis were lower than in any summer since the early 1970's, however, and those in late September 1984 were slightly below 6°C for the first time since September 1972 (table 5). Although this did not seem to greatly delay autumnal mixing in November 1984, it marked the return of the potential for resistance to mixing that was common in the fall of earlier years, in which a previous spring meromixis occurred.

Stratification Characteristics of the Bay

A series of graphs depicting the depth distribution (stratification) of four variables at the deepest part of the bay (station 1) each year from 1978 through 1984 are plotted at the end of this section (fig. 7A-7G, p. 30-43). The variables are water temperature, specific conductance, dissolved oxygen, and chloride concentration. Comparison of these patterns with those of 1970-72, given by Diment and others (1974), allows the following observations.

Water Temperature

Profiles showing the vertical distribution of water temperature, specific conductance, and chloride at station 1 in August 1971 and in August 1982 are given in figures 6A and 6B, respectively (p. 28-29). Comparison of the temperature profiles for these 2 years shows a well-developed metalimnetic thermocline that remained at the same depth and did not change in thickness. Six of the seven years from 1978 through 1984 (figs. 7A-7G) suggest inverse thermal stratification beneath the ice cover, but only three of these years (1978, 1979, and 1984) had sufficient sampling to obtain a consistent plot (figs. 7A, 7B, 7G) during ice cover. The 1979 plot (fig. 7B) suggests that the cold, dense, oxygen-saturated saline water that enters the deep part of the bay during ice cover occasionally disrupts inverse thermal stratification. This was more obvious in the early 1970's (Diment and others, 1974) because saline concentrations were higher and the sampling beneath the ice more frequent. In general, the thermal stratification patterns of 1978-84 (figs. 7A-7G) are similar to those of the early 1970's, and in both periods, bottom-water temperatures during summer stratification were always 2°C to 3°C lower after a spring meromixis (fig. 7G) than after a complete vernal mix (figs. 7A-7F).

Specific Conductance

The specific-conductance profiles for August 1971 and August 1982 (fig. 6A, 6B) show differing gradients through the metalimnion. The summers of 1970, 1971, and 1972 showed differences of about 250, 300, and 500 µS/cm (microsiemens per centimeter at 25° celsius) from the top to the bottom of the metalimnetic thermocline (Diment and others, 1974). Most of the metalimnetic gradients of the 1978-84 summers (figs. 7A-7G) are poorly developed and showed differences of only 50 to 150 µS/cm. Metalimetic gradients that developed in the late summers of 1979 and 1984 were the best defined, but the top-to-bottom differences were only about 150 µS/cm (figs. 7B, 7G). Although the specific conductance values through the water column in the summer of 1984 (fig. 7G) were higher than those of the six preceding years, they remained much lower than those of 1970-72 (fig. 6A; Diment and others, 1974).

All specific-conductance contours in figure 7 reflect the influence of chloride throughout the water column. This is especially true during and just after ice cover (late December to early April), when abrupt increases in specific conductance and strong stratification of the bottom water coincide with chloride inflows during winter thaws and spring runoff. This relation is evident in the winter months of each year (figs. 7A-7G). Although the specific conductance of bottom water was relatively high during each winter and early spring of 1978-84, it was about 35 percent lower than that of the same seasons in the early 1970's (compare fig. 7 with Diment and others, 1974), which is consistent with the reduction in salt concentrations within the bay after 1974-75.

Dissolved Oxygen

The epilimnion of the bay is well oxygenated during the growing season because of the high biologic productivity of the bay. The bay also receives ample oxygen under the ice from the well-oxygenated, relatively dense water that enters from tributaries. Oxygen stratification formed throughout the water column under ice cover each winter during 1978-84 (fig. 7A-7G) as it did in the winters of 1970-72. Anoxic conditions developed in the bottom water under ice during 1978 and 1979 (figs. 7A, 7B), when a pronounced inverse thermal stratification occurred; this also was a common occurrence in the winters of 1970-72. After 1979, however, anoxia did not develop or persist to the extent that it did in the early 1970's (figs. 7C-7G). With weaker chemical stratification beneath the ice (because of reduced salt inflow), the cold, well-oxygenated water entering the basin after 1979 was able to disrupt the bottom-water stratification more readily than in high-salt years. Thus, as long as the bottom water is replenished with oxygen frequently during winter, the oxygen demand of the bottom sediments will be matched or exceeded, and anoxic conditions probably will not develop.

The bay mixed completely to the bottom each spring from 1975 through 1983 (figs. 7A-7F); thus, any anoxic or low-oxygen conditions that developed during ice cover were destroyed during spring turnover, when oxygen was redistributed throughout the water column. Oxygen persisted longer in the upper and middle waters of the hypolimnion during 1978-84 than during 1970-72 and often lasted from mid- to late June before it was consumed (figs. 7B, 7E, 7F, 7G). During 1970-72, incomplete mixing caused at least 9 months of consistent anoxia in the bottom water each year and 6 to 7 months of anoxia each year up to the lower part of the metalimnetic thermocline. After 1978, however, as indicated in figures 7B-7F, the bay had only 5 to 6 months of consistent anoxic conditions per year as long as complete mixing occurred each spring and fall. When mixing failed to occur in April 1984 (fig. 7G), anoxic conditions developed earlier than in previous years in bottom waters, then persisted throughout the hypolimnion, for 7.5 months. This was the longest period of anoxia the bay had experienced since the early 1970's (Diment and others, 1974).

Chloride

Chloride concentrations in the water column during August 1971 and August 1982 are compared in figures 6A and 6B. Although the amount of chloride in the bay was significantly less in the early 1980's than in the early 1970's, chloride is still the major dissolved constituent that controls the mixing patterns and stratification characteristics of the bay (fig. 7A-7G). The lines of equal chloride concentration through the summer months of 1978-83 are

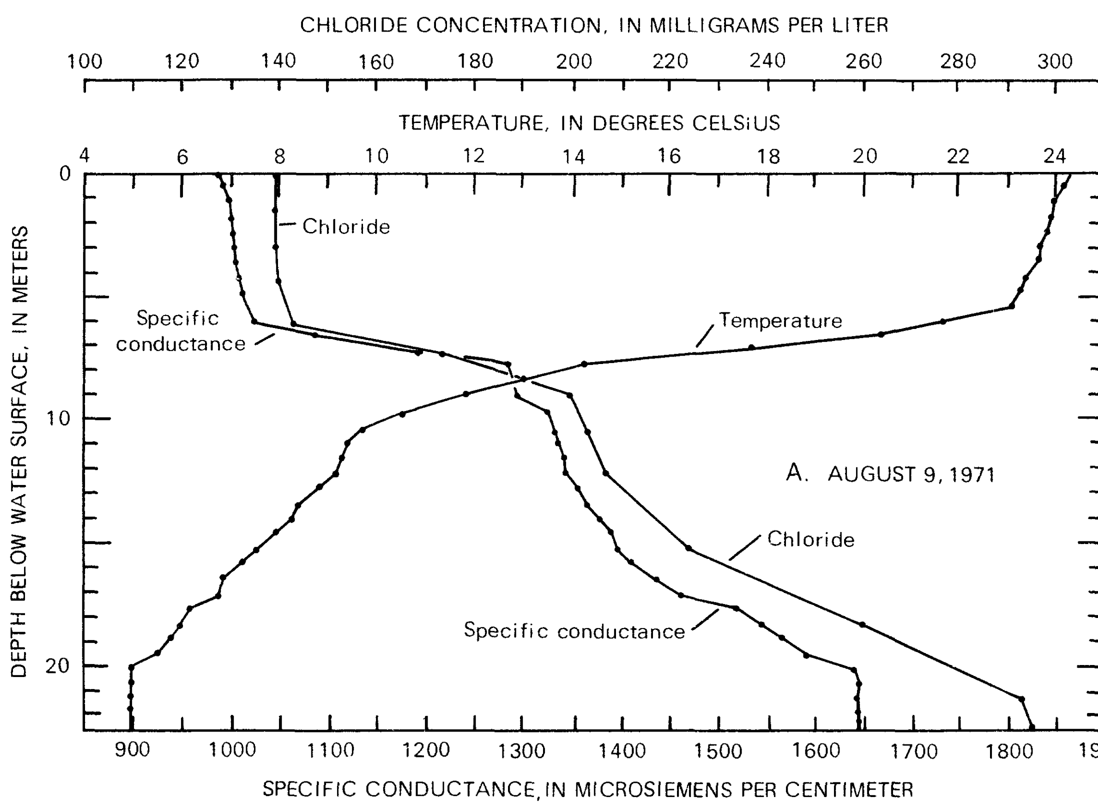


Figure 6A.--Vertical distribution of water temperature, specific conductance, and chloride concentration in Irondequoit Bay, station 1, on August 9, 1971.

few and widely dispersed (figs. 7A-7F), which indicates poorly defined chloride stratification. This in turn allows for relatively rapid mixing during fall turnover and contrasts sharply with the strong chloride stratification of the summers of 1970-72 (fig. 6A).

The chloride contour lines during ice cover and immediately after spring mixing (late December to early April, figs. 7A-7G) illustrate the accumulation of chloride-laden water in the deep part of the bay during winter thaws and spring runoff. This is evident for each winter of 1978-84. Relatively cold, chloride-laden, dense, well-oxygenated water enters the bay from Irondequoit Creek at the south end, from Densmore Creek to the west, and from small streams around the shore of the bay. Much of this water enters during short periods of rapid runoff and affects the stratification characteristics of the bay by (1) disturbing the development of inverse thermal stratification; (2) replenishing the dissolved oxygen that is being consumed near the bottom; (3) enhancing the overall chemical stratification (chloride plus other dissolved constituents) of the bottom water, as reflected by specific conductance; (4) adding to the reservoir of chloride that was carried over from the previous fall mix; and (5) increasing the net density gradient that must be overcome after the ice melts if the bay is to mix completely to the bottom.

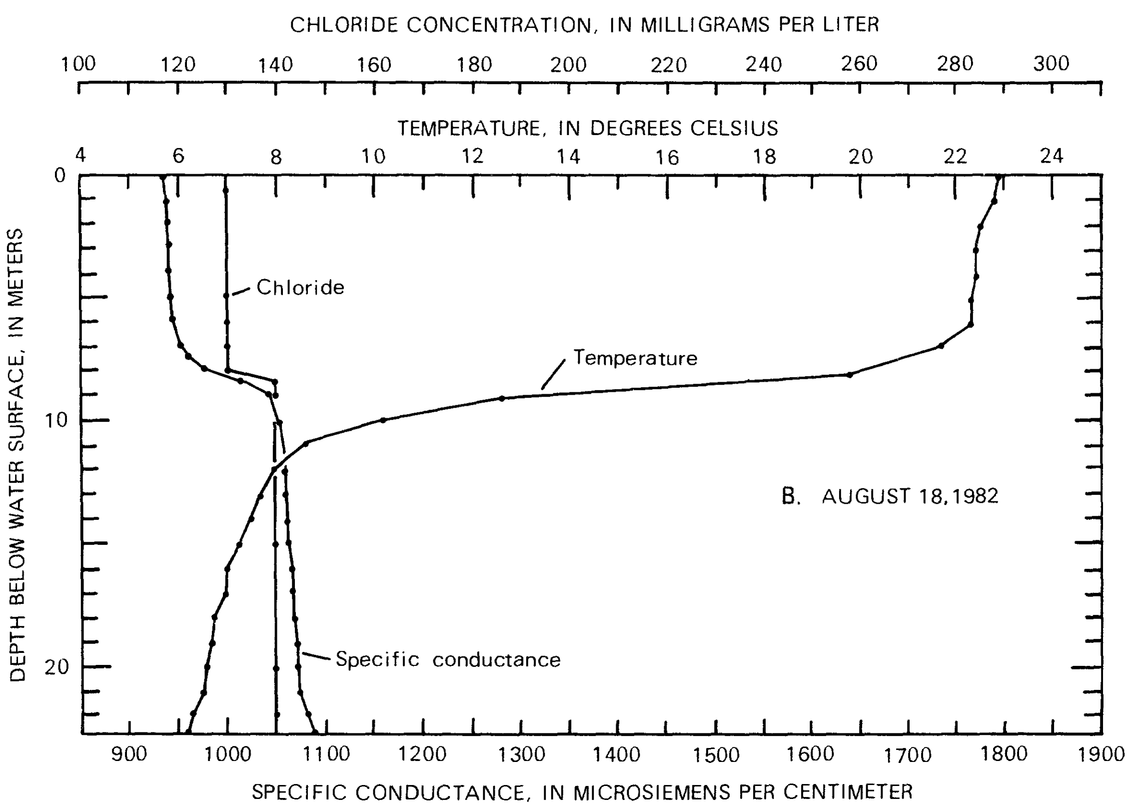
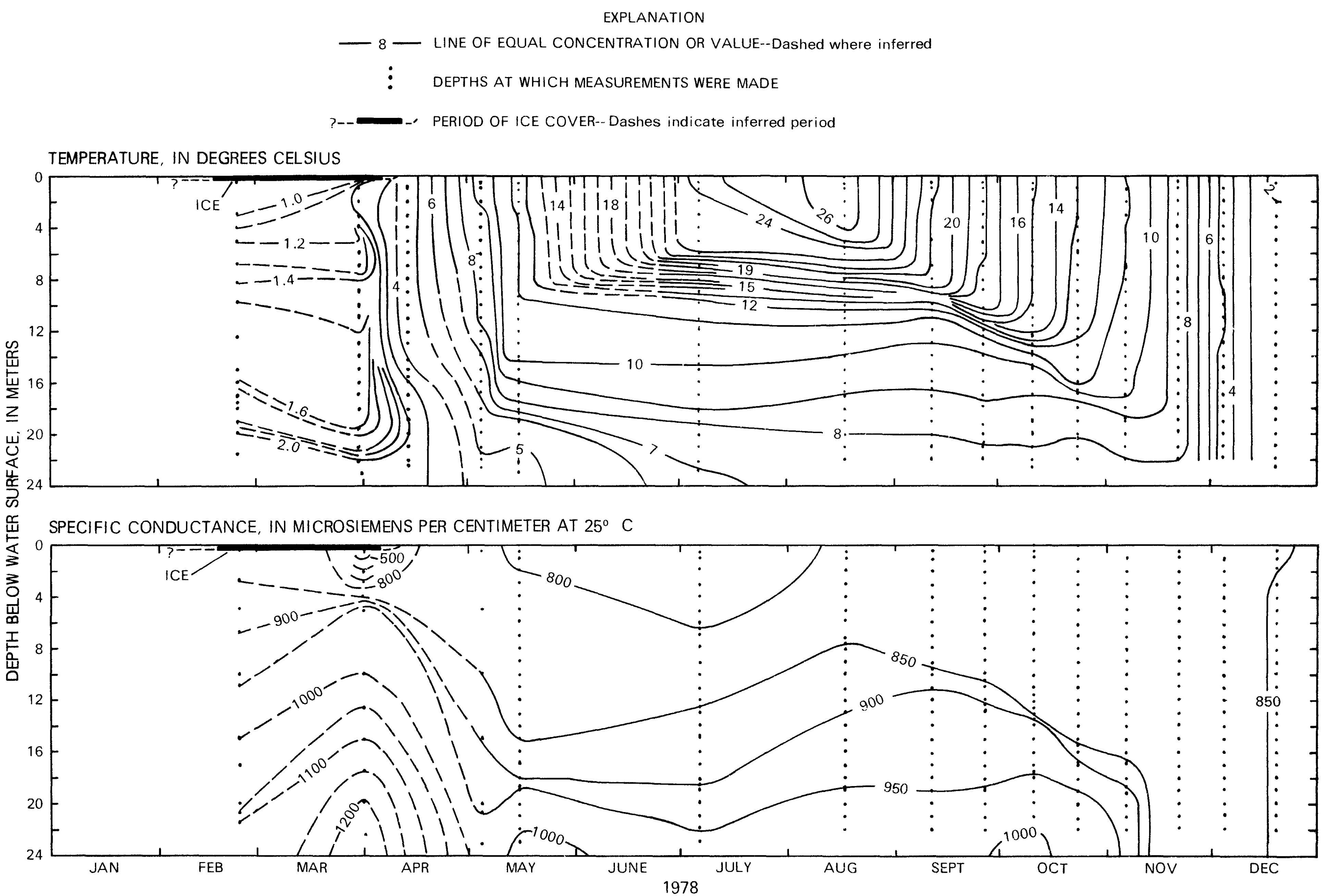


Figure 6B.--Vertical distribution of water temperature, specific conductance, and chloride concentration in Irondequoit Bay, station 1, on August 18, 1982.


EXPLANATION
8 LINE OF EQUAL CONCENTRATION OR VALUE--Dashed where inferred
DEPTHS AT WHICH MEASUREMENTS WERE MADE
?-- PERIOD OF ICE COVER-- Dashes indicate inferred period
TEMPERATURE, IN DEGREES CELSIUS
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25° C
DEPTH BELOW WATER SURFACE, IN METERS
ICE
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
1978

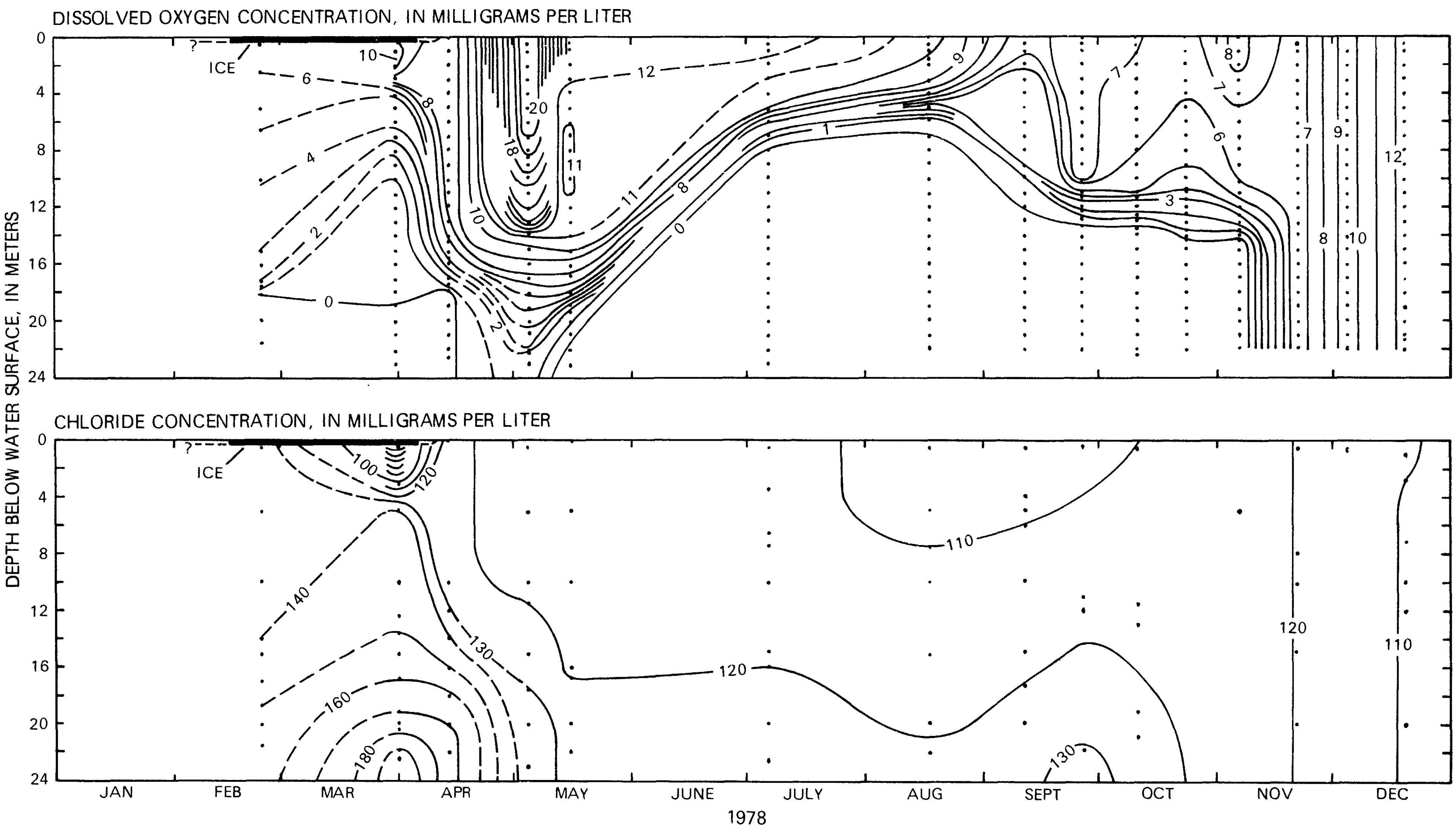
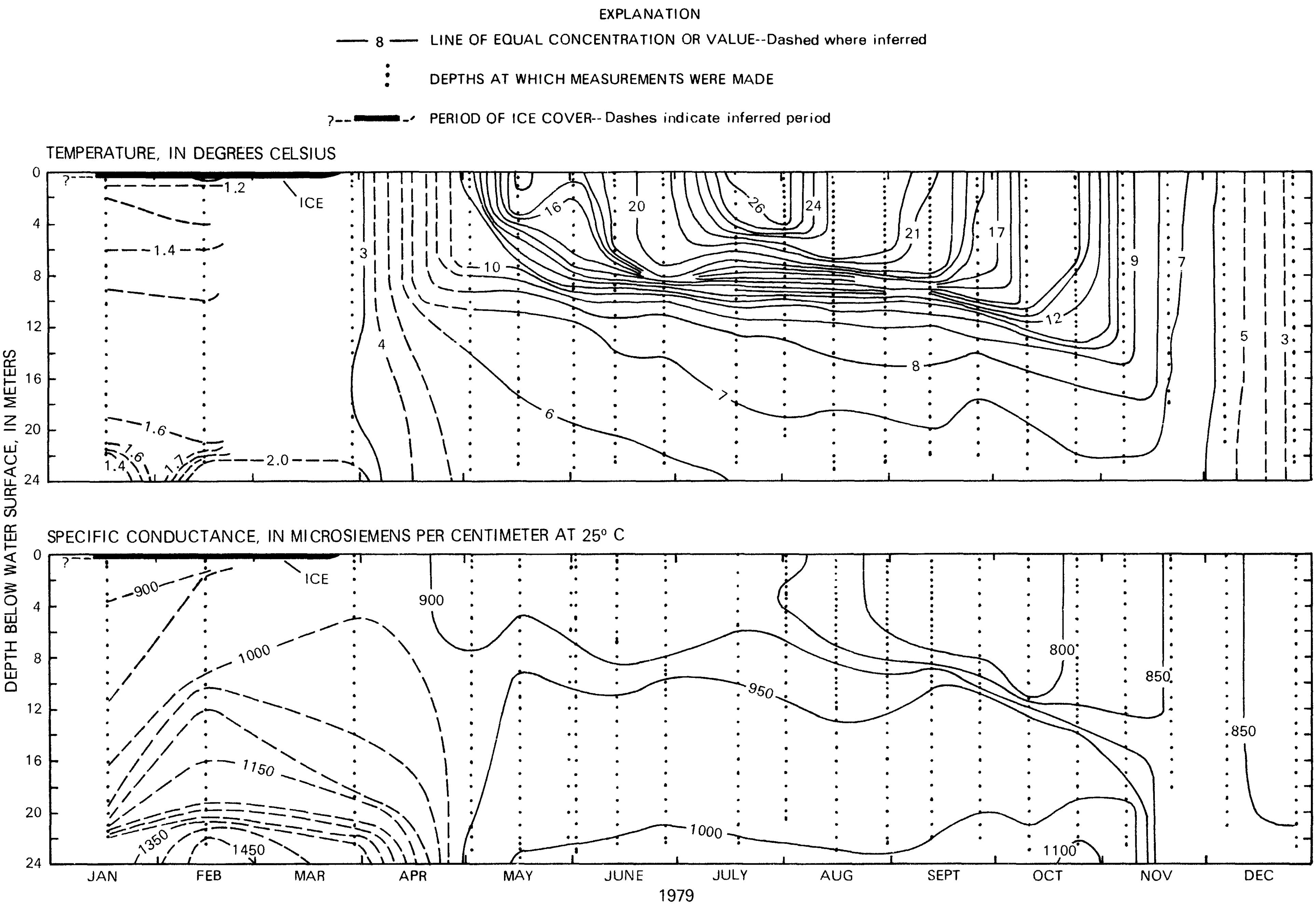


Figure 7A.--Vertical distribution of water temperature, specific conductance, dissolved oxygen, and chloride concentration in Irondequoit Bay, station 1, calendar year 1978.


EXPLANATION
8 LINE OF EQUAL CONCENTRATION OR VALUE--Dashed where inferred
DEPTHS AT WHICH MEASUREMENTS WERE MADE
? PERIOD OF ICE COVER-- Dashes indicate inferred period
TEMPERATURE, IN DEGREES CELSIUS
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25° C
DEPTH BELOW WATER SURFACE, IN METERS
ICE
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
1979

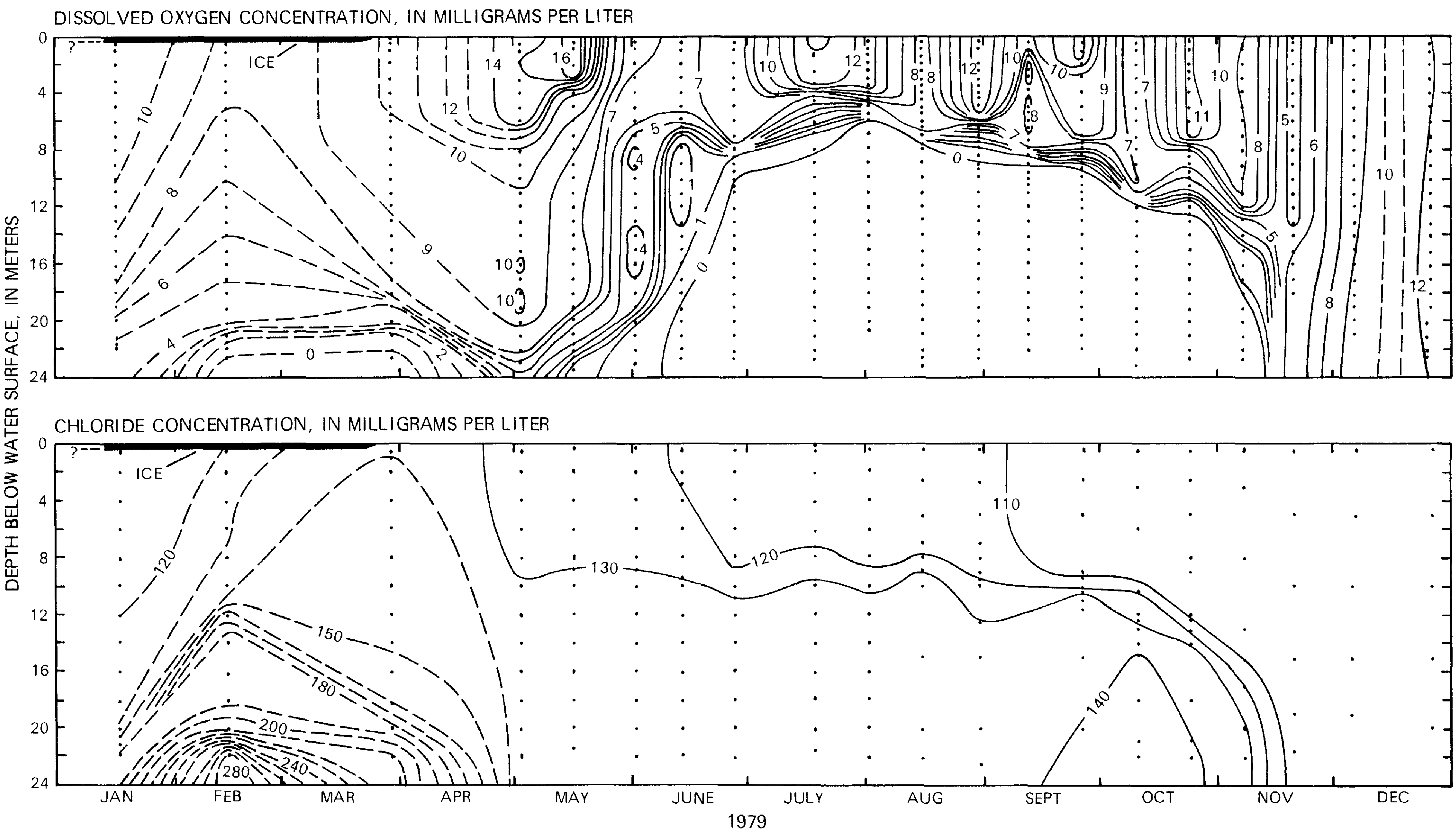
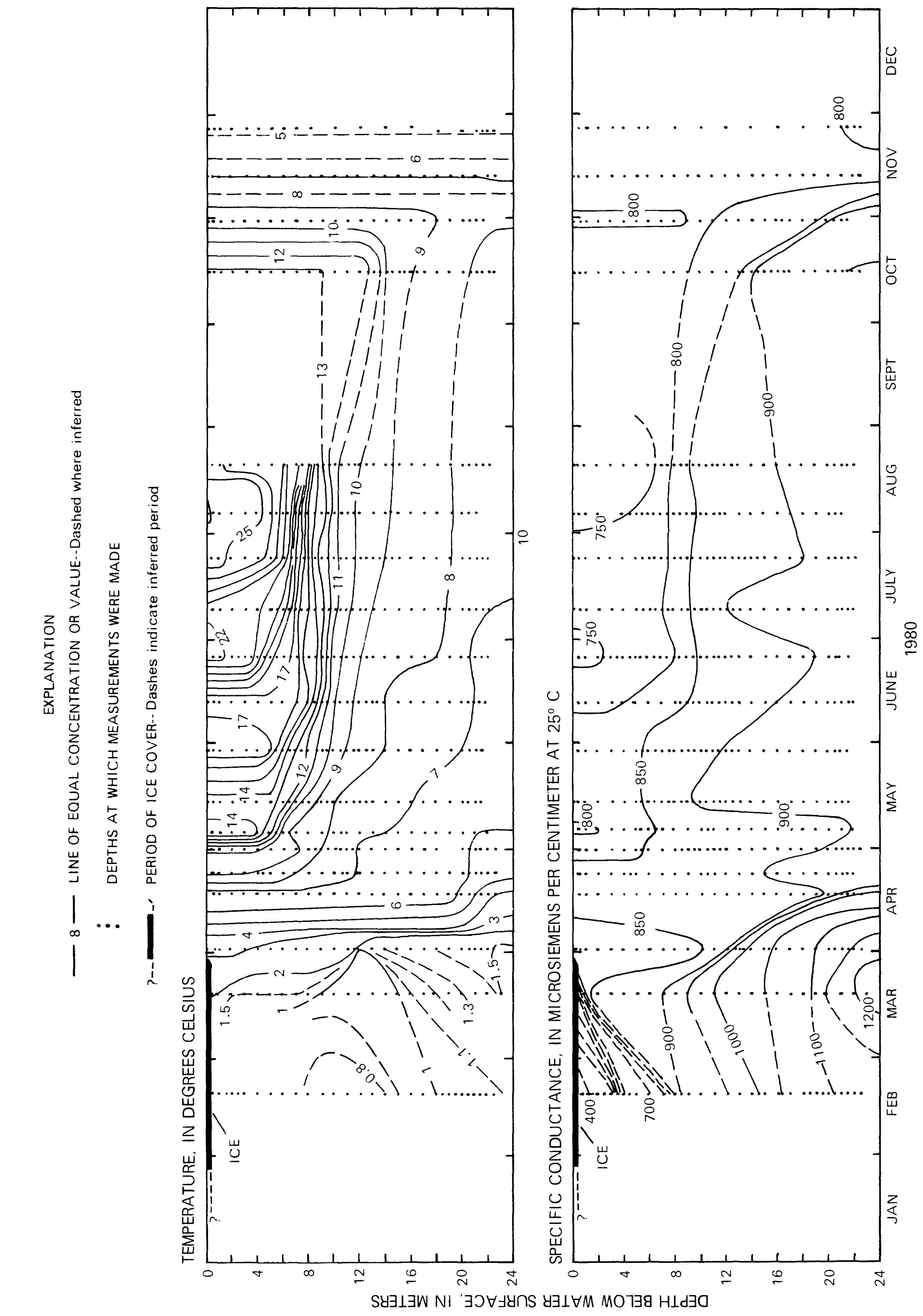


Figure 7B.--Vertical distribution of water temperature, specific conductance, dissolved oxygen, and chloride concentration in Irondequoit Bay, station 1, calendar year 1979.


EXPLANATION
8 LINE OF EQUAL CONCENTRATION OR VALUE--Dashed where inferred
DEPTHS AT WHICH MEASUREMENTS WERE MADE
? PERIOD OF ICE COVER-- Dashes indicate inferred period
TEMPERATURE, IN DEGREES CELSIUS
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25° C
DEPTH BELOW WATER SURFACE, IN METERS
ICE
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
1980

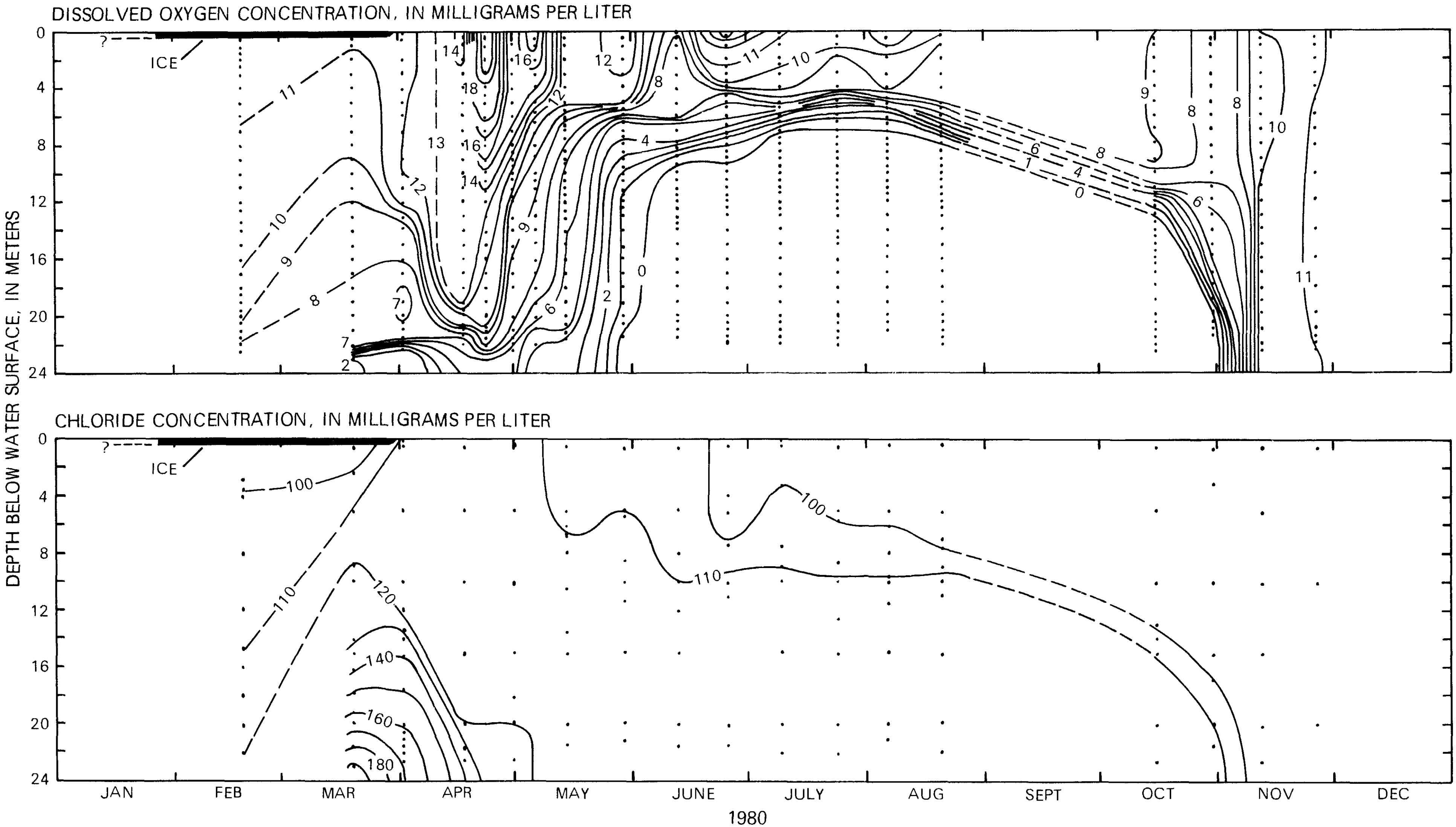
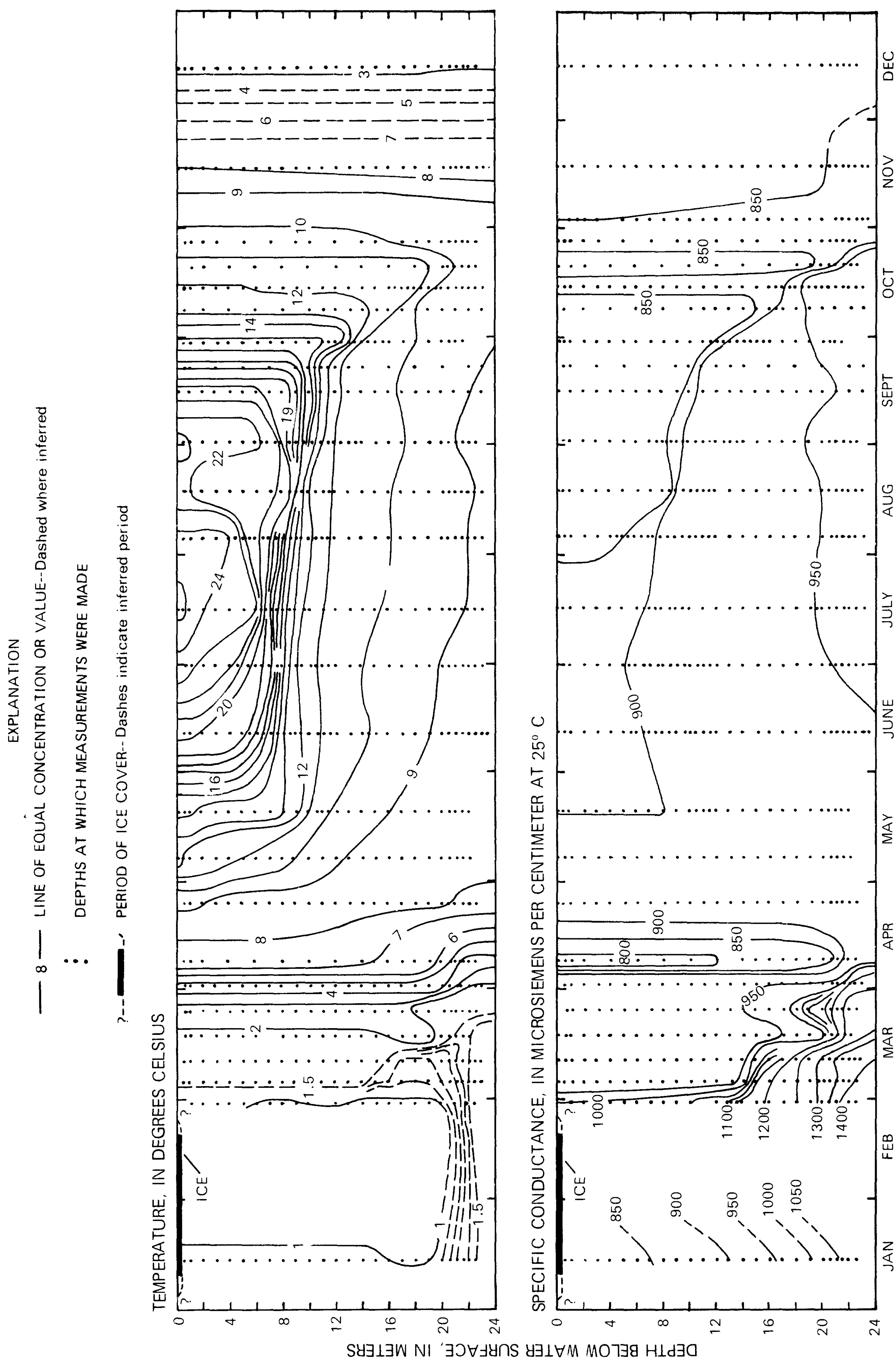


Figure 7C.--Vertical distribution of water temperature, specific conductance, dissolved oxygen, and chloride concentration in Irondequoit Bay, station 1, calender year 1980.



EXPLANATION
8 LINE OF EQUAL CONCENTRATION OR VALUE--Dashed where inferred
DEPTHS AT WHICH MEASUREMENTS WERE MADE
PERIOD OF ICE COVER--Dashes indicate inferred period
TEMPERATURE, IN DEGREES CELSIUS
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25° C
DEPTH BELOW WATER SURFACE, IN METERS
ICE
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
1981

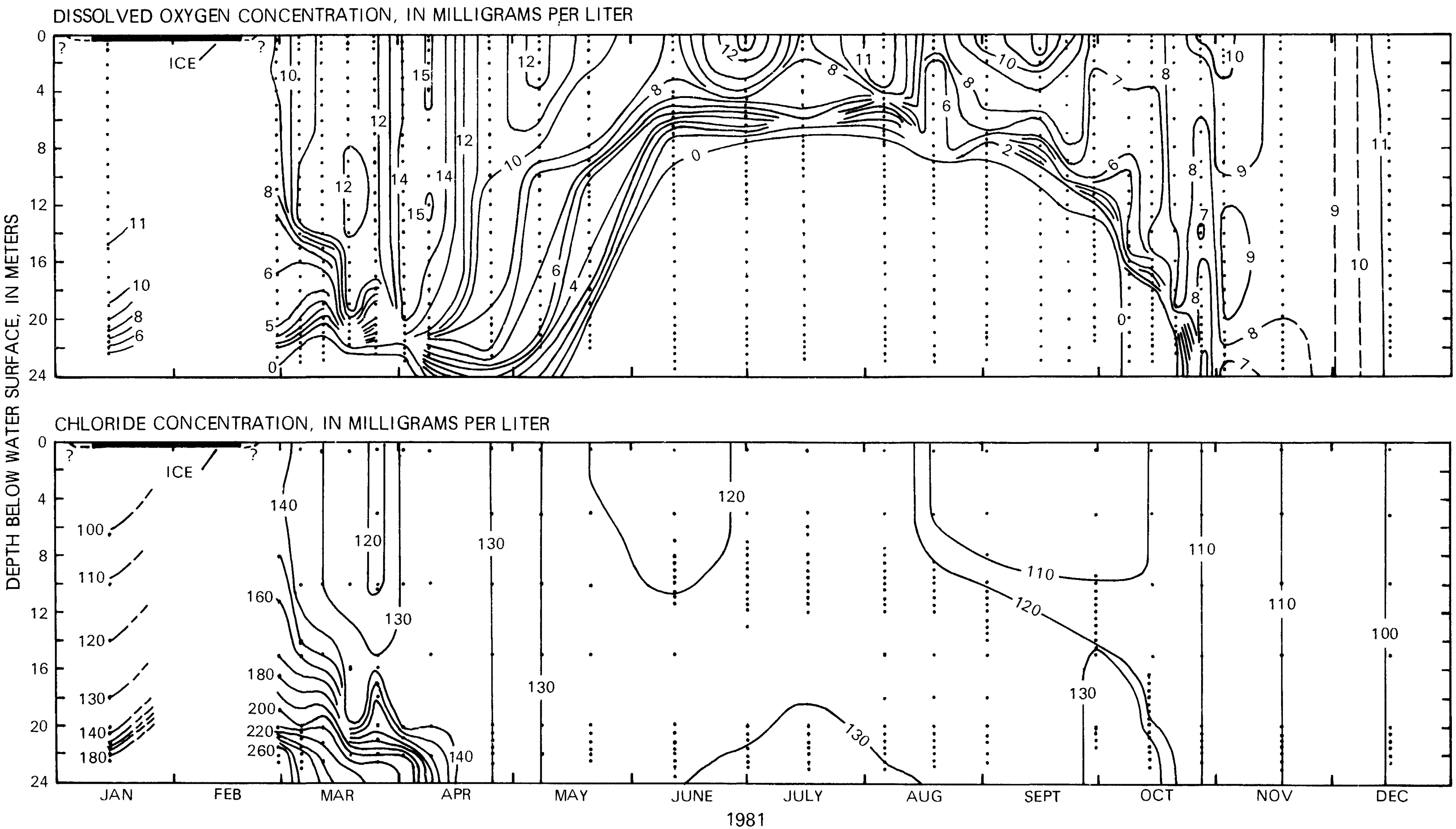
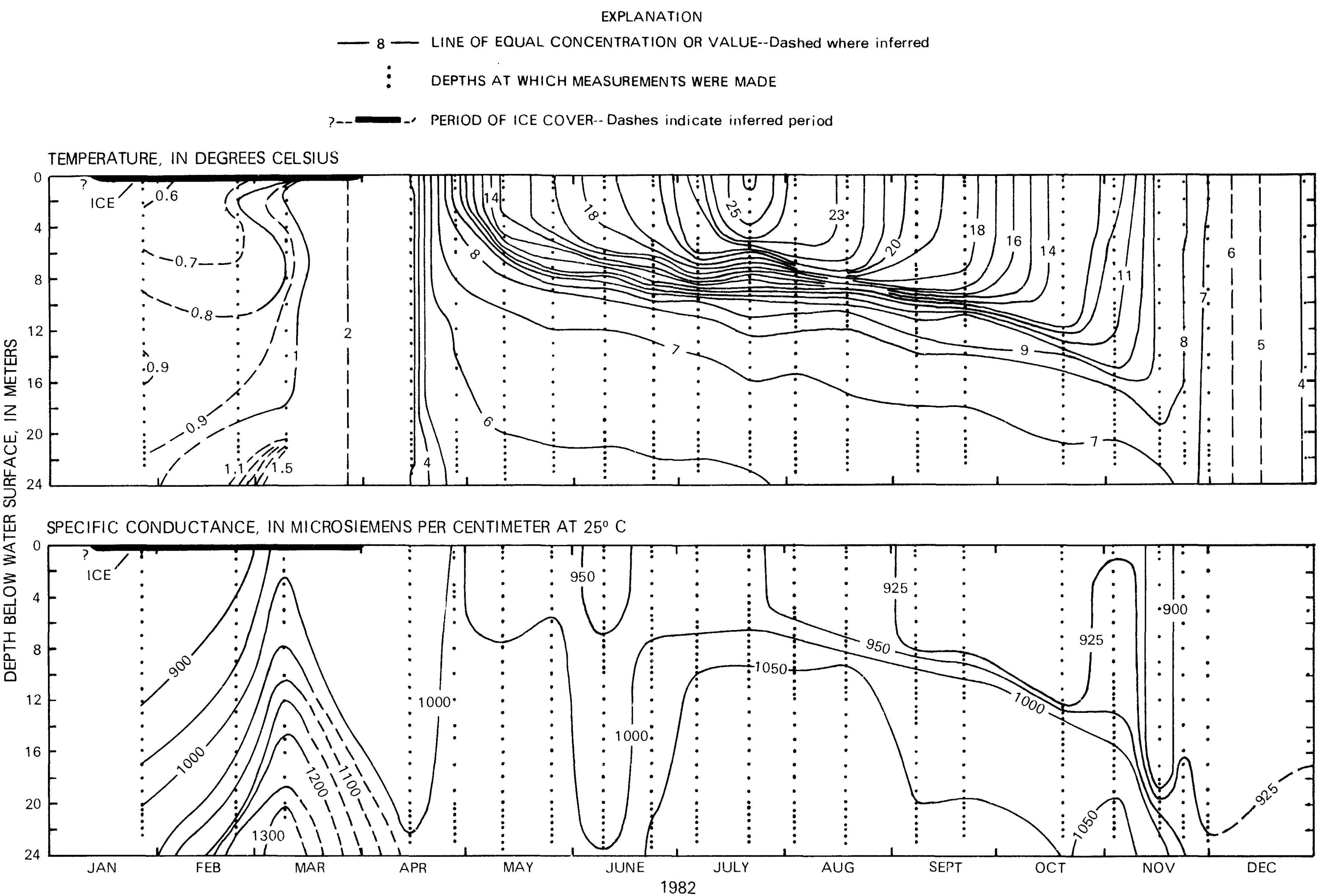


Figure 7D.--Vertical distribution of water temperature, specific conductance, dissolved oxygen, and chloride concentration in Irondequoit Bay, station 1, calender year 1981.


EXPLANATION
8 LINE OF EQUAL CONCENTRATION OR VALUE--Dashed where inferred
DEPTHS AT WHICH MEASUREMENTS WERE MADE
? PERIOD OF ICE COVER--Dashes indicate inferred period
TEMPERATURE, IN DEGREES CELSIUS
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25° C
DEPTH BELOW WATER SURFACE, IN METERS
ICE
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
1982

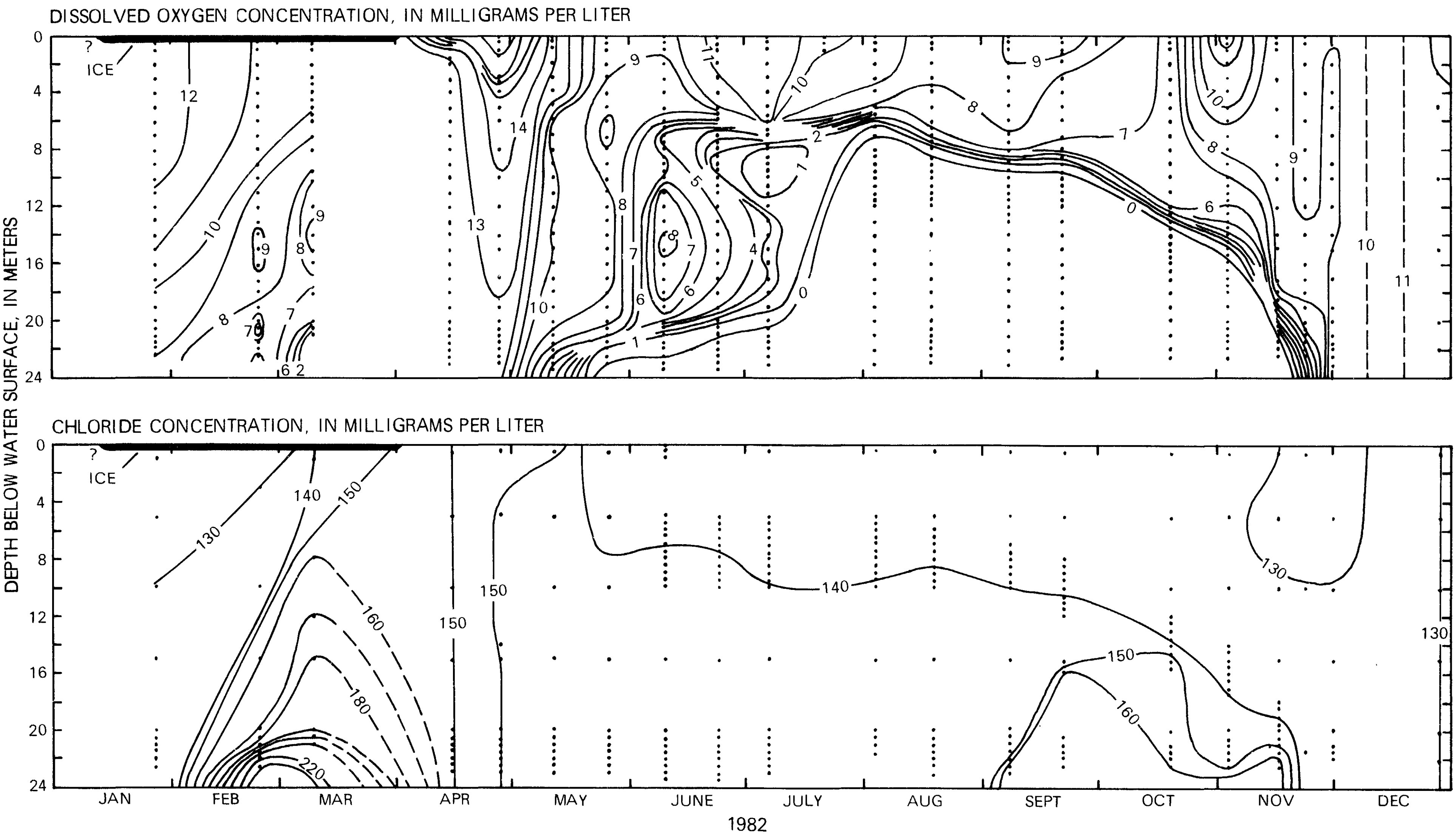


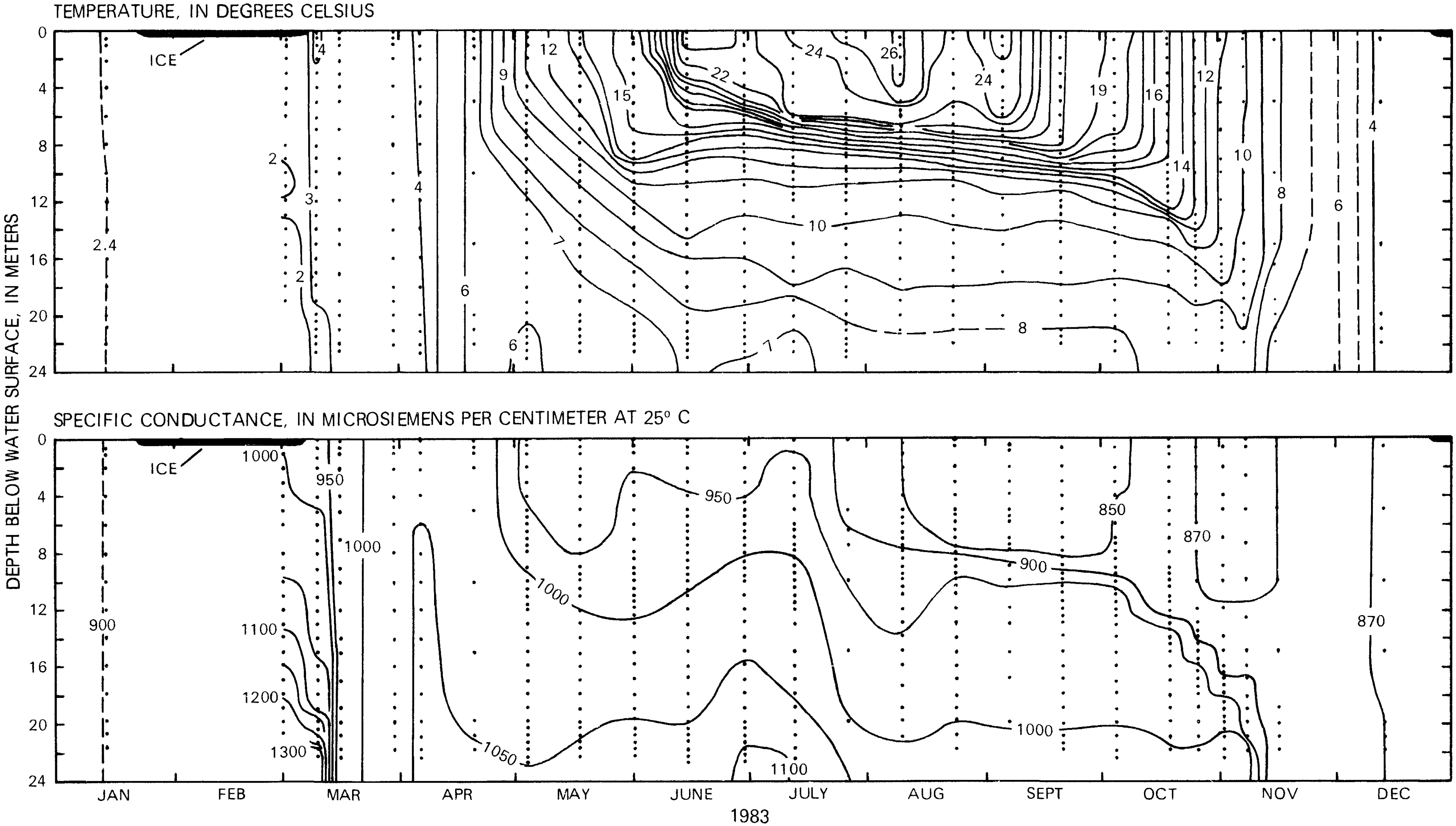
Figure 7E.--Vertical distribution of water temperature, specific conductance, dissolved oxygen, and chloride concentration in Irondequoit Bay, station 1, calendar year 1982.

EXPLANATION

— 8 — LINE OF EQUAL CONCENTRATION OR VALUE--Dashed where inferred

⁝ DEPTHS AT WHICH MEASUREMENTS WERE MADE

?--▬-- PERIOD OF ICE COVER--Dashes indicate inferred period



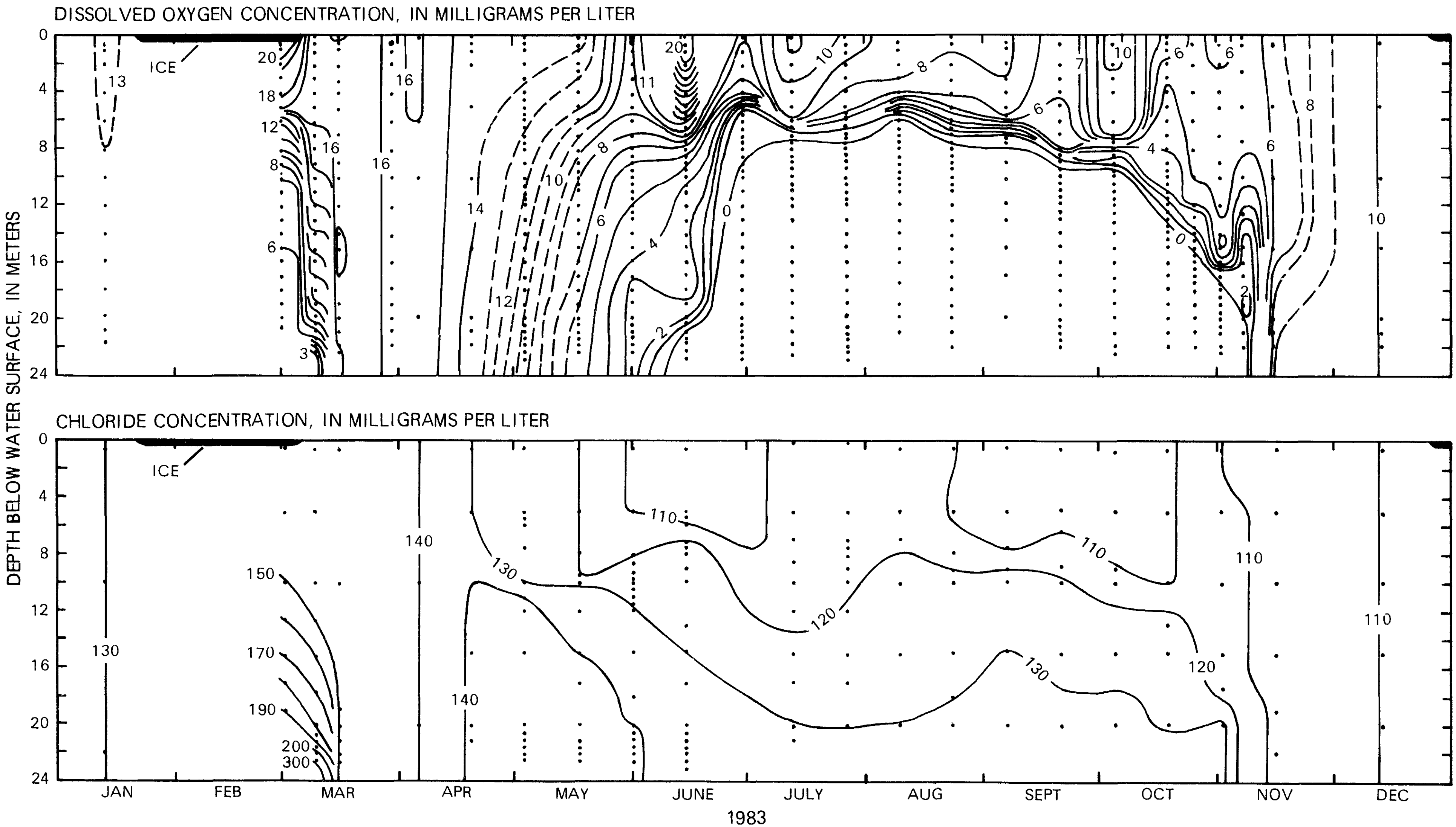
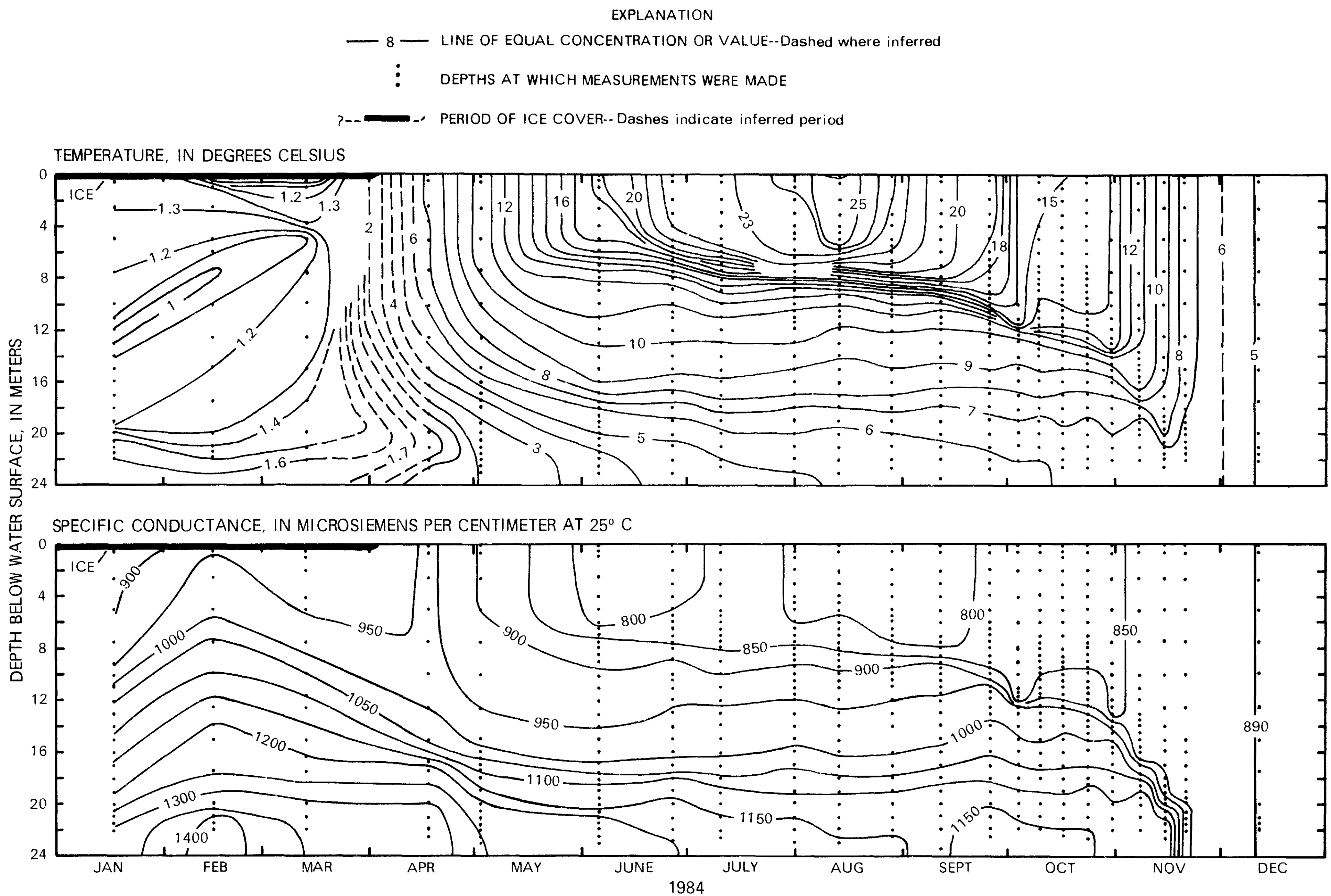


Figure 7F.--Vertical distribution of water temperature, specific conductance, dissolved oxygen, and chloride concentration in Irondequoit Bay, station 1, calendar year 1983.


EXPLANATION
8 LINE OF EQUAL CONCENTRATION OR VALUE--Dashed where inferred
DEPTHS AT WHICH MEASUREMENTS WERE MADE
?-- PERIOD OF ICE COVER-- Dashes indicate inferred period
TEMPERATURE, IN DEGREES CELSIUS
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25° C
ICE
DEPTH BELOW WATER SURFACE, IN METERS
0
4
8
12
16
20
24
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
1984

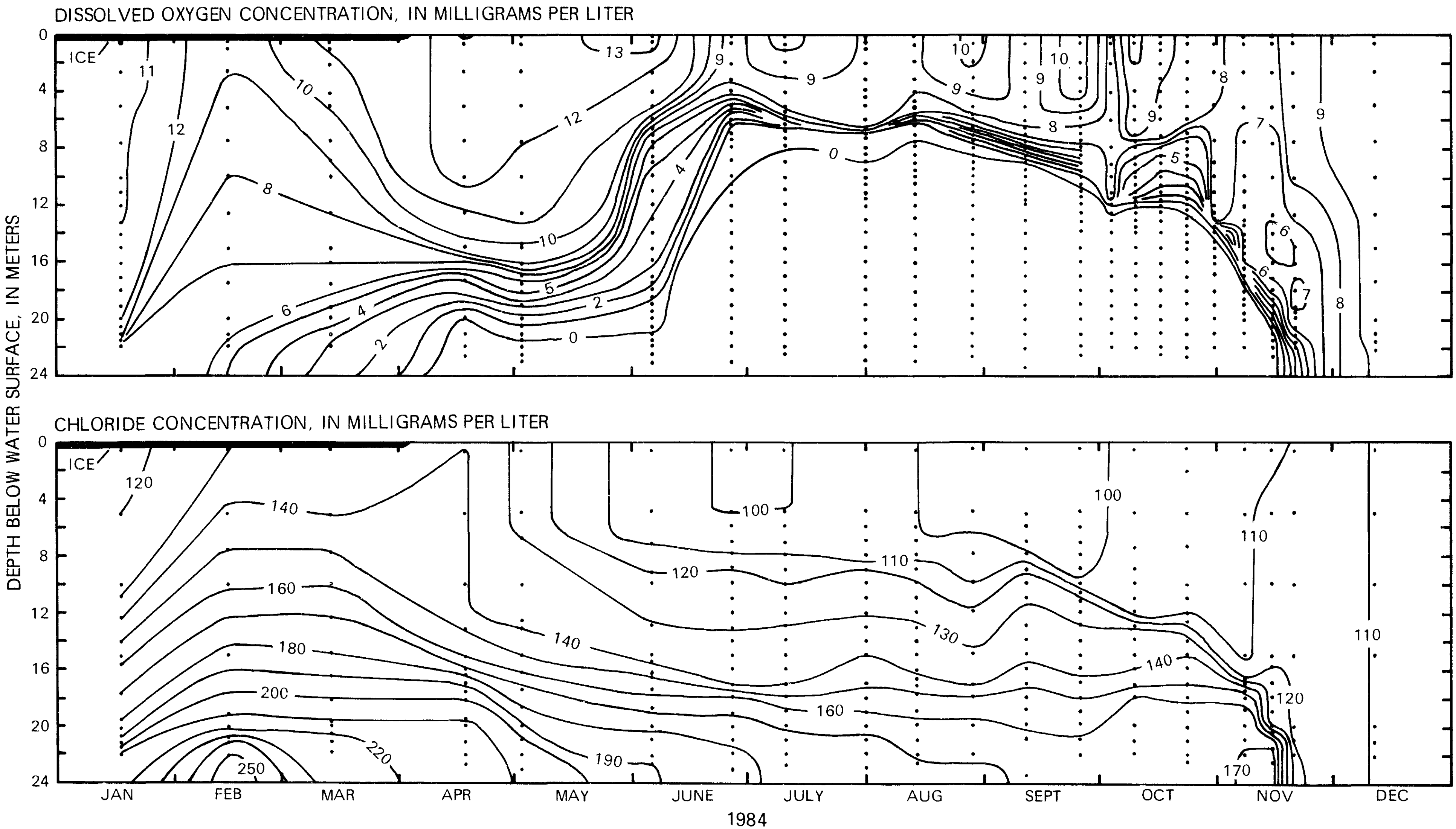


Figure 7G.--Vertical distribution of water temperature, specific conductance, dissolved oxygen, and chloride concentration in Irondequoit Bay, station 1, calendar year 1984.

RETURN OF SPRING MEROMIXIS IN 1984

Spring holomixis resumed by 1975 at the latest (table 5; Burton, 1976) and continued each spring until 1984 (fig. 7G). Although the use of salt within the basin increased slightly in 1981-82 (34,600 metric tons), 1982-83 had only 153 cm of snow and a reduced use of salt (18,900 metric tons). In 1983-84, however, snow was frequent, and the use of salt doubled to 37,800 metric tons. The salt that entered the bay during ice cover increased the gradient through the water column each month of that winter (fig. 7G) more than in any of the previous six winters (7A-7F). In addition, precipitation (sleet, snow, freezing rain) in March was frequent with alternating freezing and thawing (National Oceanic and Atmospheric Administration, 1984), which resulted in increased use of salt in late winter and early spring; therefore, chloride-laden water continued to enter the bay just before, during, and after the ice cover melted April 3, 1984.

Relatively high chloride loads entered the bay from Irondequoit Creek throughout March and early to mid-April 1984. Thus, as the water column warmed to maximum density and mixing began in the upper waters of the bay, chloride-laden runoff maintained the chloride stratification (and therefore the density gradient) in the lower half of the water column. (See fig. 7G.) By April 17, chloride in the water column was mixed (140 mg/L) to only about 12 m below water surface. The temperature at 12 m was 5.2°C; that at the surface was 7.2°C. Although the upper half of the water column was still being mixed by the work of the wind and heat, the chloride gradient of the bottom water was maintained. By May 2, the 140-mg/L-concentration zone had dropped only 1 m, to the 13-m depth, at which the temperature was 7.7°C; that at the surface was 10.5°C. Surface mixing continued, but thermal stratification had developed by mid-May, and complete mixing did not occur below about 13 m. Even though the chloride concentration at 13 m decreased to 130 mg/L by early June, it remained at about that depth until the onset of fall mixing, while the chloride gradient below it diffused only slightly.

Complete fall mixing occurred about November 20, 1984. The amount of salt in the water column at the time of fall mixing in 1984 (8,400 metric tons) did not greatly exceed the amount after fall mixing in 1983 (8,240 metric tons). Thus, the bay gained little new salt from 1983 to 1984 despite the incomplete spring mix. The return of spring meromixis in 1984 was less a function of the amount of salt that entered the bay than the time at which it entered. This suggests that, if moderate but consistent loads of salt enter the bay during the winter, and if loading continues during and just after the ice cover melts (when mixing occurs), then the chloride-enhanced density gradient of the bottom water of the bay can inhibit complete mixing.

SUGGESSTIONS FOR FURTHER STUDY

For continued prudent management of the bay, the observations presented herein suggest a need to:

1. Expand the chloride-monitoring program on the bay to include temperature, specific conductance, dissolved oxygen, and chloride profiles at stations 2 and 3 (pl. 1) at least monthly.

2. Conduct frequent water-column measurements under ice and before and during spring mixing at stations 1 and 2 to document in detail the mixing processes with respect to time and depth.

3. Develop a chloride budget of the bay and its drainage basin. This would include studying the ground water and soil components to determine whether they are sinks or have become sources of the chloride salts that are distributed in the basin.

4. Design a quantitative model to simulate the chloride concentration, stratification, and mixing patterns of the bay in the spring and the fall, given the amount of salt that enters the bay, the times at which it enters, and the meteorological conditions within its drainage basin.

SUMMARY AND CONCLUSIONS

Irondequoit Bay is a coastal bay on the southern shore of Lake Ontario and is a major water resource of Monroe County, N.Y. It is surrounded by the suburbs of Rochester and forms an urban lake that is an important recreational asset. The bay's drainage basin occupies 438 km^2 and contains urban and suburban areas, farms, and woodlands. It is intersected by a network of highways and roads that are treated with deicing salts. Use of salt was heaviest in the late 1960's and early 1970's.

Irondequoit Creek--the major stream in the bay's watershed--receives most of the runoff containing salt and discharges it directly to the bay. Studies in the early 1970's showed that the bay not only had been culturally eutrophic for decades but that salts from deicing, in use since the 1950's, were accumulating throughout the water column. Results of these studies showed that (1) summer chloride concentrations in the creek and in water at the surface of the bay had increased fourfold since the 1950's, (2) runoff containing these salts accummulated in the bottom water and caused a density gradient that prevented complete mixing in the spring months of 1970-73, (3) summer chemical and thermal stratification was prolonged later each fall as the net mass of chloride in the bay increased each year, and (4) about half the salt used for deicing in the winter was removed by surface runoff; the remainder was presumably stored in the soil and may have entered the ground water.

In the mid-1970's, Monroe County began a cooperative effort with towns in the county to decrease the use of deicing salts and implemented a program to divert all sewage from the bay's drainage basin. This study, done in 1985, in cooperation with the Monroe County Department of Health, documented the changes in chloride concentration, mixing patterns, and stratification of the bay during the 10 years of decreased use of deicing salts from the 1974-75 winter through the 1983-84 winter.

Salt use in the drainage basin increased steadily in the late 1960's to a maximum of 76,600 metric tons in the winter of 1969-70. Salt use in the next four winters, although declining slightly, was still relatively high until 1974-75, when the results of the towns' effort to reduce the use of salt became evident. By the winter of 1979-80, salt use had decreased 70 percent below the 1969-70 amount. From 1980 to 1984 it increased again, but nevertheless, the net amount of salt distributed annually within the basin from 1969 through 1984 decreased by 61 percent. Coincident with the salt reduction, chloride concentrations in Irondequoit Creek at base flow (late summer) decreased, and chloride concentrations of the epilimnion of the bay during summer also declined. Other workers have reported a 40-percent reduction in the chloride load from the creek to the bay between 1970-72 and 1980-81.

In spring 1975, shortly after the salt-reduction program began, the bay's water column completely mixed to the bottom and continued to mix completely until the spring of 1984. Fall mixing occurred every year during 1969-84. During the early years of incomplete spring mixing, (1970-73), the salt content of the bay increased each year and reached a maximum of about 18,800 metric tons in spring 1972. Upon resumption of spring mixing and continuation of fall mixing in 1975, the salt content declined and, by spring 1980, had decreased by 53 percent to about 8,800 metric tons. In each of the next 4 years, the salt content remaining after each spring mix increased moderately and reached about 11,000 metric tons in 1984, which amounts to a 42-percent net reduction in salt content in the bay after spring mixing since the spring of 1972. The salt content after fall mixing also declined; it decreased by 45 percent from a high of 12,600 metric tons in 1971 to 7,000 metric tons by the fall of 1980. Thereafter, the salt content after fall mixing increased moderately to about 8,400 metric tons in 1984, which is equivalent to a 33-percent net reduction since fall 1971.

Direct thermal stratification in the bay in 1978-84 was similar to that of the early 1970's. The metalimnetic thermocline resided at the same depth and had a thickness similar to that of 1970-72. Evidence of inverse thermal stratification was observed during ice cover in 1978-84 but was less clearly defined than in the early 1970's.

Specific-conductance in the summer metalimnion gradients were poorly developed during 1978-84; the top-to-bottom differences were 80 to 70 percent less than in the early 1970's. This reflects the decrease in chloride concentration throughout the water column between spring and fall mixing and the strong influence of chloride on specific conductance in the past. The gradients during ice cover continued to clearly define the chemical stratification of the bottom water through 1984, however. Seasonal fluctuations in specific conductance reflect chloride inflows from winter thaws and early spring snowmelt. Although specific conductance of the bottom water during ice cover was still relatively high in 1978-84, it was about 35 percent lower than in the early 1970's.

The epilimnion of the bay continues to be well oxygenated because of its high biologic productivity. Oxygen stratification developed under the ice in 1980-84 as in the early 1970's, but strongly anoxic bottom conditions beneath the ice, which were common in the early 1970's, appeared only in the winters of 1978 and 1979 and not thereafter. With weaker chemical stratification beneath the ice (due to lower salt concentration), the cold, well-oxygenated water entering the bay is able to disrupt the bottom-water stratification more readily than in the years of high salt concentration. When the bottom water is frequently replenished with oxygen, the oxygen demand of the bottom sediments is matched or exceeded, and anoxic conditions probably will not develop under ice cover.

The bay mixed completely during each spring from 1975 through 1983, but not in 1984. Complete spring turnover distributes oxygen throughout the water column and eliminates any anoxic or low-oxygen conditions that might develop under ice cover. Oxygen in the upper and middle waters of the hypolimnion persisted longer in 1980-84 than in the early 1970's. Spring meromixis during 1970-72 caused at least 9 months of consistent anoxia in the bottom water each year, but when complete mixing resumed each spring, only 5 to 6 months of anoxic conditions persisted each year. When the bay failed to mix completely in the spring of 1984, anoxic conditions in the hypolimnion lasted for about 7.5 months. This was the longest period of anoxia in 12 years.

Chloride concentrations throughout the water column during the summers of 1978-83 were less than those in the summers of 1970-72. This is a result of the decrease in chloride concentration in the bay between spring and fall mixing and indicates a weak summer gradient of chloride, which facilitates fall mixing. Chloride was still the major dissolved constituent that controlled the mixing patterns and stratification characteristics of the bay in 1984, however. Comparisons of chloride concentrations at differing depths under ice cover indicate an accumulation of chloride-laden water in the bottom waters of the bay, especially after winter thaws and during spring runoff. Relatively cold, chloride-laden, dense, well-oxygenated water that enters the bay during the winter and early spring will determine the strength of thermal, chemical, and oxygen stratification during ice cover and also the density gradient that must be overcome after ice melts if the bay is to mix completely to the bottom in spring.

The bay is dimictic and is naturally holomictic. Its chemical quality and mixing patterns are influenced by the quality of water from Irondequoit Creek, the physical and chemical characteristics of its bottom sediments, its morphometry, and seasonal weather conditions. Despite the general decrease in the use of salt in the bay's drainage basin since 1974 and the resumption of complete spring mixing in 1975, the bay failed to mix completely in the spring of 1984. This happened because the amount of salt used in the basin increased slightly between 1980 and 1984, with the greatest increase in 1983-84. Moreover, salt was distributed frequently in the late winter of 1984, close to the time of ice melt and the onset of mixing. Thus, the incomplete spring mixing in 1984 resulted less from the increased amount of salt entering the bay than the time at which the salt entered. The bay remains susceptible to spring meromixis and thus will continue to require prudent management of deicing-salt distribution in its drainage basin.

REFERENCES CITED

Bannister, T. T. and Bubeck, R. C., 1978, Limnology of Irondequoit Bay, Monroe County, New York, in J. Bloomfield, ed., Lakes of New York State: New York, Academic Press, p. 105-221.

Bannister, T. T. and Burton, R. S., 1980, Nitrogen and phosphorous discharges by Irondequoit Creek and total inputs to Irondequoit Bay, 1976-1979: Rochester, N.Y., University of Rochester, Department of Biology, Irondequoit Bay Report no. 5, 22 p.

Bannister, T. T., Weidemann, A. D., and Wilke-Mounts, S. A., and Phillips, Lisa, 1982, New benthic maps of the bay and revised area depth and volume depth functions: Rochester, N.Y., University of Rochester, Department of Biology, Irondequoit Bay Report no. 11, 41 p.

Bubeck, R. C., 1972, Some factors influencing the physical and chemical limnology of Irondequoit Bay, Rochester, New York: Rochester, N.Y., University of Rochester, Ph.D. dissertation, 290 p.

Bubeck, R. C., Diment, W. H., Deck, B. L., Baldwin, A. L., and Lipton, S. D., 1971, Runoff of deicing salt--effect on Irondequoit Bay, Rochester, New York: Science, v. 172, p. 1128-1132.

Burton, R. S., 1976, Improvement in Irondequoit Bay following a decrease of road salting in the watershed: Rochester, N.Y., Rochester Committee for Scientific Information, Bulletin 198, 8 p.

Cherkauer, D. S. and Ostenso, N. A., 1976, The effect of salt on small, artificial lakes: Water Resources Bulletin, v. 12, no. 6, p. 1259-1266.

Cressey, G. B., 1966, Land forms, in Thompson, J. H., ed., Geography of New York State: Syracuse, N.Y., Syracuse University Press, p. 19-53.

Crowther, R. A. and Hynes, H. B. N., 1977, The effect of road deicing salt on the drift of stream benthos: Environmental Pollution, v. 14, p. 113-126.

Davis, R. L., 1978, Effects of urbanization on small watersheds in Penfield, New York: Rochester, N.Y., University of Rochester, Ph.D. dissertation, 355 p.

Dennis, H. W., 1973, Salt pollution of a shallow aquifer, Indianapolis, Indiana: Ground Water, v. 11, no. 4, p. 18-22.

Diment, W. H., Bubeck, R. C., and Deck, B. L., 1973, Some effects of deicing salts on Irondequoit Bay and its drainage basin: National Academy of Sciences, National Academy of Engineering, Highway Research Board, Highway Research Record no. 425, p. 23-35.

Diment, W. H., Bubeck, R. C., and Deck, B. L., 1974, Effects of deicing salts on waters of the Irondequoit Bay drainage basin, Monroe County, New York, in Coogan, A. H. ed., Fourth symposium on salt: Cleveland, OH, Northern Ohio Geological Society, p. 391-405.

REFERENCES CITED (continued)

Dobson, H. H., 1967, Principal ions and dissolved oxygen in Lake Ontario: Proceedings, Tenth Conference on Great Lakes Research: Ann Arbor, MI, International Association for Great Lakes Research, p. 337-359.

Fairchild, H. L., 1935, Genesee valley hydrography and drainage: Proceedings of the Rochester Academy of Science, v. 7, p. 157-188.

Field, R., Struzeski, E. J., Masters, H. E., and Tafuri, A. N., 1973, Water pollution and associated effects from street salting: Cincinnati, Ohio, National Environmental Research Center, U.S. Environmental Protection Agency, Environmental Protection Technology Series, EPA-R2-73-257, 48 p.

Fraser, A. S., 1981, Salt in the Great Lakes: National Water Research Institute, Environment Canada, 23 p.

Free, B. M. and Mulamoottil, G. G., 1983, The limnology of Lake Wabukayne, a storm-water impoundment: Water Resources Bulletin, v. 19, no. 5, p. 821-827.

Frost, L. R., Jr., Pollock, S. J., and Wakelee, R. F., 1981, Hydrologic effects of highway deicing chemicals in Massachusetts: U.S. Geological Survey Open-File Report 81-209, 63 p.

Goldman, C. R. and Horne, A. J., 1983, Limnology: New York, McGraw-Hill, 464 p.

Grossman, I. G. and Yarger, L. B., 1953, Water resources of the Rochester area, New York: U.S. Geological Survey Circular 246, 30 p.

Gupta, M. K., Agnew, R. W., and Kobriger, N. P., 1981, Constituents of highway runoff, Volume I, State of the art report: Federal Highway Administration, Federal Highway Administration Report FHWA/RD-81/042, 111 p.

Hanes, R. E., Zelazny, L. W., and Blaser, R. E., 1970, Effects of deicing salts on water quality and biota; literature review and recommended research: National Academy of Sciences, National Academy of Engineering, Highway Research Board, National Cooperative Highway Research Program Report No. 91, 70 p.

Hanes, R. E., Zelazny, L. W., Verghese, K. G., Bosshart, R. P., Carson, E. W., Blaser, R. E., and Wolf, D. D., 1976, Effects of deicing salts on plant biota and soil, experimental phase: National Academy of Sciences, National Academy of Engineering, Highway Research Board, National Cooperative Highway Research Program Report 170, 88 p.

Hennigan, R. D., 1970, Environmental reconnaissance report on Irondequoit Creek: Rochester, N.Y., Irondequoit Bay Pure Waters District, Monroe County Pure Waters Agency, 117 p.

Highway Research Board, 1967, Environmental considerations in use of deicing chemicals: National Academy of Sciences, National Academy of Engineering, Highway Research Board, Highway Research Record No. 193, 42 p.

_______ 1973, Environmental degradation by deicing chemicals and effective counter measures: National Academy of Sciences, National Academy of Engineering, Highway Research Board, Highway Research Record No. 425, 81 p.

Hoffman, R. W., Goldman, C. R., Paulson, S., and Winters, G. R., 1981, Aquatic impacts of deicing salts in the central Sierra Nevada Mountains, California: Water Resources Bulletin, v. 17, no. 2, p. 280-285.

Huling, E. E. and Hollocher, T. C., 1972, Ground-water contamination by road salt--steady-state concentrations in east central Massachusetts: Science, v. 176, p. 288-290.

Hutchinson, F. E., 1970, Environmental pollution from highway deicing compounds: Journal of Soil and Water Conservation, v. 26, no. 4, p. 144-146.

Judd, J. H., 1970, Lake stratification caused by runoff from street deicing: Water Research, v. 4, p. 521-532.

Kappel, W. M., Yager, R. M., and Zarriello, P. J., 1986, Quantity and quality of urban storm runoff in the Irondequoit Creek basin near Rochester, New York, Part 2--Quality of storm runoff and atmospheric deposition, runoff-quality modeling, and potential of wetlands for sediment and nutrient retention: U.S. Geological Survey Water Resources Investigations Report 85-4113, 93 p.

Leggette, R. M., Gould, L. O., and Dollen, B. H., 1935, Ground-water resources of Monroe County, New York: Rochester, Monroe County Regional Plannng Board, 186 p.

Molles, M. C., 1980, Effects of road salting on aquatic invertebrate communities: U.S. Department of Agriculture, Forest Service, Ft. Collins, Co., Eisenhower Consortium Bulletin No. 10, 9 p.

Monroe County Planning Council, 1964, Primary requirements for drainage planning. Drainage study--stage II--Rochester-Monroe County metropolitan area: Rochester, N.Y., Monroe County Planning Council, 117 p.

National Oceanic and Atmospheric Administration, 1984, Local climatological data, annual summary with comparative data, Rochester, New York: Ashville, N.C., National Climatic Data Center, 4 p.

O'Brien and Gere, 1983, Nationwide urban runoff program, Irondequoit basin study, final report: Rochester, N.Y., Irondequoit Bay Pure Waters District, Monroe County Department of Engineering, 164 p.

REFERENCES CITED (continued)

Odell, T. T., 1940, Bays and ponds of the shore area, in A biological survey of the Lake Ontario watershed: New York State Department of Conservation, supplement to 29th annual report, p. 82-97.

Pesacreta, G. J. and Makarewicz, J. C., 1982, Meromixis in Ides Cove, N.Y.--causes and recovery: Journal of Freshwater Ecology, v. 1, no. 5, p. 467-481.

Peters, N. E. and Turk, J. T., 1981, Increases in sodium and chloride in the Mohawk River, New York, from the 1950's to the 1970's attributed to road salt: Water Resources Bulletin, v. 17, no. 4, p. 586-598.

Pollock, S. I. and Toler, L. G., 1973, Effects of highway deicing salts on ground water and water supplies in Massachusetts: National Academy of Sciences, National Academy of Engineering, Highway Research Board, Highway Research Record 425, p. 17-22.

Schroeder, R. A., 1985, Sediment accumulation rates in Irondequoit Bay, New York based on lead-210 and cesium-137 geochronology: Northeastern Environmental Science, v. 4, no. 1, p. 23-29.

Scott, W. S., 1976, The effect of road deicing salts on sodium concentration in an urban water course: Environmental Pollution, v. 10, p. 141-153.

_______1980, Road salt movement into two Toronto streams: Journal of the Environmental Engineering Division, Proceedings of the American Society of Civil Engineers, v. 106 (EE3), p. 547-560.

Sherwood, S. D., 1981, Irondequoit Bay watershed population estimate: Rochester, N.Y., Center for Governmental Research, 8 p.

Skougstad, M. W., Fishman, M. J., Friedman, L. C., Erdmann, D. E., and Duncan, S. S., eds., 1979, Methods of determination of inorganic substances in water and fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 626 p.

Tressler, W. L., Austin, T. S., and Orban, E., 1953, Seasonal variation of some limnological factors in Irondequoit Bay, New York: The American Midland Naturalist, v. 49, no. 3, p. 878-903.

U.S. Environmental Protection Agency, 1971, Environmental impact of highway deicing: Water Pollution Control Research Series Report 11040GKK06/71, 120 p.

_______1979, Methods for chemical analysis of water and wastes: Cincinnati, Ohio, U.S. Environmental Protection Agency, Environmental Monitoring and Support Laboratory, EPA-6001/4-79-020, 260 p.

Wagner, L. A., 1982, Drainage areas of New York streams, by river basins--a stream gazetteer, Part 1--data compiled as of October 1980: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-1055, 359 p.

Waller, R. M., and Finch, A. J., 1982, Atlas of eleven selected aquifers in New York: U.S. Geological Survey Water-Resources Investigations Open-File Report 82-553, chapter 5, Irondogenesee area, p. 83-103.

Waller, R. M., Holecek, T. J., Stelz, W.G. Belli, J. L., and Mahon, K. I., 1982, Geohydrology of the preglacial Genesee valley, Monroe County, New York: U.S. Geological Survey Open-File Report 82-552, 5 sheets.

Westing, A. H., 1969, Plants and salt in the roadside environment: Phytopathology, v. 59, p. 1174-1181.

Wetzel, R. G., 1983, Limnology, 2nd edition: Philadelphia, Pa., Saunders College Publishing, 767 p.

Wilcox, D. A., 1986, The effects of deicing salts on water chemistry in Pinhook Bog, Indiana: Water Resources Bulletin, v. 22, no. i, p. 57-65.

Wulkowicz, G. M. and Saleem, Z. A., 1974, Chloride balance of an urban basin in the Chicago area: Water Resources Research, v. 10, no. 5, p. 974-982.

Yager, R. M., Zarriello, P. J., and Kappel, W. M., 1985, Geohydrology of the Irondequoit Creek basin near Rochester, New York: U.S. Geological Survey Water-Resources Investigations Report 84-4259, 6 sheets.

Young, R. A., 1983, The geologic evolution of the Genesee valley region and early Lake Ontario--a review of recent progress: Proceedings of the Rochester Academy of Sciences, v. 15, no. 2, p. 85-98.

Zarriello, P. J., Harding, W. E., Yager, R. M., and Kappel, W. M., 1985, Quantity and quality of storm runoff in the Irondequoit Creek basin near Rochester, New York, Part 1.--Data-collection network and methods, quality assurance program, and description of available data: U.S. Geological Survey Open-File Report 84-610, 44 p.