Effects of Deicing Salts on the Waters of the Irondequoit Bay Drainage Basin, Monroe County, New York

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ABSTRACT

In recent years Monroe County, New York (population 712,000) used about two percent of the salt used for highway deicing in the United States. The Irondequoit Bay drainage basin (population 206,000), which is primarily within the county, received nearly one percent. The disproportionate use of deicing salt reflects the high frequency of small snowfalls, winter temperature ranges, and the vigorous implementation of a bare pavement policy in a populous region.

A study of the Irondequoit Bay drainage basin reveals the following: (1) The concentration of chloride during the summer in Irondequoit Creek (the principal input to Irondequoit Bay) and the surface waters of the bay have risen fourfold since the widespread use of deicing salts. (2) Winter concentrations of chloride in Irondequoit Creek reach 600 mg/l. (3) Maximum concentrations in ten small creeks range from 260–46,000 mg/l chloride during winter. (4) The saline runoff imposes a sufficient density gradient upon Irondequoit Bay that it does not mix completely during the spring. Moreover, the period of summer stratification has been prolonged a month (as compared with 1939) by the density gradient imposed by the salt runoff. (5) Approximately one-half of the salt used for deicing during a winter is removed by surface runoff, the remainder is stored in the soil and ground water. One-half to two-thirds of the salt runoff takes place during the salting season (December through March). (6) Chloride concentrations in most wells that have been monitored over the years have risen; however, interpretation is difficult because some natural ground water in the area is known to be salty.

INTRODUCTION

The anomalously high usage of deicing salts in the Irondequoit Bay drainage basin makes it a good place to study the effects of deicing salts. So far we have been primarily concerned with the chloride concentrations in the surface and ground waters and little attention has been given to the effects of the salt on the biota (Westing, 1969, U.S.E.P.A., 1971, Hanes et al., 1970, Highway Research Board, 1973) or to complex geochemical reactions that may influence the nutrient and heavy metal concentrations in the water (Benoit, 1969, Kramer, 1964, Feick, et al., 1972, Yeaple, 1973).

The effects of deicing salts on the physical behavior of Irondequoit Bay for the year 1969–70 have been reported by Bubeck et al. (1971) along with an attempt to estimate the fraction of salt that remains stored in the ground water. Data were also acquired in 1970–71 and 1971–72 (Bubeck, 1972, Diment et al., 1973) and the program was expanded to include more intensive monitoring of Irondequoit Creek, smaller streams, and some wells. These results we report here along with a summary of previous results.

METHODS

Temperature was measured in situ with a thermistor, 3-lead cable, 5-dial Wheatstone bridge and electronic null detector. The relative accuracy is about 0.002 deg. C. and the absolute accuracy about 0.02 deg. C. Electrical conductivity was also measured in situ with a Leeds and Northrup 4959 electrolytic conductivity bridge operated at 1000 Hz with a 1.0 cell. Conductivities (± 3 percent) were corrected to 25 deg. C by the relation $L_{25} = L_T [1 + 0.019 (T-25)]$ where L is conductivity and T is temperature. Dissolved oxygen(± 0.1 mg/liter) and chloride

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(± 2 percent) determinations were made on samples retrieved with a Van Dorn water sampler by the azide modification of the Winkler Technique (APHA, 1971) and the mercuric nitrate method (APHA, 1971), respectively.

Discharge of Irondequoit Creek at Browncroft Blvd. was determined by daily observation of water level which was converted to discharge by rating curves established for this site. A Gurley pygmy-type current meter and a standard velocity-area method (Grover and Harrington, 1966) were used. Several rating curves were developed so as to properly take into account the effect of fluctuations in the water level of Irondequoit Bay.

The variation in the level of Irondequoit Bay is nearly sinusoidal with a period of one year and with maximum and minimum in June and December, respectively. The total range in level during the period of observations was 1.3 meters. Inasmuch as all depths are reported with reference to the water level at the time of the observation, a small correction is needed if a fixed datum is desired. This correction can be obtained from the Lake Survey Center's Monthly Bulletin of Lake Levels.

CHARACTERISTICS OF THE DRAINAGE BASIN

The area of the Irondequoit Bay drainage basin (Fig. 1) is approximately 396 km^2, while that of Irondequoit Creek is 340 km^2 (Monroe County Planning Council, 1964). The average precipitation (all forms) is 83 cm and is roughly equally proportioned among the months (U.S. Dept. Commerce, 1972). Significant snow falls between mid-November and mid-April with a rather gradual trend into, and out of, the months with snow cover. Lake Ontario remains mostly unfrozen throughout the winter; conse-

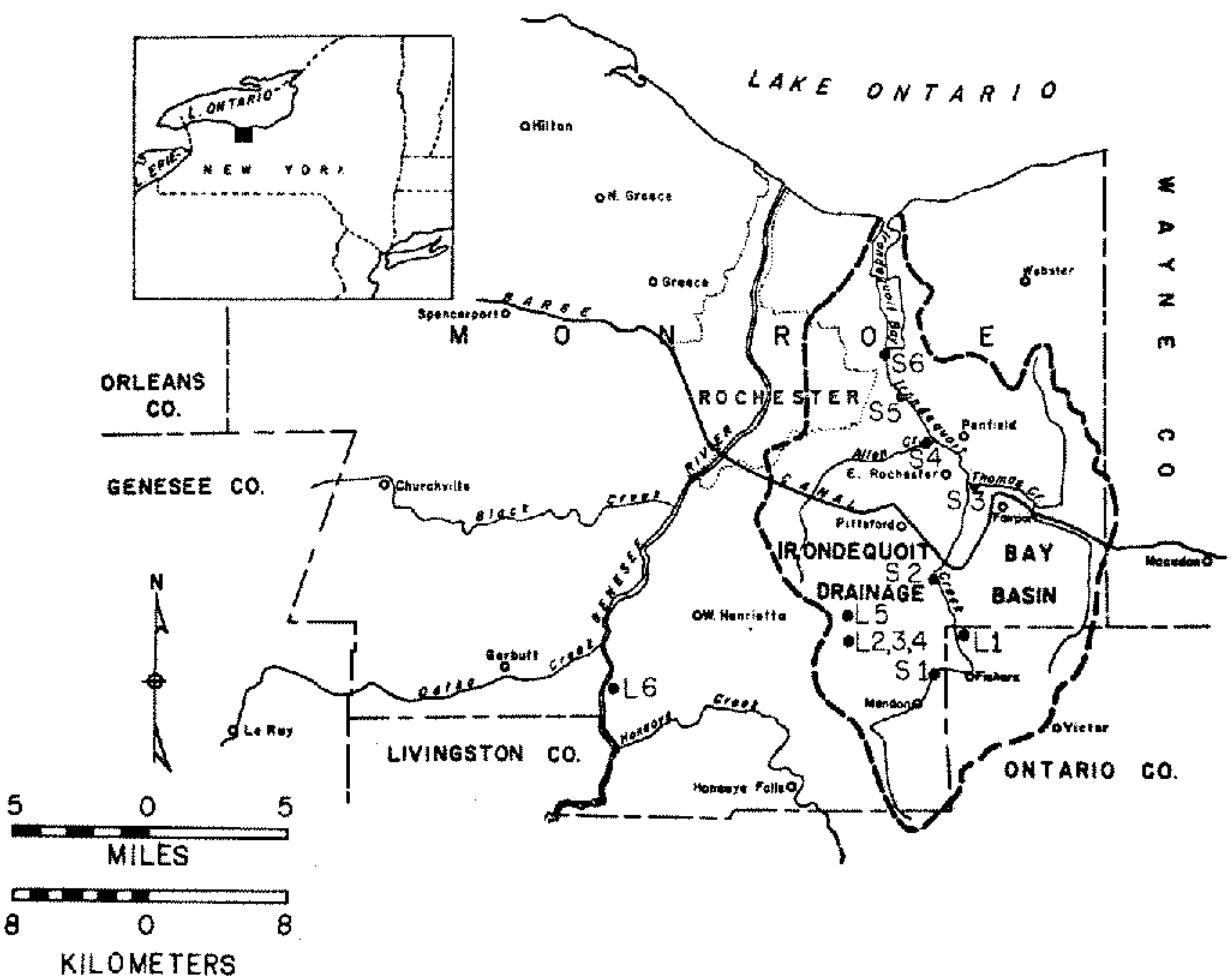

Figure 1. Map showing locations of Irondequoit Bay drainage basin (dashed line) and sampling localities (numbered) referred to in text and tables.

quently, cold air masses moving across it acquire moisture and heat, which upon reaching the shore, cause cloudiness and frequent but small snowfalls. Another reason why anomalously high amounts of deicing salt are used is that salt is particularly effective in the temperature ranges encountered in Monroe County winters. Sodium chloride is not an effective deicer below about −6°C (Salt Institute, 1967). However, the temperature at the Monroe County airport rarely remains below this for more than a few days at a time (Fig. 5).

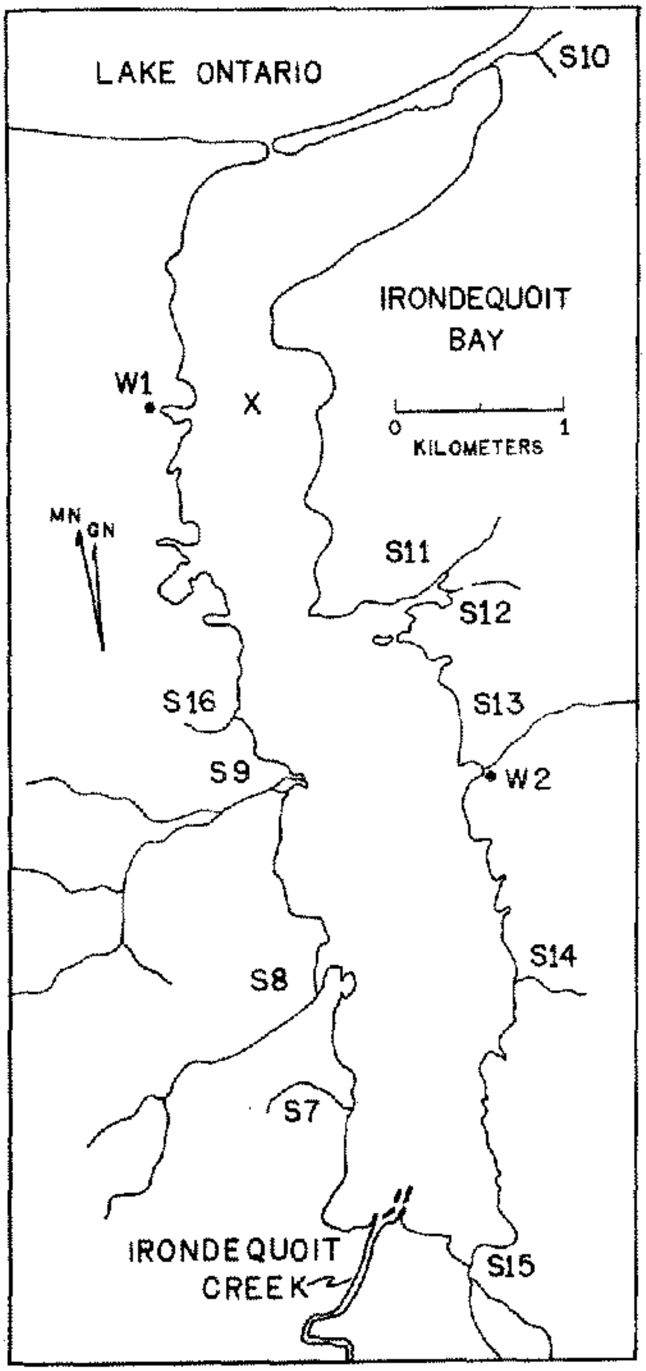

Figure 2. Map of Irondequoit Bay showing location of sampling localities. X indicates deepest point in bay and location of measurements.

The basin is mantled with a thin veneer of glacial debris which rarely exceeds 50 m in thickness except in the buried valley of the pre-glacial Genesee River. The northern section of this buried valley is the site of the present-day Irondequoit Creek. Some of the Paleozoic sedimentary rocks underlying the glacial debris contain minor lenses of salt and in a few regions saline ground water has been tapped both in the Paleozoic rocks and the overlying glacial debris. Moreover, some saline springs have been reported (Hall, 1843, Fairchild, 1935). These naturally saline waters are not significant contributors of chloride to the major streams or the bay. However, the possibility of their presence must be considered when ascribing ground water contamination to deicing salt.

The population of the drainage basin is about 206,000 and expanding. The southern-most part of the basin is largely rural but the population density increases rapidly to the north, from patches of suburbia, to densely suburbanized and urbanized areas. The basin is laced with limited access highways which receive large applications of deicing salts.

SALT USAGE

The national use of deicing salt has increased exponentially with a doubling time of five years since 1940 (Fig. 3). Locally the rate of increase was greatest during implementation of the bare pavement policy (ca. 1960–65) and somewhat less rapid thereafter.

Salt statistics were compiled for the various towns in the county and drainage basin for the winters of 1965–66 through 1972–73 (Table 1). For a given winter there is a high degree of correlation in salt usage among the various towns. The correlation of salt usage with total snowfall is not particularly good simply because one or several unusually heavy snowfalls strongly bias the result.

In recent years, at least, all of the salt used for deicing was nearly pure NaCl with small amounts ($\lesssim$ 0.25 kg/metric ton) of Prussian Blue (ferric ferrocyanide) used as a decaking agent (Wood, 1971, U.S.E.P.A., 1971). We write mainly in terms of chloride because this was the ion measured. In most cases sodium is present in nearly stoichiometric proportions but this is not necessarily so, especially in the ground water (Hanes et al., 1970, Kunkle, 1971).

IRONDEQUOIT CREEK

Summer chloride concentrations near the mouth of Irondequoit Creek (average annual flow $\sim 5\ m^3/sec$) have increased tenfold since 1913 and about fourfold since the widespread use of salt for deicing (Fig. 4). Summer concentrations in the surface waters of the bay behave similarly, although the curves cross (Fig. 4) in the late 1950's, which indicates that creek concentrations are higher in the winter and/or that other saline sources enter the bay. Both statements are true as will subsequently become evident.

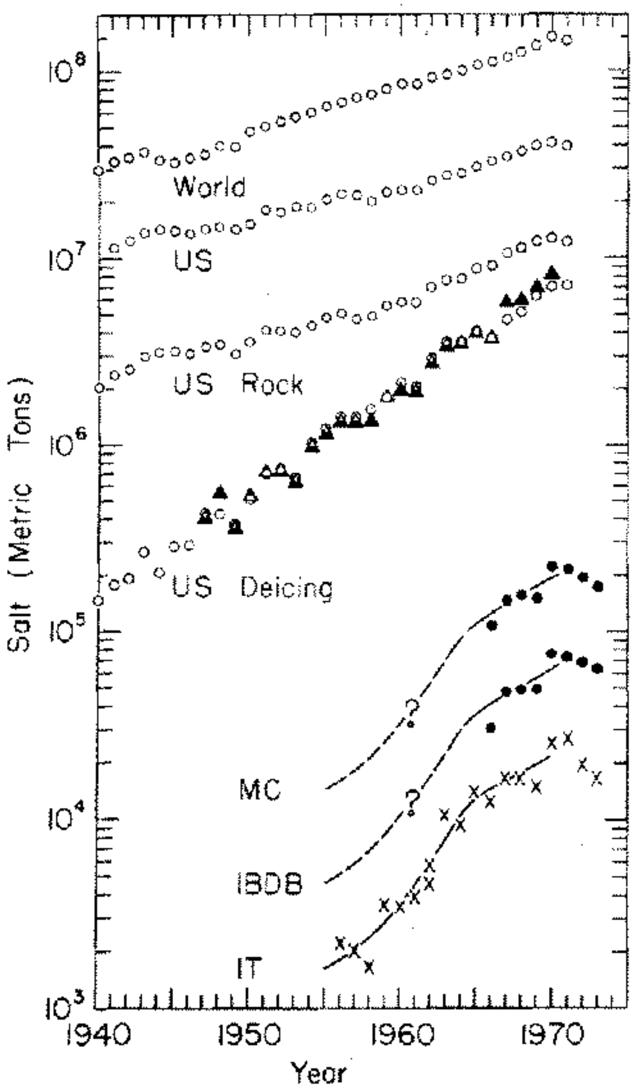

Figure 3. Salt production and salt usage for deicing. *World*: Total salt production including brine, evaporated, and rock salt; *United States*: total national production as above; *United States rock salt*: national production of rock salt; *United States deicing salt*: national use of salt for deicing; *MC*: deicing salt used in Monroe County; *IBDB*: deicing salt used in Irondequoit Bay drainage basin; *TI*: deicing salt used in the town of Irondequoit (included because it has the only accessible local data prior to 1965 and forms the basis for extrapolating the other local curves to earlier times). Open circles represent data for the U. S. Bureau of Mines (1940-1971); triangles, the Salt Institute; solid dots, the International Salt Company and Morton Salt Company; and crosses, the town of Irondequoit. The records for the localities comprising the county and the drainage basin are not complete, but the data shown are probably low by no more than 5 percent.

TABLE I

Deicing salt used in Monroe County (MC) and the Irondequoit Bay Drainage Basin (IBDB).

Winter	Salt used MC	(Metric tons)* IBDB	IBDB/MC	Snowfall** (cm)
1965-66	109,200	30,800	.282	262
1966-67	148,400	47,400	.319	188
1967-68	156,900	49,300	.314	195
1968-69	151,500	49,600	.327	203
1969-70	224,000	76,600	.342	304
1970-71	214,600	73,500	.342	362
1971-72	196,800	68,900	.350	267
1972-73	173,900	64,000	.368	185

* Salt statistics were mainly provided by the International Salt Company (1965-1973) and the Morton Salt Company (1971-1973).

**Recorded at the Monroe County Airport by the National Weather Service.

These curves when compared with the salt usage curve strongly suggest that the main increase in chloride is a consequence of runoff of deicing salt.

Inspection of the summer chloride data for various positions along the creek (Table II) indicates that the creek becomes progressively more salty downstream. This suggests that at least some of the smaller streams must be quite salty. It is also notable (Table III) that the upland lakes have rather low chloride concentrations. Taken as a whole these data suggest that the main source of chloride is deicing salt. A plot of the creek discharge, chloride

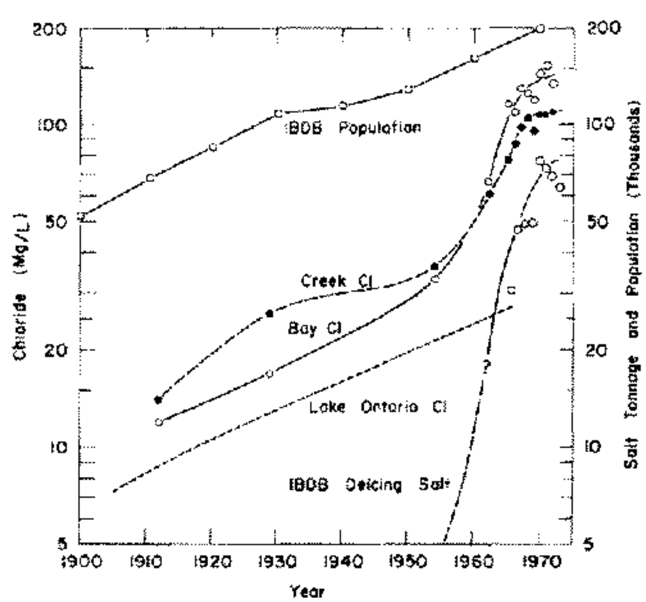

Figure 4. Chloride concentration in the surface waters of Irondequoit Bay during the summer, near the mouth of Irondequoit Creek during the summer (Bubeck et al., 1971), and in Lake Ontario (Dobson, 1967). The deicing salt tonnage curve is from Figure 3 and involves the assumptions stated therein. Population is from the U.S. Bureau of the Census. Where a town straddles the basin boundary, salt and population were apportioned on an area basis. IBDB, Irondequoit Bay drainage basin.

TABLE II

Chloride concentration in Irondequoit Creek and its principal tributaries from 13 May 1970 to 20 November 1970. See Figure 1 for sampling locations

No.	Location	Range (mg/1)	Mean (mg/1)
S1	Irondequoit Creek (Mile Square Rd.)	36-84	50
S2	Irondequoit Creek (Thornell Rd.)	36-49	43
S3	Thomas Creek (Baird Road)	70-147	107
S4	Allens Creek (Nalge Co.)	87-207	132
S5	Irondequoit Creek (Blossom Road)	76-125	105
S6	Irondequoit Creek (Empire Blvd., near mouth)	73-185	110

TABLE III

Chloride concentrations in upland lakes and in shallow holes. See Figure 1 for locations.

No.	Location	Concentration (mg/1)	Dates
L1	Crossmans Pond	4- 5	14 May 71
L2	Devils Bathtub	2- 3	1 Oct. 71
L3	Deep Pond	13-23	1 Apr. 71
L4	Round Pond	6-13	2 July 71
L5	Clover Gravel Pit	62-64	23 Apr. 71
L6	Rush Landfill Site	29-32	28 Apr. 71

concentration, and NaCl transport near the mouth of the creek from November 1970 to December 1972 (Fig. 5) proves the point. This diagram and the plot of the average monthly salt and creek discharge at the same location (Fig. 6) illustrate several aspects of salt runoff. (1) Most of the salt runoff occurs during the winter during thaws, although there is substantial runoff of salt during April, May, and June (Fig. 6). (2) The chloride concentration frequently exceeds 250 mg/l (the U.S. Public Health Service recommended limit for drinking water) during the winter. (3) During the non-salting seasons the salt removal gradually declines approximately in proportion to runoff. During this period chloride concentrations decrease, but only slightly, and their variation is small except at times of high discharge when they are low.

Although the chloride discharge in the winter is mainly from deicing salts, the summer values (low flow) may be significantly influenced by other factors: The chlorides discharged by the sewage treatment plants; the diversion of Genesee River water into the Barge Canal and thence into the Irondequoit Creek drainage basin (Figs. 1 and 12). It is not clear what the quantitative effects are, particularly on the chloride concentrations in the creek. It is

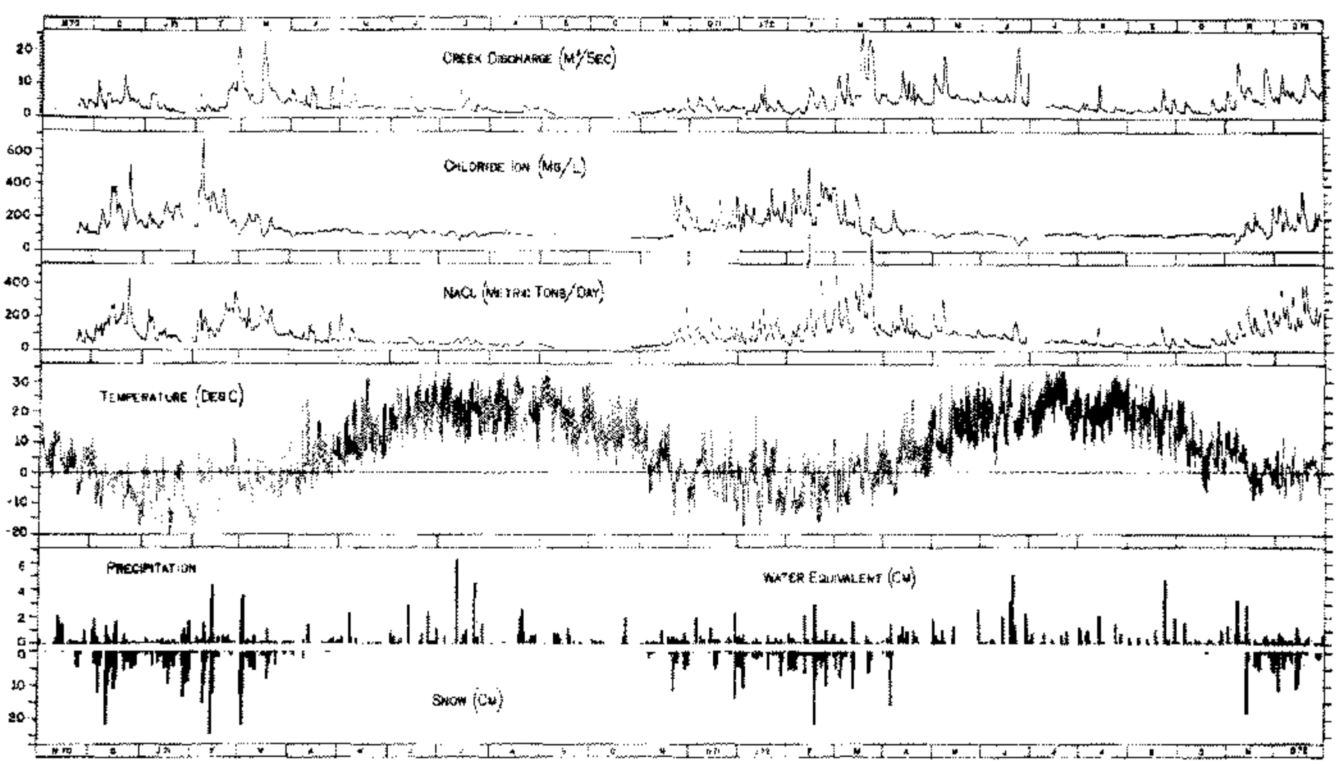

Figure 5. Discharge, chloride ion concentration, and NaCl transport for Irondequoit Creek at Browncroft Blvd. Precipitation and temperatures (maximum and minimum) were recorded at the Monroe County Airport by the National Weather Service.

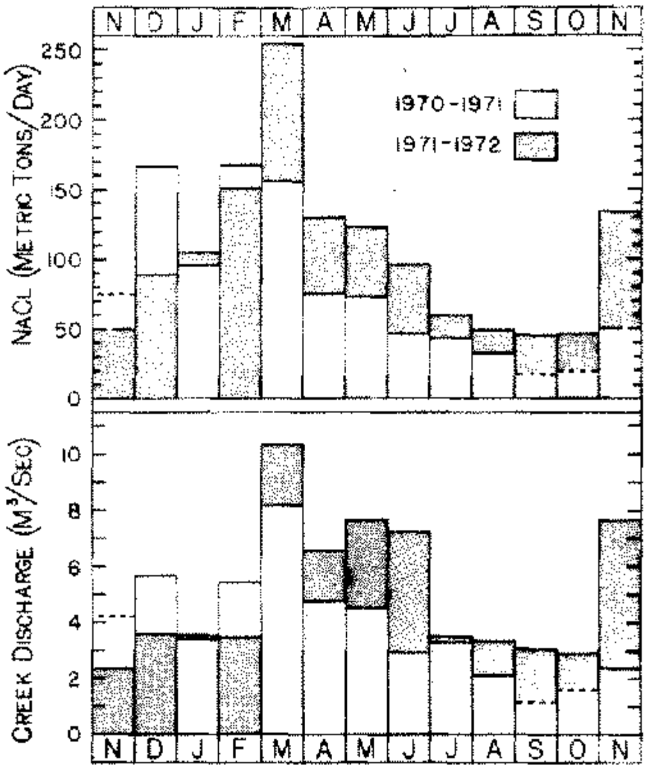

Figure 6. Average monthly NaCl and creek discharge from Irondequoit Creek at Browncroft Blvd.

clear, however, that if this chloride is subtracted, the estimate of the amount of deicing salt remaining in the drainage basin will increase.

SMALL STREAMS

Ten small streams flowing directly into Irondequoit Bay and two wells close to the bay were sampled biweekly from 5 July 1970 to 7 August 1971 (Fig. 2). Although small, these streams are the largest in that part of the basin not drained by Irondequoit Creek; thus, their combined flows represent close to the total for this region (Bubeck, 1972).

The average chloride concentration (Table IV) for each stream is high in each season. Indeed they are all higher than either Irondequoit Creek or the surface waters of the bay for the same season. During the salting season all of the small streams exhibit anomalously high concentrations and some extraordinarily high values at times.

GROUND WATER

Aside from the base flow data for the streams, we have little information on the salt content of the ground water. Only a few residential areas utilize ground water. Most are supplied from Lake Ontario or Hemlock Lake, 24 km south of the drainage basin.

The two shallow wells which we monitored (Table IV) exhibit anomalously high chloride. It is notable that the concentrations in both are significantly lower during the salting season than at other times. We take this to mean that the frozen ground impedes the penetration of the salty runoff.

The Monroe County Health Department monitors wells used to supply water to the public. Although all of these wells show an increase in chloride, the increases are generally small. However, the water producing strata in most of these wells are relatively deep and salty ground waters may not have reached them yet. The great increases in chloride exhibited by a few of the wells are probably not the result of contamination by deicing salts, but the result of inclusion of naturally saline waters by sustained high production. The issue is not completely resolved, however.

The base flow data for the streams, particularly in the northern part of the basin suggests that much of the shallow ground water exceeds 250 mg/l in chloride and that in places it is much higher. How high will the chloride concentrations go? One way to get a notion of this is to calculate a steady state concentration based on the assumption that present salt usage continues indefinitely and that the salt is uniformly distributed over the basin. After a time the concentration of salt will equal the amount of salt that infiltrates the ground divided by the quantity of water that percolates into the ground.

Huling and Hollocher (1972) have done this for a suburban-urban area of Boston and find a steady state chloride concentration of about 100 mg/l based on an average application rate of 107 metric tons of salt/km^2 year. Assuming the same hydrologic conditions for the Irondequoit Bay drainage basin where the average application rate of salt for the winters 1965–66 through 1970–71 was 137 metric tons/km^2 year, the steady state chloride concentration would be slightly higher (128 mg/l). If the usage for the peak salting winter (1969–70) is used (76,600 metric tons/year or 193 metric tons/km^2 year) the steady state value of 180 mg/l would result. In view of the rapid suburbanization of the rural parts of the basin it is likely that a steady state value will exceed 200-300 mg/l, as it already has in the base flows of the small streams of the northern part of the basin (Table IV). This is a greatly simplified argument for many reasons. The salt is not uniformly distributed and we should expect to find a complex arrangement of high and low salinity zones in the ground water. Indeed, it is possible to conceive of a situation where the salty percolate near roads could sink downward through an aquifer (by displacement of less dense water) and accumulate at the base of an aquifer. Under appropriate conditions this salty zone could thicken with time. The end result could be a thick zone of salty water that is not potable by any standard.

TABLE IV

Range and average chloride concentration (mg/1) of small streams flowing directly into Irondequoit Bay and two wells close to bay. See Figure 2 for locations.

No.	Stream or Well	5 Jul. 70 22 Nov. 70	5 Dec. 70 28 Mar. 71	24 May 71 7 Aug. 71
S 7	Southwest	261-364 305	281- 1668 1250	307-585 409
S 8	Snider Island	95-324 272	491- 2122 967	223-360 291
S 9	Densmore Creek	159-380 224	431- 2502 1328	251-445 373
S10	Northeast Storm Drain	153-507 268	478-46,000 8937	92-699 467
S11	Helds Cove 1	89-258 189	281-13,300 2508	234-555 432
S12	Helds Cove 2	218-276 244	245- 400 304	not sampled
S13	Glen Edith	193-411 342	248- 6796 1327	323-546 438
S14	Penfield STP	144-266 203	141- 261 207	171-201 185
S15	Buckaneer Restaurant	108-216 160	164- 227 192	121-185 156
S16	Rochester Canoe Club	144-198 176	not sampled	160-243 182
W 2	Kress' Well (Glen Edith)	545-650 575	345- 395 367	350-548 429
W 1	68 Schnackel Drive Well	201-252 234	150- 251 184	174-273 234

IRONDEQUOIT BAY

Irondequoit Bay (43° 13'N, 77° 32'W; 1.5 X 6 km; area 6.7 km^2, volume 0.046 km^3, maximum depth 23 m) provides a rather striking example of salt accumulation (Fig. 7) because of the high salt input and because its outlet to Lake Ontario is restricted to a shallow ($\sim$ 2 m) channel which permits little exchange of the deeper bay waters with the lake.

From the chloride, electrical conductivity, and temperature isopleths for the past few years (Figs. 8–10), it is evident that cold salty water begins to accumulate on the bottom as the salting season begins (Fig. 7). Salinity increases throughout the winter, and in the spring its gradient is sufficient to prevent mixing completely to the bottom as is evident from the continuity of the isopleths. The bay mixed completely in the spring of 1940 (Tressler, et al., 1953). The maximum depth of vernal mixing generally decreased for the past several years: 1970 (18 meters), 1971 (15) and 1972 (12). However, in the spring of 1973 the bay mixed to 20 meters. The latter part of the winter of 1972–73 was unusually mild, less deicing salt was used, and significantly less salt entered the bay (see also Fig. 7).

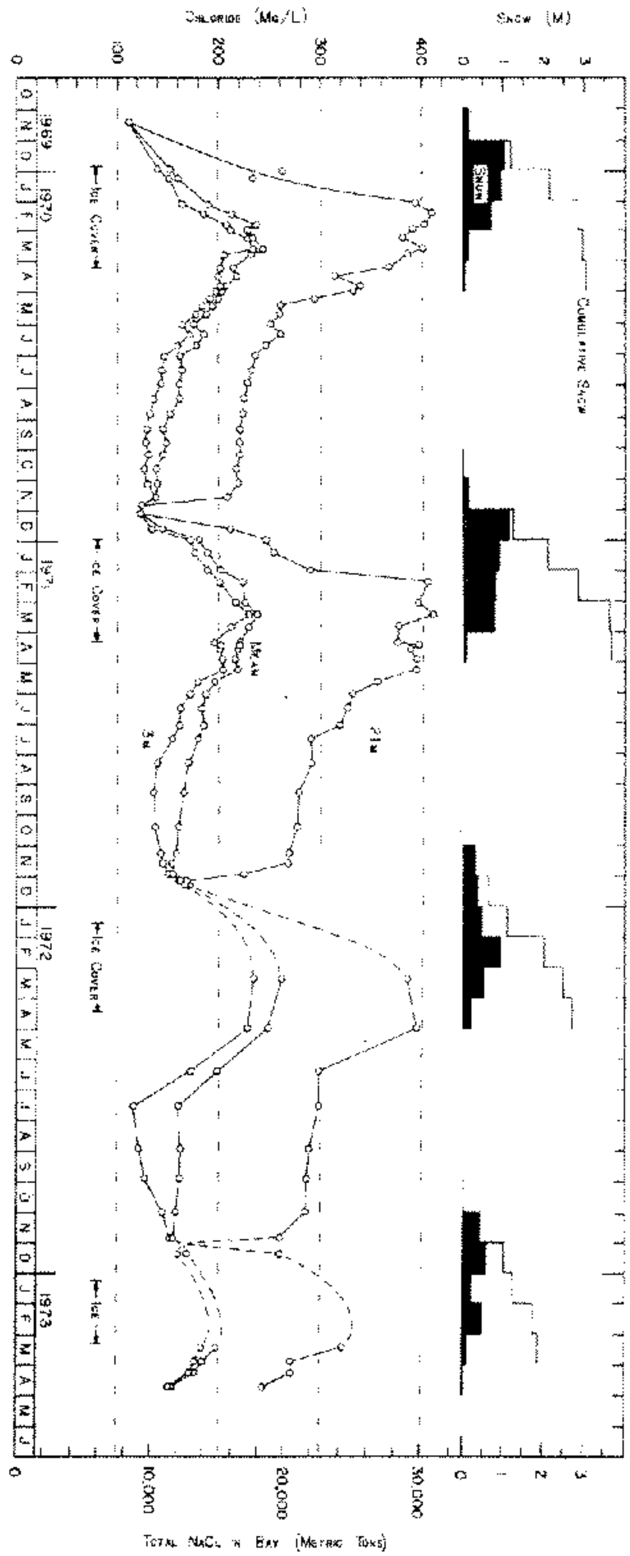

Figure 7. Chloride concentration in Irondequoit Bay at station X. Concentration is given at depths of 3 and 21 m in the bay. Concentrations at other depths are shown in Figures 8-10. The mean concentration was obtained by dividing total chloride in the bay by the volume of the bay; the equivalent in terms of NaCl is expressed by the scale on the right. Snowfall was recorded by the National Weather Service at the Monroe County Airport.

Thus, a smaller stabilizing salinity gradient existed at the time of spring mixing than in the preceding three years. Moreover, the ice melted a month earlier than usual; consequently, the bay was exposed to a longer period of mixing (a succession of cold snaps kept the surface waters of the bay near the temperature of maximum density). These contrasts among the years illustrate the sensitivity of the spring mixing to the amount of salt entering the bay and to the details of climate.

It is also notable that salt transport out of the bottom waters is more rapid (Figs. 8–10) as long as the temperature remains below the temperature of maximum density (a few tenths of a degree below 4 deg. C, depending on salinity and pressure). Under such conditions a destabilizing gradient due to temperature exists, and at least at times, thermohaline convection results. This is particularly well illustrated by the temperature and electrical conductivity profiles obtained two weeks after ice departure in 1972 (Fig. 11) which show an isohaline-isothermal zone below 18.5 meters. Evidently as the water at the top of the zone is warmed by conduction from above, it sinks, thus causing the convection. The process can be maintained because the diffusivity of heat from above is much greater than that of salt. Although this phenomenon has been produced in the laboratory by heating from below (Turner and Stommel, 1964; Turner, 1965; Turner, 1968); observed in Lake Vanda in the Antarctic (Hoare, 1966), in the Red Sea (Turner, 1969), and in Green and Round Lakes, Fayetteville, N.Y. (Diment, 1967), it does not seem to have been reported previously for the condition where the convecting layer is below the temperature of maximum density.

Another effect of the density gradient imposed by the salt runoff is the prolongation of the period of summer stratification. Tressler's et al. (1953) data for 1939 indicate that the bay mixed to the bottom at 12°C in early October. During the last four years it mixed completely at 8–9, 7–8, 4–5 and 4–5 deg. C about 13 November 1969, 25 November 1970, 10 December 1971, and 1 December 1972, respectively. This progression suggests that in the future the bay may not mix completely in the fall if deicing salt usage continues to increase. However, lacking a complete theory describing the descent of the thermocline in the fall, this cannot be predicted with certainty. Evidently many factors are involved, two of which are: the increase in salinity of the bottom waters in recent years, and the decrease in temperature of the bottom waters. Both tend to prolong the period of stratification. The temperature of the bottom waters in the fall is mainly dependent upon the maximum depth of mixing in the spring, i.e. the thickness of the cold (<2°C) layer of water that remains on the bottom. For the years 1939, 70, 71, and 72, these thicknesses were 0, 5, 8, and 11 meters in early spring, and the bottom temperatures at the end of September of each year were ~ 8.0, 6.9, 5.6, and 5.0 deg. C respectively.

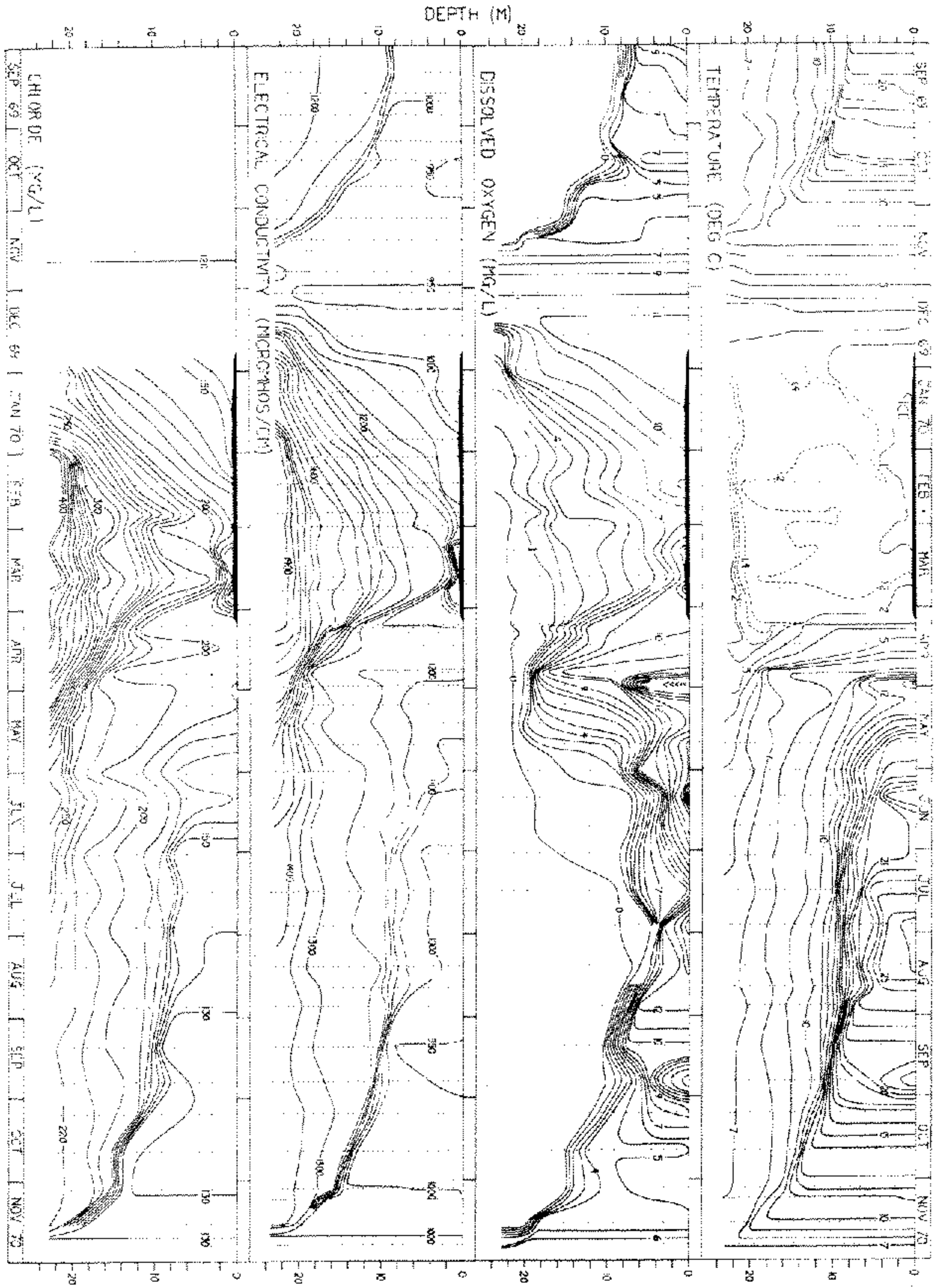

Figure 8. Temperature, dissolved oxygen, electrical conductivity at 25°C, and chloride isopleths at station X for 1969-70.

During the winter the distribution of dissolved oxygen is different from what it would be if the inputs were not salty. The inputs vary considerably in salinity (depending on whether freeze or thaw conditions prevail) and the incoming water seeks an appropriate density level within the bay; thus, dissolved oxygen in the winter is more deeply distributed within the bay (Figs. 8, 9, 10) than it would be if the inputs and the bay waters were of equal salinity (assuming the salinity is low enough that the temperature of maximum density is above the freezing point).

SALT BUDGETS

In order to determine such quantities as the amount of deicing salt that remains stored in the soil and ground water of the drainage basin a number of factors should be considered (Fig. 12) if for no other reason than to show whether they are significant or not.

Although there are natural salt lenses in some of the Paleozoic sedimentary rocks underlying the drainage basin and although high chloride concentrations in certain

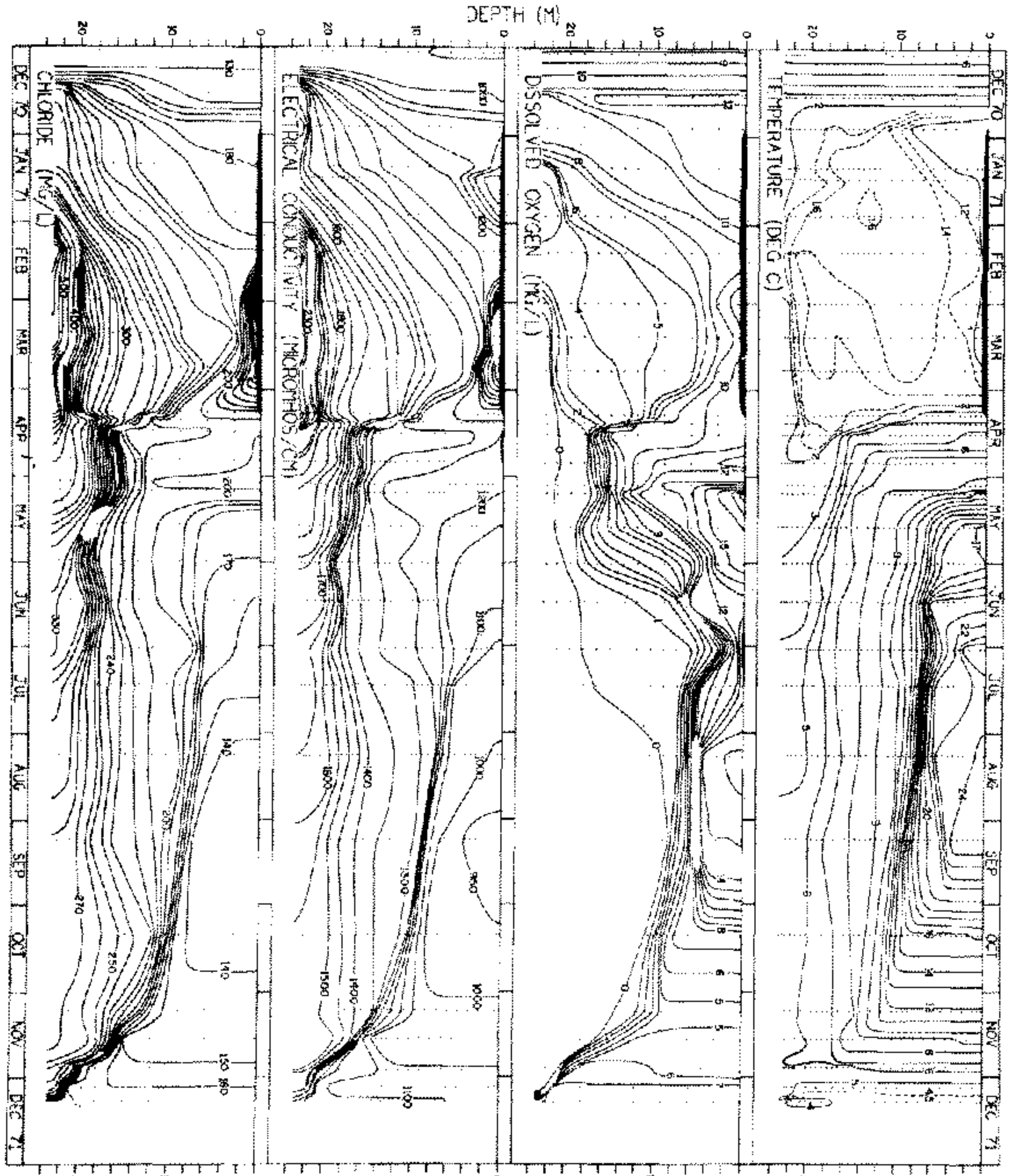

Figure 9. Isopleth diagrams for 1970-71.

wells and springs both in the basement rocks and the overlying glacial debris are probably the result of the leaching of these deposits, the contribution of the natural salt to Irondequoit Creek and Bay is probably negligible because the early creek and bay chloride concentrations are so low (Fig. 4).

Sewage contributes considerable chloride to the system but the amount is small compared with deicing salt. Each person contributes about 12 kg/year of salt to sewage (excluding salt for water softening, industry, and deicing) (see Hanes, et al., 1970, p. 28). A population of 200,000 would contribute about 2400 metric tons of salt per year, or less than 5 percent of the deicing salts applied in the drainage basin.

Now let us try to estimate the amount of salt that remains stored in the soil and ground water (Table V). Two different approaches might be used. One is to examine the salt output of the creeks (a rapidly varying quan-

Figure 10. Isopleth diagrams for 1972-73.

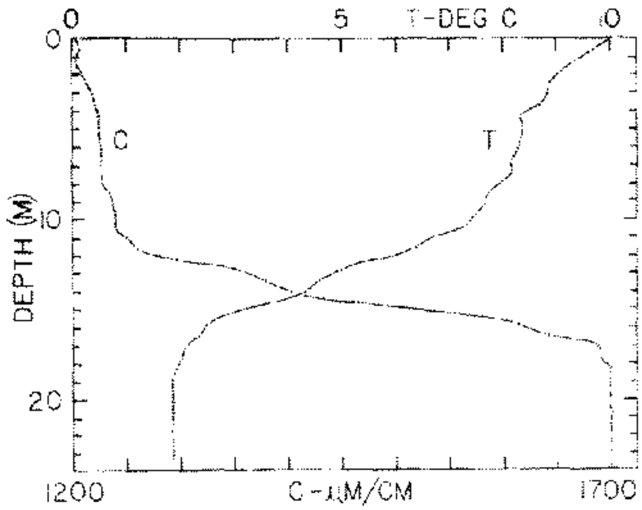

Figure 11. Temperature and electrical conductivity profile, Irondequoit Bay, station X, 30 April 1972.

tity); the other is to examine the salt content of the bay (a more slowly varying quantity).

The salt output of Irondequoit Creek at Browncroft Boulevard was determined every other day in 1970–71 and daily in 1971–72, the monthly means computed (Fig. 6), and salt discharges for the salting season (December–March) and non-salting season (April–November) determined (B and D of Table V). These numbers were then increased to include the rest of the bay drainage basin (14 percent) by increasing the salt discharges by 30 percent (salting season) and 10 percent (non-salting season). The reasons for the different percentages are: the rest of the drainage basin is more heavily salted, and the flow from the Barge Canal in winter, although salty (Fig. 13), is negligible. During the non-salting season the canal contributes roughly 1.3 m^3/sec (Bubeck, 1972) of Genesee River water to the creek, say a half or less of the total flow, depending on flow conditions.

Not all of the salt discharged by Irondequoit Creek is deicing salt. The sewage treatment plants contribute about 2,400 metric tons/yr, perhaps more; and the Genesee River, through the canal, contributes about 2,700 metric tons during the non-salting season (assuming a chloride concentration of 60 mg/l). This reduces the percentages (F in Table V) to 41%A and 60%A.

It is notable that much more salt was removed during 1971–72 than in the previous year, and that the time of the excess removal was during the non-salting season (Fig. 6). It is also notable that salt concentrations in the creek were equal or greater than they were during the preceding year. The rainfall in spring and summer of 1972 was unusually high (52 cm vs. 71 cm, April–November).

The same conclusions regarding salt run-off could be made by considering the changes of salt content in the bay,

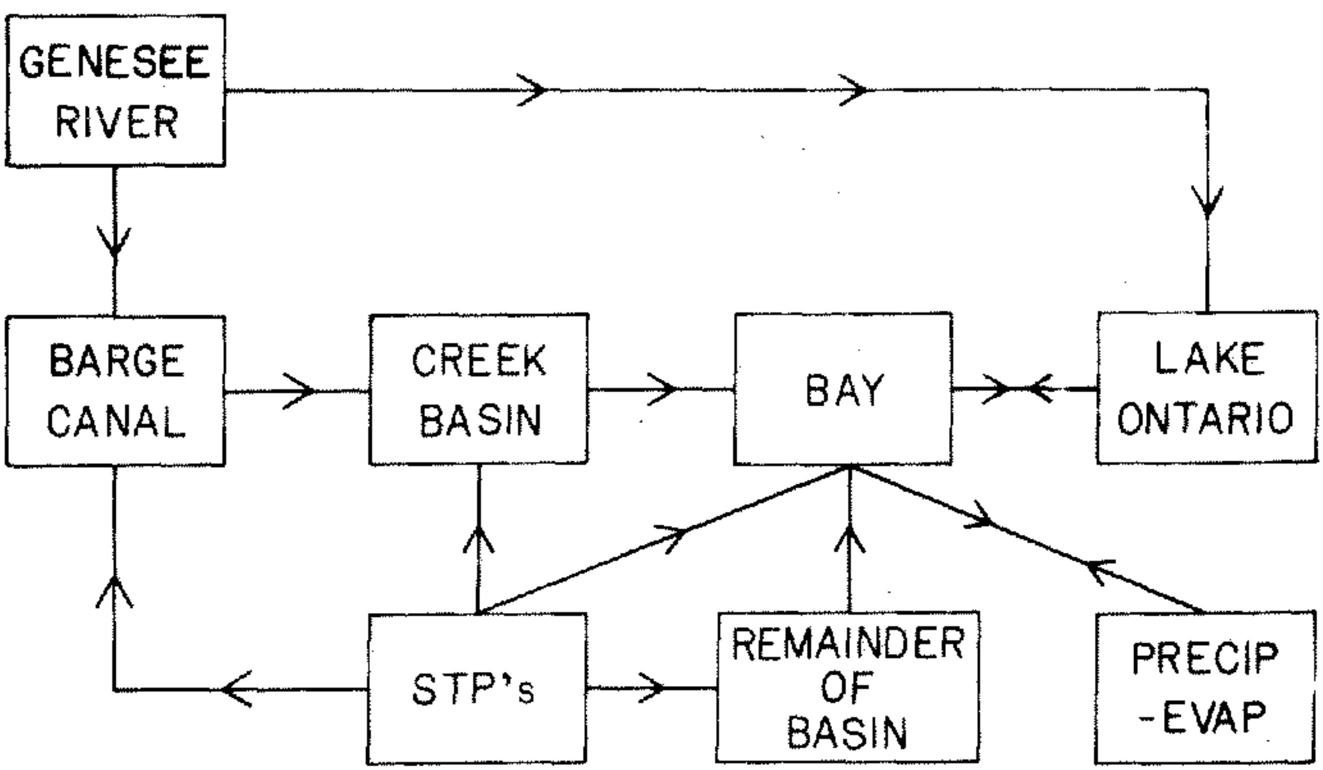

Figure 12. Flow diagram indicating sources of water and salt for Irondequoit Bay.

TABLE V

Salt budgets for Irondequoit Bay and Creek (metric tons).

		1969-70	1970-71	1971-72	1972-73
A.	Deicing salt applied in bay drainage basin	76,600	72,900	68,900	64,000
B.	Salt discharged by I. Creek (Dec.-Mar.)	—	17,700	18,300	—
C.	B + 0.3B Salt discharged by all creeks (Dec.-Mar.)	—	23,000	23,800	—
D.	Salt discharged by I. Creek (Apr.-Nov.)	—	10,800	20,800	—
E.	D + 0.1D Salt discharged by all creeks (Apr.-Nov.)	—	11,900	22,900	—
F.	C + E Salt discharged by all creeks (year)	—	34,900 48%A	46,700 68%A	—
G.	Salt increase in bay (Dec.-Mar.)	10,100	8,700	9,100	4,000+
H.	Salt decrease in bay (Apr.-Nov.)	9,200	5,800	8,300	—
I.	Salt out of bay (Dec.-Mar.)	—	17,500	—	—
J.	Salt out of bay (Apr.-Nov.)	—	17,400	31,800	—
K.	Imbalance of C = I + G (Dec.-Mar.)	—	3,200	—	—
L.	Imbalance of E = J − H (Apr.-Nov.)	—	300	600	—
M.	Imbalance of C + E = I + J + G − H (year)	—	2,900	—	—

provided little fresh water from Lake Ontario enters and mixes with the Bay waters. Indeed a discrepancy in the two approaches would be a measure of the amount of lake water entering and mixing with the bay water. The discrepancy for the non-salting season is small (L in Table 5), but that for the salting season is large. The most probable reason is that the method for calculating the salt out of the bay is not adequate for the winter months. This amount of salt out is simply the salt concentration (averaged by months) at the surface at one location, times the flow of Irondequoit Creek (averaged by months), increased by 15 percent to account for the other streams. Inspection of the isopleth diagrams for conductivity and chloride (Figs. 8, 9, 10) indicates that the bay is highly stratified near the surface under ice cover, particularly late in the winter. The relatively fresh water just under the ice is mostly creek water that flows over the more saline water in a sheet or a "stream," then out into the lake. Inasmuch as sampling was limited to fewer than 5 times a month and at only one locality, the average value could be much in error. The calculation works for the ice-free months probably because the upper waters are more thoroughly mixed and the concentrations more accurately reflect flow out to the lake.

Another way to determine how much lake water flows into and mixes with the bay water is to examine the change in concentrations in the epilimnion (water above the thermocline) when it is well mixed (late August through the fall). During this period the concentrations in the epilimnion decrease slowly and then rise slightly (Fig. 7). If one corrects for the entrainment of the salty waters from below as the epilimnion thickens in response to autumnal cooling, the decrease in concentration with time is greater and the rise replaced by a slight decrease. Once this correction is made, the change in concentration in a well mixed epilimnion can be described by the relation:

$$\frac{C - C_i}{C_o - C_i} = e^{\frac{-Rt}{V}}$$

where C is the concentration at time t and C_o is that at $t = 0$, C_i is the concentration of the inputs weighted for their relative volumes of flow, R is the volume of flow of inputs per unit time, and V is the volume of the well mixed epilimnion. At two different times (1 and 2) the difference in concentration (ΔC) of the epilimnion would be

$$\Delta C \simeq (C_1 - C_i)\frac{R\Delta t}{V}$$

provided that the exponent $RV^{-1}\Delta t$ is small, which it is for Δt's less than a month which we shall consider. It is convenient to separate C_i and R into parts due to Irondequoit Creek (subscript c) for which we have concentration and flow data and all other sources (subscript x) for which we wish to estimate concentration and flow data. For this purpose a convenient form for the expression is

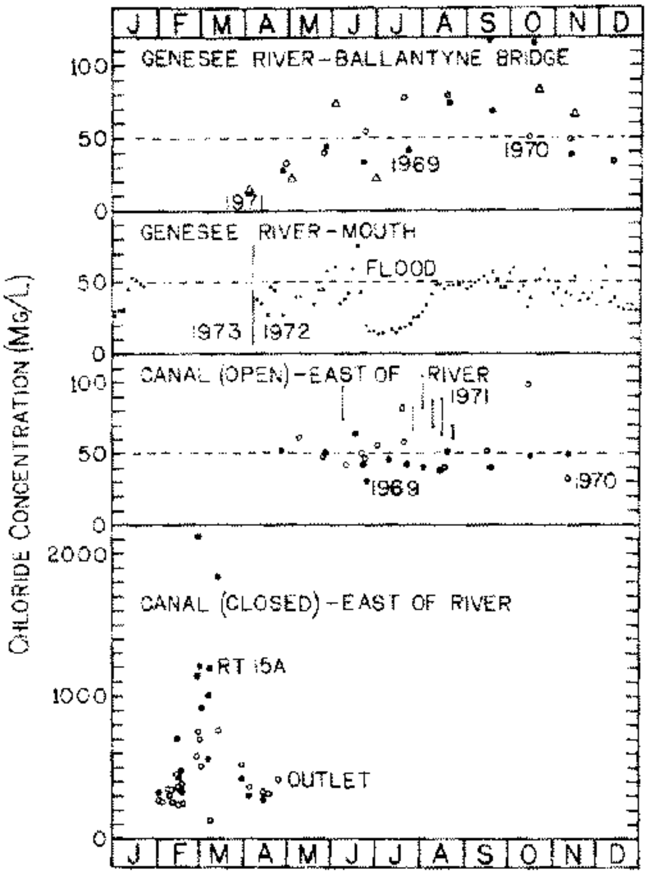

Figure 13. Chloride concentrations of the Genesee River and the N.Y. State Barge Canal. Data from Monroe County Health Department, the U.S. Environmental Protection Agency, and this investigation.

$$(C_1 - C_x)\frac{R_x}{R_c} \simeq \frac{\Delta C \overline{V}}{\Delta t\, R_c} - (C_1 - C_c)$$

where $\overline{V}$ is the average volume of the epilimnion between the two times.

The results are presented in Table VI for six intervals of time during the falls of 1971 and 1972. $\Delta C'$ is the difference in chloride concentration between the two times and ΔC is this difference corrected for chloride advected from below. The quantity $(C_1 - C_x)\, R_x/R_c$ is negative for 5 out of 6 cases. This indicates that additional flows into the bay must have a higher chloride concentration than the bay. If one assumes that R_x/R_c is 0.165 (the ratio of the areas drained by the small streams to the area drained by Irondequoit Creek) and that the chloride concentration in these streams (Table IV) is 150 mg/l higher than that of the bay, the additional chloride can be accounted for. From these considerations it can be concluded that a significant quantity of Lake Ontario water (chloride concentration about 30 mg/l) does not flow into and mix with the waters of Irondequoit Bay, unless there are other chloride rich sources to the bay that we have not taken into account. It should be noted also that this calculation is quite approximate because ΔC is small and thus quite uncertain. However, the result of the salt balance exercise (Table V) for the non-salting months supports the conclusion.

TABLE VI

Results of chloride difference calculation

Dates	$\Delta C'$	ΔC	$\frac{\overline{V}\Delta C}{R_c \Delta t}$	$C_1 - C_c$	$(C_1 - C_x)\frac{R_x}{R_c}$
8/9/71-9/8/71	− 5	−6.8	−34	+37	− 3
10/12/71-11/8/71*	+ 6	−0.8	− 5	+48	−43
11/8/71-11/18/71	+ 2	−2.8	−59	+45	+14
8/28/72-9/27/72	+ 9	−4.6	+18	+15	−33
9/27/72-10/31/72	+15	−1.9	− 8	+21	−13
10/31/72-11/25/72	+ 5	−1.4	− 4	+14	−10

*Creek data for only one half of period

CONCLUSIONS

The data clearly show that deicing salts have a notable effect on the physical behavior of Irondequoit Bay. The ecological consequences are unknown.

Continued heavy use of deicing salt will increasingly impair the ground water resources of the Irondequoit Bay drainage basin and of Monroe County. The time scale is a few years to a few tens of years, depending on the locality and the details of the ground water reservoir.

We are left with the uneasy feeling that the ground water problem might prove ultimately to be much more serious than is now evident: 1) Heavy use of deicing salts is less than a decade old; and since ground water movements are slow, the severity of some effects are not yet apparent. 2) The partition of salt among runoff, soil, and ground water is not well understood, nor is the movement of the salt through various types of aquifers. 3) The level of research and monitoring is low both with regard to the importance of the problem and the cost of deicing salts.

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