NYSDEC OHMS DOCUMENT NO. 201166576-00033

Limnol. Oceanogr., 40(4), 1995, 791–801
© 1995, by the American Society of Limnology and Oceanography, Inc.

Intrusion of saline groundwater into Seneca and Cayuga Lakes, New York

Michael R. Wing,[1] *Amy Preston, Nadine Acquisto, and William F. Ahrnsbrak*
Geoscience Department, Hobart and William Smith Colleges, Geneva, New York 14456

Abstract

Seneca and Cayuga Lakes have chloride levels 2–10 times higher than the other Finger Lakes. Approximately 170×10^6 kg of salt appear to be added to Seneca Lake from within the basin each year. The region is underlain by Silurian beds of commercial-grade rock salt ~450–600 m below the surface. It has been proposed that Seneca and Cayuga Lakes are saltier than the others because their basins intersect some of these beds.

Fieldwork supports this hypothesis. A deep water mass up to 10% saltier than the rest of Seneca Lake was observed to expand and partially fill the hypolimnion from the bottom up during summer 1991 and 1992. The saltier water was mixed into the rest of the lake in early winter, only to reappear after the thermocline was established. Sediment interstitial water profiles in both lakes reveal large regions of saline groundwater several meters below the sediment surface, and NaCl concentrations as high as 30‰ have been found.

New York's Finger Lakes occupy 11 north–south trending basins thought to be preglacial river valleys gouged by Pleistocene glaciation and dammed by moraines (von Engeln 1961). The basins are extremely deep for their surface area (max depths: Seneca, 188 m; Cayuga, 132 m) and intersect a thick sequence of Paleozoic marine sedimentary rocks that dips gently to the south–southwest with little structural deformation. Seneca and Cayuga Lakes exhibit much higher concentrations of dissolved sodium and chloride than the smaller Finger Lakes do, in spite of similar patterns of land use throughout the region.

Berg (1963) has noted that salt strata underlie the entire area and that beds of commercial-grade rock salt 450–600 m below ground level are mined at the southern end of both lakes. Because the mines are dry and lie well below the lake floors, he did not consider it probable that groundwater from these depths leaches upward into the lakes. He also considered and rejected the washings from the commercial salt processing plants themselves as the cause, because no point-sources for chlorides were indicated by the salinity distributions in the lakes, and mass balance considerations seemed to preclude it; a source for chlorides much greater than the mines could provide was necessary to maintain the sodium and chloride concentrations at their 1950s levels. However, Berg did observe that noncommercial-grade salt deposits overlie the ones being exploited commercially and that Seneca and Cayuga Lakes, because of their much greater depths, might intersect salt strata or seepages of saline connate water from which the shallower lakes are isolated.

Such a hypothesis would account for Seneca Lake being saltier than Cayuga (because it is more deeply eroded). The regional dip of the bedrock would cause the salt-bearing strata to outcrop near the north end of both lakes, and saline groundwater is in fact found in some near-surface wells and springs near the north end of Cayuga Lake (Berg 1963).

In their chapter on Finger Lakes limnology, Schaffner and Oglesby (1978) noted that the principal sources of sodium and chloride to Seneca and Cayuga Lakes still had not been identified. Berg's (1963) hypothesis was considered the most likely one, but Schaffner and Oglesby (1978, p. 349) cautioned that ". . . the location and quantity of any such inflows directly to the lake remain to be verified." Their data showed significant increases in sodium and chloride concentrations over Berg's (1963) values in nearly all the Finger Lakes, but the increases were proportionately much greater in the smaller lakes (up ~100%) than in Seneca Lake (up 37%) or Cayuga Lake, which dropped slightly (*see Fig. 1.*).

Neither Schaffner and Oglesby (1978) nor Berg (1963) knew the extent of the bedrock erosion beneath the floors of the lakes, but Mullins and Hinchey (1989) showed that it extends as far as 304 m below sea level in Seneca Lake (or 440 m below lake level). This finding has obvious significance to the salt question because the commercial-grade salt strata considered by Berg are only slightly deeper, even at the southern ends of the lakes. Mullins and Hinchey's (1989) data show that as a general rule, the Finger Lakes are underlain by at least their own depths of glacial and lacustrine sediments. In the case of Seneca Lake, a maximum sediment thickness of 270 m underlies 188 m of water.

[1] Present address: R. Morrison and Assoc., Inc., 28714 Valley Center Rd., Suite L, Valley Center, CA 92082.

Acknowledgments

This study was supported in part by a research grant from the Seneca Lake Pure Waters Association and by Hobart and William Smith Colleges.

We thank Bud Rago and Antony Compese, masters of the HWS *Explorer*, and John Abbot, first mate, for their professional service. We thank Pradeep Jangbari, Tom Pearson, and Dave Persson for helpful conversations and access to NYSDEC files, as well as Dave Weller for water chemistry records spanning several decades. We thank Adam Polcek and Chih-Wei Tsai for preliminary bathymetric work on Seneca Lake. Don Woodrow provided many insights and conversations.

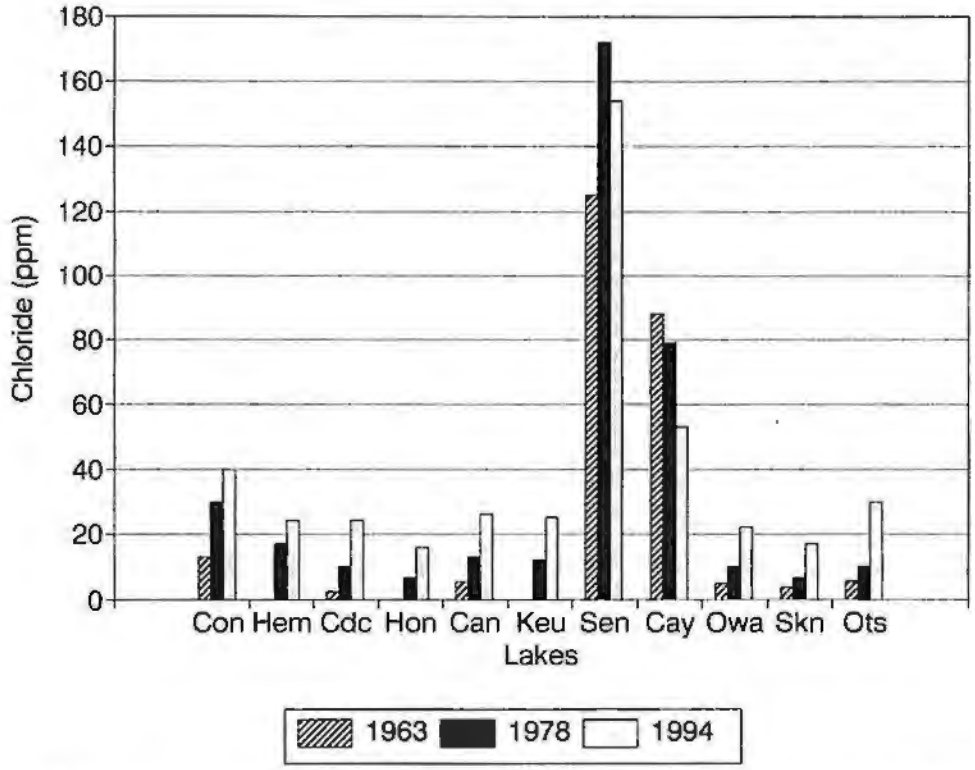

Fig. 1. Chloride concentrations (ppm) in 11 Finger Lakes spanning three decades: 1963 data from Berg (1963); 1978 data from Schaffner and Oglesby (1978); 1994 data from this study. Abbreviations: Con—Conesus Lake; Hem—Hemlock Lake; Cdc—Canadice Lake; Hon—Honeoye Lake; Can—Canandaigua Lake; Keu—Keuka Lake; Sen—Seneca Lake; Cay—Cayuga Lake; Owa—Owasco Lake; Skn—Skaneateles Lake; Ots—Otisco Lake.

Finally, it is noteworthy that Onondaga Lake, near Syracuse, New York, is a brackish lake which has long been known to have salt springs along its shores (Murphy 1978). The same salt-bearing strata which underlie the Finger Lakes region (in the upper Silurian Syracuse Formation of the Salina Group) outcrop near Syracuse, as their name implies. Indeed, salt mining was important to the early economic history of the Syracuse area: the city was once named "Salina" and today continues to be known as "salt city." Any discussion of chlorides in Onondaga Lake today is complicated by the fact that the lake has been heavily polluted by nearby chemical plants. Probably less than half of Onondaga's chlorides enter the lake in naturally occurring seeps and springs (Murphy 1978).

Since the paper by Schaffner and Oglesby (1978), little progress has been made on the question of the origin of Seneca and Cayuga Lakes' dissolved salts. Our study assesses the changes that the last two decades have brought and examines the possibility that significant quantities of chlorides are added to Seneca and Cayuga Lakes by non-point-sources within the lakes' basins. Our efforts were focused on Seneca Lake because it is the deeper and saltier of the two and because it is more easily accessed by our research vessel.

Methods

Surface water samples from streams and lakes were collected in 500-ml Nalgene plastic bottles which had been rinsed three times with sample before filling. Samples were refrigerated unfiltered and analyzed within 3 d. Deep water samples from Seneca Lake were collected in 4-liter Niskin bottles and processed in the same manner.

Water samples of 25–100-ml volume were titrated for chloride with a solution of 0.0282 N silver nitrate to an orange endpoint with potassium chromate indicator solution. Analytical error for titrations was generally ± 2 ppm. Water samples were titrated for total alkalinity with 0.02 N sulfuric acid to a pink end point with phenolphthalein and bromocresol green/methyl red indicator solutions, as given by Wetzel and Likens (1991). Sediment pore-water samples were titrated in a similar manner, except that aliquots were smaller (usually 1 ml), and analytical error ran as high as ± 100 ppm. Such an analytical error was judged insignificant in solutions that approached 20,000 ppm chloride.

Sodium, potassium, calcium, and magnesium in sediment pore-water solutions and lake-water samples were determined directly against appropriate blanks and stan-

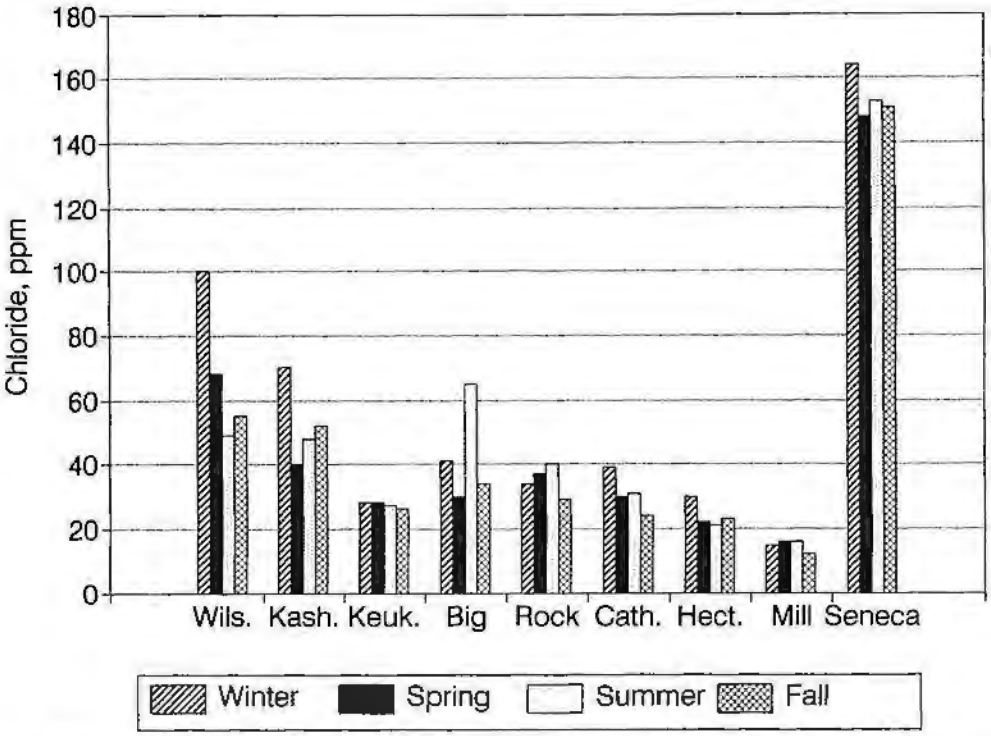

Fig. 2. Chloride concentrations (ppm) in eight tributaries of Seneca Lake and its outlet sampled four times in 1992. Abbreviations: Wils.—Wilson Creek; Kash.—Kashong Creek; Keuk.—Keuka outlet; Big—Big Stream; Rock—Rock Stream; Cath.—Catherine Creek; Hect.—Hector Falls Creek; Mill—Mill Creek; Seneca—Seneca Lake outlet.

dards on an ARL 3140 inductively coupled plasma atomic emission spectrometer. Analytical error was <10% of the reported concentrations. It was necessary to dilute the saline pore-water samples 1:50 with double-distilled water so as not to saturate the photomultiplier detectors.

Conductivity/temperature/depth (CTD) profiles were acquired with a SeaBird Electronics SBE-19 CTD equipped with pH and dissolved oxygen meters. Ship's positions were determined with a Magellan Navpro 1000 global positioning system. Depths in the lakes were found with a Sitex 301A precision depth recorder.

Sediment cores were acquired with a 3-m piston coring system (Alpine Geophysical) with an optional 2.4-m extension. All cores reported here were of the 3-m variety except one (Seneca E), for which the 2.4-m extension was used (total corer length, 5.4 m). Cores were collected in tenite butyrate liners (3 m long, 3.8-cm o.d., 3.2-cm i.d., Busada Mfg. Co.), capped, and immediately sawed open at intervals of 30–40 cm. Sediment subsamples were removed with a steel spatula, collected in Ziploc plastic bags, and refrigerated. Aliquots of 50 ml of sediment were removed into Nalgene centrifuge tubes and centrifuged for 30–45 min at 5,000 rpm. At the end of this procedure, several milliliters of sediment pore waters were carefully drawn off with Pasteur pipettes and the fluids analyzed as described above.

Results and discussion

Chloride concentrations in the Finger Lakes—Our measurements of chloride in surface samples from the nine smaller Finger Lakes collected in fall 1992 (Fig. 1) all show significant increases over the values of Schaffner and Oglesby (1978), while the chloride concentrations of Seneca and Cayuga Lakes appear to have declined by ~10 and 30%, respectively. An increase in the use of chloride salts for de-icing roads across the region may be the cause for the observed chloride enrichment in the smaller lakes. Another process must account for the decline in chloride concentrations in Seneca and Cayuga Lakes.

Although direct wastewater input from salt companies could not account for the lakes' chloride levels in the 1960s, there were several years in the early 1970s when direct dumping of salt into the lakes had clear and significant impacts on chloride concentrations (Ahrnsbrak 1975). Thus, Likens (1974) found that in 1970–1971, twice as much chloride was discharged from Cayuga Lake as entered it through tributaries. Effler et al. (1989) have modeled the decline of chloride levels in Cayuga Lake after the cessation of large-scale dumping by salt-mining plants and purport to show that no groundwater source of salt input into Cayuga Lake is necessary to balance the lake's salt budget. Their model relies on estimates of the

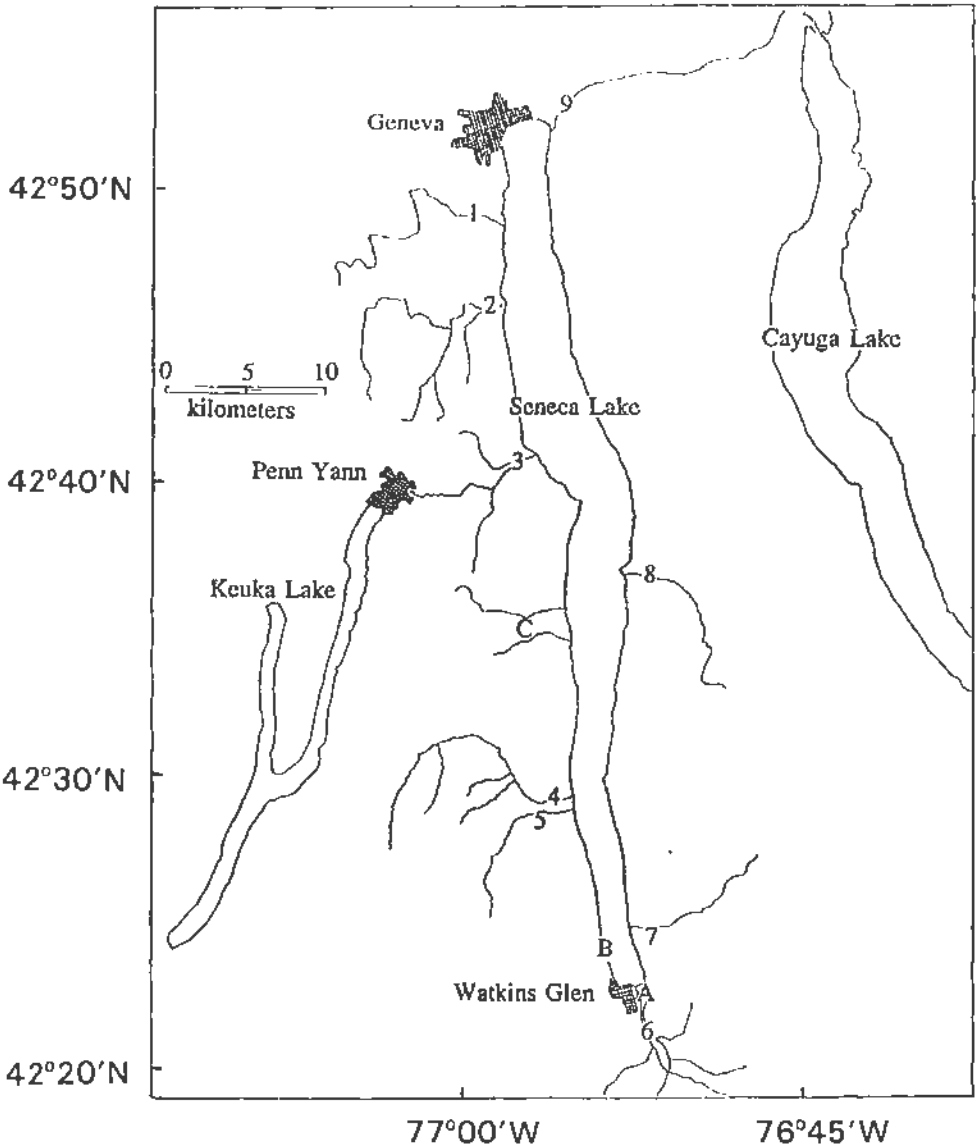

Fig. 3. Locations of tributaries, salt-mining plants, municipalities, and lakes in and adjacent to Seneca Lake's watershed. Map symbols: 1—Wilson Creek; 2—Kashong Creek; 3—Keuka outlet; 4—Big Stream; 5—Rock Stream; 6—Catherine Creek; 7—Hector Falls Creek; 8—Mill Creek; 9—Seneca Lake outlet; A—Cargill Salt Plant; B—Akzo Salt Plant; C—Morton Salt Plant.

lake's water retention time, the value of which can vary widely from year to year (Oglesby 1978), and they do not neglect to take this into account. Whether the model by Effler et al. accurately describes the behavior of Cayuga Lake, we find it instructive to apply the same model to Seneca Lake to determine whether that lake's salt budget can be balanced without significant input from saline groundwater.

Modeling chloride concentration in Seneca Lake—Eight medium-sized and large tributaries of Seneca Lake and its outlet were sampled and analyzed for chloride four times in 1992 to determine whether chloride loading by tributaries could account for the high chloride levels of the lake (Fig. 2). Figure 3 shows the locations of the tributaries, the locations of the three salt-mining plants, and the three largest municipalities in the lake's watershed, as well as the drainage relationships of Keuka, Seneca, and Cayuga Lakes. Keuka Lake drains directly into Seneca Lake, which is the only instance under normal flow regimes of one Finger Lake draining into another. The outlet of Seneca Lake flows through a wetland area to the

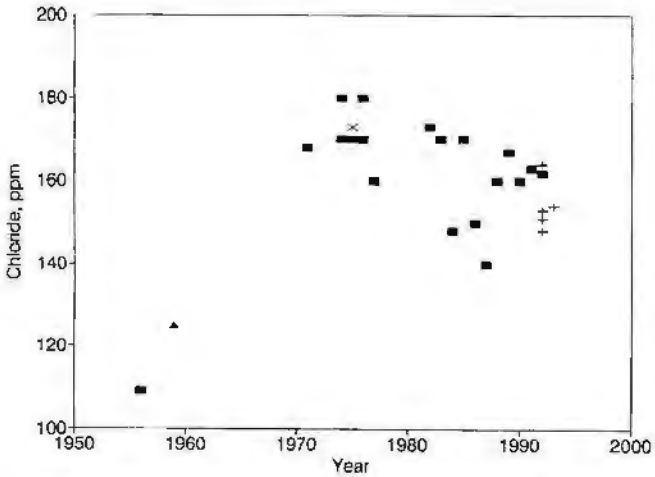

Fig. 4. Time series of chloride concentrations in Seneca Lake surface water. Data symbols: ▲—from Berg 1963; X—from Schaffner and Oglesby 1978; ■—from the City of Geneva water treatment plant records; +—from this study.

north of Cayuga Lake and rarely flows into Cayuga Lake (Effler et al. 1989). However, during periods of very high hydraulic loading, such as the floods of April 1993 and June 1972 (Oglesby 1978), the Seneca outlet can flow into Cayuga Lake.

The eight tributaries shown in Fig. 2 collectively drain more than half of Seneca Lake's watershed. Indeed, the Keuka outlet alone drains ~25% of the Seneca/Keuka watershed. The two tributaries with the highest chloride levels (Wilson and Kashong) are two of the smallest sampled. A good estimate of the average tributary water chloride concentration entering the lake is 30 ppm, while that of the water leaving the lake is 150 ppm. Seneca Lake has an estimated water retention time of 18 yr (Schaffner and Oglesby 1978), and the volume is 15.54×10^9 m^3. If the salinity of Seneca Lake has been in a steady state over the last two decades, a simple mass balance calculation shows that $\sim 170 \times 10^6$ kg of NaCl would have to be added to the lake each year from within its basin: (15.54×10^9 m^3 water) × (1/18 yr) × (10^3 kg water/m^3 water) × (120 kg Cl/10^6 kg water) × (58.5 kg NaCl/35.5 kg Cl) = 170×10^6 kg yr^{-1} NaCl.

In fact, the lake has undergone a decline in chloride levels of 10–15% in two decades, as shown by historical data from Berg (1963), Schaffner and Oglesby (1978), annual records from the City of Geneva water treatment plant, and this study. Figure 4 shows a rise to 175 ppm by the early 1970s followed by a modest decline since then, a decline that cannot be accounted for by simple flushing of the 175-ppm lake water with 30-ppm tributary water in the absence of other significant inputs. Following the model of Effler et al. (1989) for chloride loading and lake flushing in Cayuga Lake, we have

$$[\mathrm{Cl}]_t = \Sigma W/Q[1-\exp(-Qt/V)] + [\mathrm{Cl}]_0\exp(-Qt/V).$$

$[\mathrm{Cl}]_t$ is Cl concentration at time t, $[\mathrm{Cl}]_0$ is initial Cl concentration at $t = 0$, V is lake volume, Q is annual discharge flow to the lake's outlet, ΣW is the sum of all Cl loads, and t is time.

For Seneca Lake, $Q/V = 1/18$ yr^{-1}. If the lake had experienced no chloride loading other than that from tributary water in the past two decades ($\Sigma W/Q = 30$ ppm), its chloride concentration would be ~78 ppm today, not the 150 ppm that we observed. Indeed, an application of this model to the observed decline in chloride concentrations (~175–150 ppm in 20 yr) results in a $\Sigma W/Q$ of 138 ppm. Interestingly, this value is consistent with the

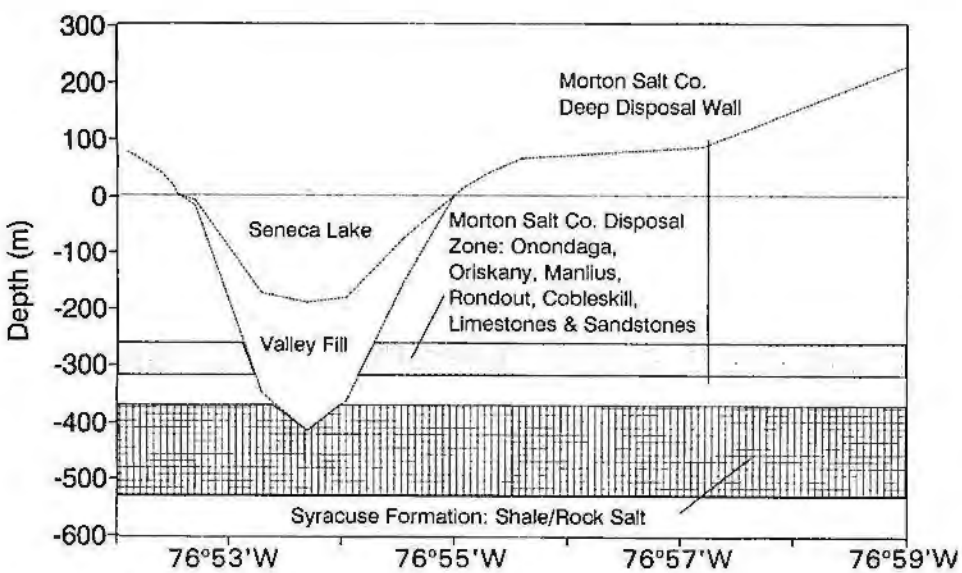

Fig. 5. Schematic latitudinal bedrock profile of Seneca Lake at 42°35'N.

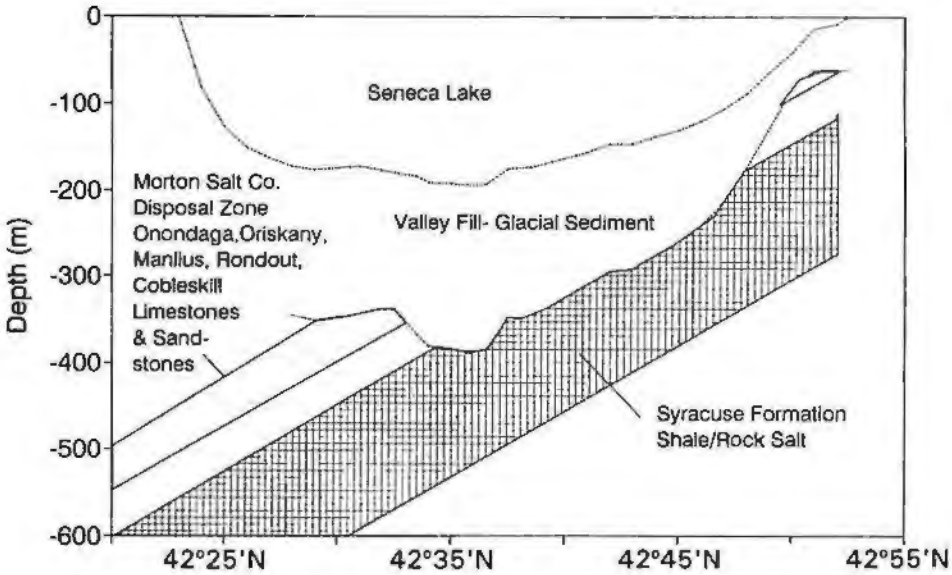

Fig. 6. Schematic longitudinal bedrock profile of Seneca Lake at maximum depth.

pre-1970s' value of 110–125 ppm reported by Berg (1963), Schaffner and Oglesby (1978), and the City of Geneva records, if a modest allowance is made for the increased use of road salts in the watershed. No aspect of this model and no historical data available to us suggest that Seneca Lake ever had or ever could have had chloride concentrations <100 ppm. Thus, the contention by Effler et al. (1989) that Cayuga Lake lacks significant saline groundwater input cannot be generalized to its saltier neighbor.

The bedrock geology of Seneca Lake—The two salt-mining concerns at the south end of Seneca Lake (A and B, Fig. 3) operate today. Their discharges of chlorides into the lake are monitored by the New York State Department of Environmental Conservation (DEC). DEC records show that their combined daily discharge is <3,600 kg of chloride per day—a few percent of the amount needed to maintain the lake at its current salinity level. The Morton Salt plant near Himrod (C, Fig. 3), no longer operates. However, DEC records show that in the mid- and late-1970s, Morton Salt pumped $\sim 1 \times 10^9$ kg of waste salt as brine down a deep disposal well on its property. The disposal zone lies well below the lake floor, but not below the depth of bedrock erosion found by Mullins and Hinchey (1989). Knowledge of the depths and thicknesses of bedrock units near Himrod (Subsurface, Inc. unpubl. rep.), of the locations of outcrops of the same formations (Rickard and Fisher 1970), and of the bedrock profiles of Mullins and Hinchey (1989) permits the construction of the schematic latitudinal and longitudinal bedrock profiles shown as Figs. 5 and 6. The profiles leave little doubt that the bedrock basin of Seneca Lake penetrates the salt-bearing Syracuse formation and

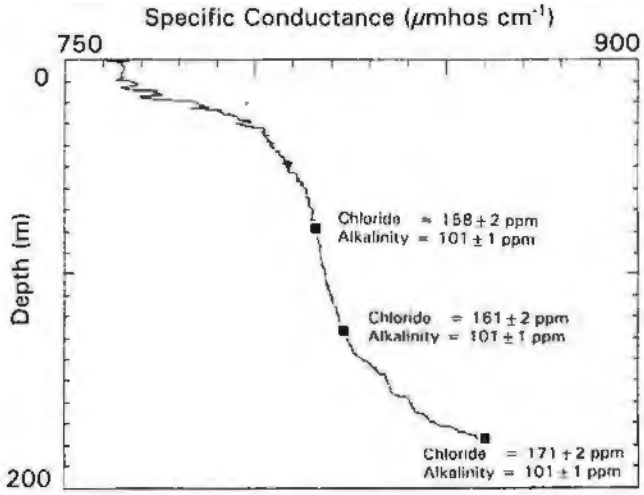

Fig. 7. Vertical water-column specific conductance profile in the deepest station of Seneca Lake (42°35.8'N, 76°53.7'W) on 6 August 1992 with chloride and total alkalinity concentrations.

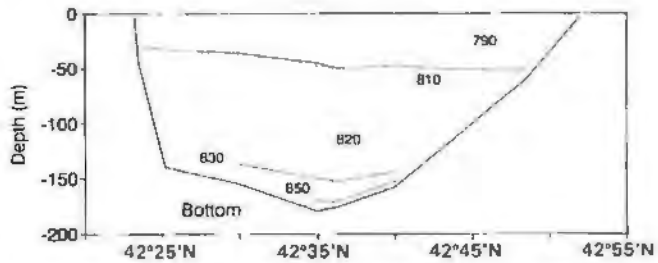

Fig. 8. North–south sections of specific conductance (μmhos cm⁻¹) in Seneca Lake on 10 July 1991.

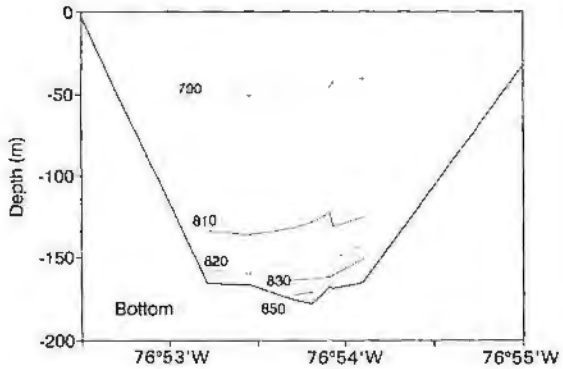

Fig. 9. East–west sections of specific conductance (μmhos cm^{-1}) in Seneca Lake (42°35'N) on 8 July 1991.

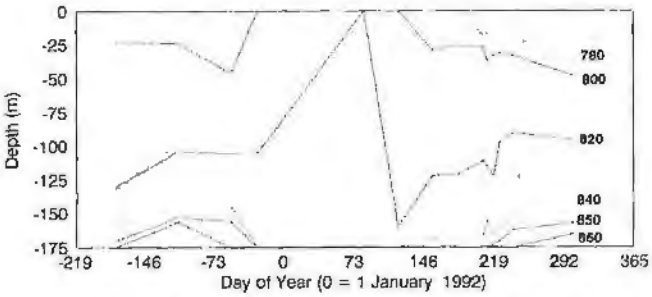

Fig. 10. Depth-time distribution of isopleths of specific conductance (μmhos cm^{-1}) in Seneca Lake (deepest station) in 1991 and 1992.

the disposal zone of Morton Salt. The regional dip places them into contact with the lake's basin for tens of kilometers. Deep saline seepage from these rock units through the sediments and into the water column is thus likely.

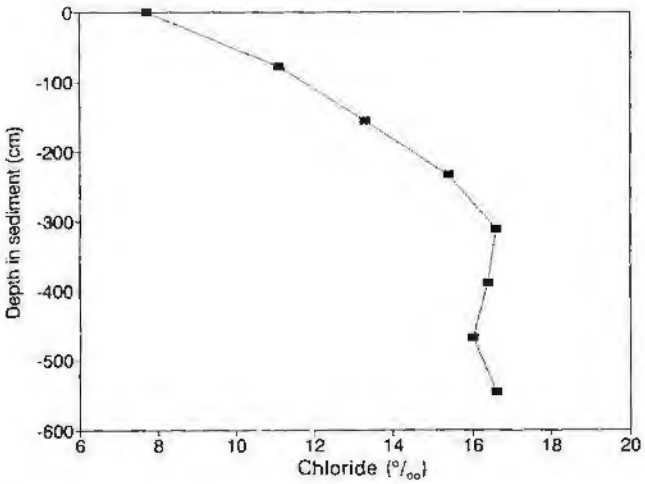

Fig. 11. Chloride concentration in interstitial water samples of sediment core Seneca E.

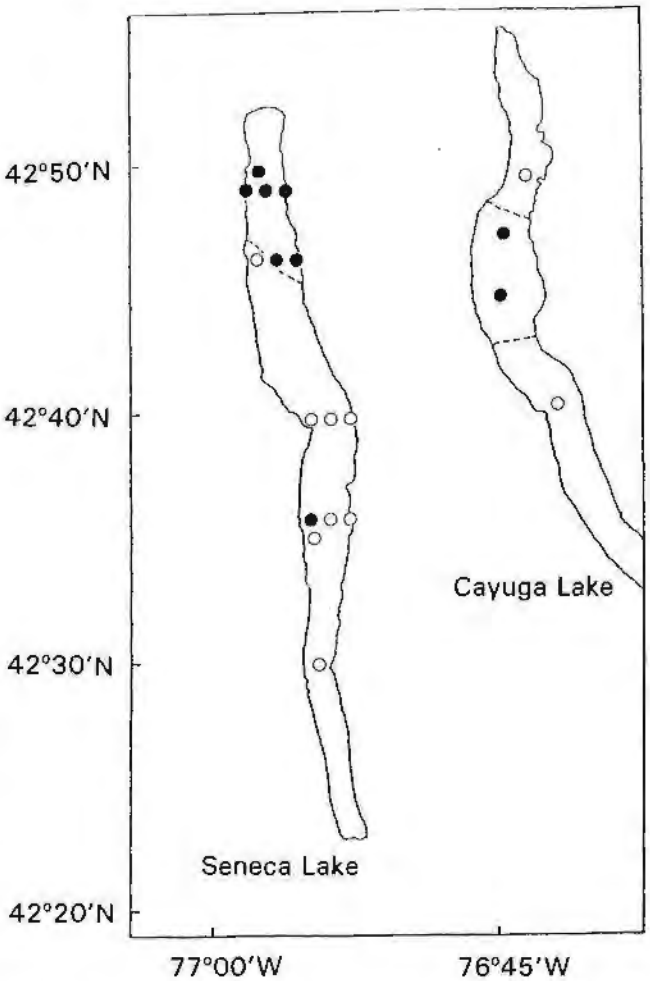

Fig. 12. Locations of sediment cores in Seneca and Cayuga Lakes. Interstitial chloride concentration >4‰ within 2.5 m of the sediment–water interface—●; interstitial chloride concentration <4‰ within 2.5 m of the sediment–water interface—O.

Water-column conductivity profiles in Seneca Lake—Evidence for such a seepage process can be seen in water-column conductivity profiles during summer/autumn months when the lake is thermally stratified. A typical summer vertical conductivity profile (Fig. 7) shows a steady increase in conductivity with depth below the thermocline. Water samples collected simultaneously with the CTD cast are found to have chloride concentrations that also increase with depth. The higher conductivity is entirely accounted for by the increase in chloride concentration. Vertical conductivity profiles thus can serve as a proxy for chloride concentrations in the hypolimnion of Seneca Lake. Oglesby (1978) observed a similar pattern in Cayuga Lake.

If either of the salt-mining operations at the extreme southern end of Seneca Lake represents a significant point-source for dissolved chlorides, one might expect conductivity values at the south end of the lake to be highest.

Table 1. Locations and water depths of selected sediment cores in Seneca and Cayuga Lakes.

Core	Landmark	N lat, W long	Water depth (m)
Seneca 1	Clark Pt. center	42°48.75′, 76°57.77′	71
Seneca 2	Clark Pt. west	42°48.83′, 76°58.22′	38
Seneca 3	Clark Pt. east	42°48.73′, 76°56.98′	61
Seneca 4	Kashong Pt. center	42°45.92′, 76°56.93′	123
Seneca 6	Kashong Pt. east	42°45.91′, 76°56.64′	123
Seneca 7	Kashong Pt. west	42°45.90′, 76°57.65′	65
Seneca 8	Belhurst Castle	42°49.90′, 76°57.91′	61
Seneca 9	Plum Pt. west	42°35.85′, 76°54.38′	164
Seneca 10	Plum Pt. center	42°35.79′, 76°53.75′	188
Seneca 11	Plum Pt. east	42°35.60′, 76°53.17′	168
Seneca 12	Long Pt. center	42°39.85′, 76°53.69′	163
Seneca 13	Long Pt. east	42°39.99′, 76°52.99′	112
Seneca 14	Long Pt. west	42°40.00′, 76°54.47′	150
Seneca 15	Peach Orchard Pt.	42°29.67′, 76°54.01′	162
Seneca 16	Plum Pt. west	42°35.34′, 76°54.50′	122
Seneca A	Belhurst Castle	42°49.97′, 76°57.96′	62
Seneca E	Belhurst Castle	42°49.93′, 76°57.97′	62
Cayuga 1	Sheldrake Pt.	42°40.13′, 76°40.82′	118
Cayuga 2	Aurora	42°45.11′, 76°45.18′	73
Cayuga 3	Ellis Pt.	42°46.98′, 76°44.80′	40
Cayuga 4	Farleys Pt.	42°48.46′, 76°44.41′	24

Instead, the deep conductivity sections seem to follow the contours of the lake floor (Fig. 8). Not once in four north–south transects of the lake (10 July, 10 September, and 7 November 1991 and 29 April 1992) did we observe any significant excess in water-column conductivity at the southern end. In fact, water-column conductivity at this end was lower than the lake average in spring, presumably due to input from Catherine Creek, Seneca Lake's second largest tributary. It is surprising that in a lake so long and narrow (56 × 4 km) a slight east–west gradient in conductivity sections was repeatedly observed (8 July 1991 and 30 June and 29 October 1992; Fig. 9). On each occasion, conductivities appeared to be slightly greater on the west side than on the east. It is noteworthy that the Morton Salt Company's installation in Himrod is located 3 km west of the lake at 42°35′N—the latitude along which the east–west transects were made.

Seneca Lake is classified as a warm monomictic lake (Berg 1963). It rarely develops ice cover and circulates freely all winter. Thus, the deep chloride enrichment in the hypolimnion which accumulates in summer and autumn is mixed into the overlying water and homogenized in winter. Figure 10 shows the depth-time distribution of water-column conductivity for the last 6 months of 1991 and all of 1992. In both years, the epilimnion conductivities declined during the period of summer–autumn stratification, while the hypolimnion conductivities steadily increased. The fresher epilimnion can be attributed to mixing with warm and relatively low-salinity input from tributaries. The increasing salinity in the hypolimnion is indicative of saline input from some other source.

Sediment interstitial water profiles in Seneca and Cayuga Lakes—Seventeen sediment cores were collected from Seneca Lake and four from Cayuga Lake. Four to eight subsamples from each were centrifuged, and the interstitial fluids were analyzed for chloride. Selected cores were also analyzed for total alkalinity and major cations. Table 1 lists the locations of selected sediment cores, and Table 2 gives the chloride results. The interstitial water chloride gradient in a representative sediment core is shown in Fig. 11. Groundwater with chlorinity nearly that of seawater is present 2–3 m below the sediment–water interface in many locations in Seneca and Cayuga Lakes, and the sharp chloride gradients near the interface strongly suggest the vertical diffusion of saline water. Although considerable spatial variability in near-surface chloride gradients can be seen, a map of core locations (Fig. 12) shows that broad regions at the north end of both lakes exhibit uniformly high near-surface chloride gradients. Only one sediment core south of 42°40′N (Seneca 9) exhibited pore-water chlorides 4‰ within 2.5 m of the sediment–water interface, although a number of others in this region were in the range of 1–3‰. Seneca 9 is adjacent to the Morton Salt plant and might reflect a localized source. However, we consider it unlikely that Morton Salt's disposal well could be responsible for all of the saline groundwater under the north ends of the lakes. A bed of lake sediment 60 km^2 in area and 50 m thick that has a water content of 25% at 16‰ chloride would contain 20×10^9 kg of NaCl, and this does not take into account any of the saline groundwater in the 20–30 km of rock

Table 2. Chloride concentrations (‰) in interstitial water samples of selected sediment cores listed in Table 1.

Seneca 1	Depth (cm)	0	44	84	124	164	204	244	
	Cl^-	4.4	7.1	9.1	10.0	13.3	15.7	15.8	
Seneca 2	Depth (cm)	0	41	79	117	155	193	231	
	Cl^-	1.2	1.4	2.1	3.3	3.8	4.2	4.7	
Seneca 3	Depth (cm)	0	49	94	139	184	229	274	
	Cl^-	0.9	1.8	2.7	3.3	4.1	4.9	5.2	
Seneca 4	Depth (cm)	0	41	82	123	164	205	246	287
	Cl^-	2.7	5.6	6.8	8.5	8.9	9.8	10.6	11.5
Seneca 6	Depth (cm)	0	43	85	128	171	214	256	299
	Cl^-	5.5	12.2	14.9	16.8	17.1	15.7	17.6	17.9
Seneca 7	Depth (cm)	0	33	67	100	134	167	203	236
	Cl^-	0.2	0.2	0.3	0.3		0.4		0.4
Seneca 8	Depth (cm)	0	42	85	127	169	211	253	296
	Cl^-	14.5	16.8	17.8	18.1	18.2	18.5	20.1	13.1
Seneca 9	Depth (cm)	0	34	68	102	136			
	Cl^-	6.7	14.3	14.8	14.7	14.6			
Seneca 10	Depth (cm)	0	41	82	123	164	205	246	288
	Cl^-	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4
Seneca 11	Depth (cm)	0	33	67	101	135	169	203	236
	Cl^-	0.7	0.9	1.0	1.0	1.0	1.1	1.1	1.1
Seneca 12	Depth (cm)	0	33	67	101	135	168	202	235
	Cl^-	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Seneca 13	Depth (cm)	0	41	82	123	164			
	Cl^-	0.6	0.8	0.8	0.8	0.9			
Seneca 14	Depth (cm)	0	38	76	114	152	190	228	266
	Cl^-	1.1	1.4	1.8	2.1	2.5	2.7	3.0	3.5
Seneca 15	Depth (cm)	0	37	74	111	148	185		
	Cl^-	2.9	2.6	3.0	2.6	2.7	3.1		
Seneca 16	Depth (cm)	0	40	81	122	162	203	243	284
	Cl^-	0.7	0.6	0.7	0.8			1.0	1.1
Seneca A	Depth (cm)	0	41	82	123	164	205	246	287
	Cl^-	1.7	2.7	3.4	4.3	5.2	6.3	7.4	8.6
Seneca E	Depth (cm)	0	78	156	234	312	390	468	546
	Cl^-	7.7	11.1	13.3	15.4	16.6	16.4	16.0	16.6
Cayuga 1	Depth (cm)	0	37	74	111	148	185		
	Cl^-	0.4	0.3	0.1	0.1	0.1	0.1		
Cayuga 2	Depth (cm)	0	36	73	109	145	181	218	254
	Cl^-	1.7	4.3	4.2	5.3	8.7	8.8	13.2	11.5
Cayuga 3	Depth (cm)	0	42	84	126	167	209	251	293
	Cl^-	0.5	1.0	1.4	2.1	2.8	3.5	4.2	4.1
Cayuga 4	Depth (cm)	0	38	76	114	152	190	228	266
	Cl^-	0.4	0.6	0.8	1.2	1.4	1.6	1.9	2.0

between Morton Salt and the north ends of the lakes. A billion kilograms would hardly suffice.

Saline groundwater under Seneca and Cayuga Lakes has not previously been reported in the literature, although Harriss (1967) found an increasing chloride gradient with depth in near-surface Seneca Lake sediments (max [Cl], 152 ppm). He seems not to have understood the significance of his finding to the question of high salinity in the lake and attributed his results to evaporation of rainwater solutions in soils in the watershed. Sediment pore-water chloride concentrations very similar to ours were obtained by Grotzinger (1979).

Table 3 lists interstitial water concentrations of sodium, calcium, magnesium, and potassium as well as total alkalinity and chloride for three Seneca Lake cores. Sodium concentrations increase proportionately with chloride in all cores, but the behavior of calcium, magnesium, and potassium is more varied. Their ionic concentrations increase with depth in cores Seneca 1 and Seneca A but not in Seneca E, which could be indicative of chemical heterogeneities in the groundwater fluids. A report by Drimmie et al. (unpubl.) of highly saline and chemically heterogeneous fluids in Lake Ontario sediments suggests that such phenomena are not limited to the largest of New York's Finger Lakes.

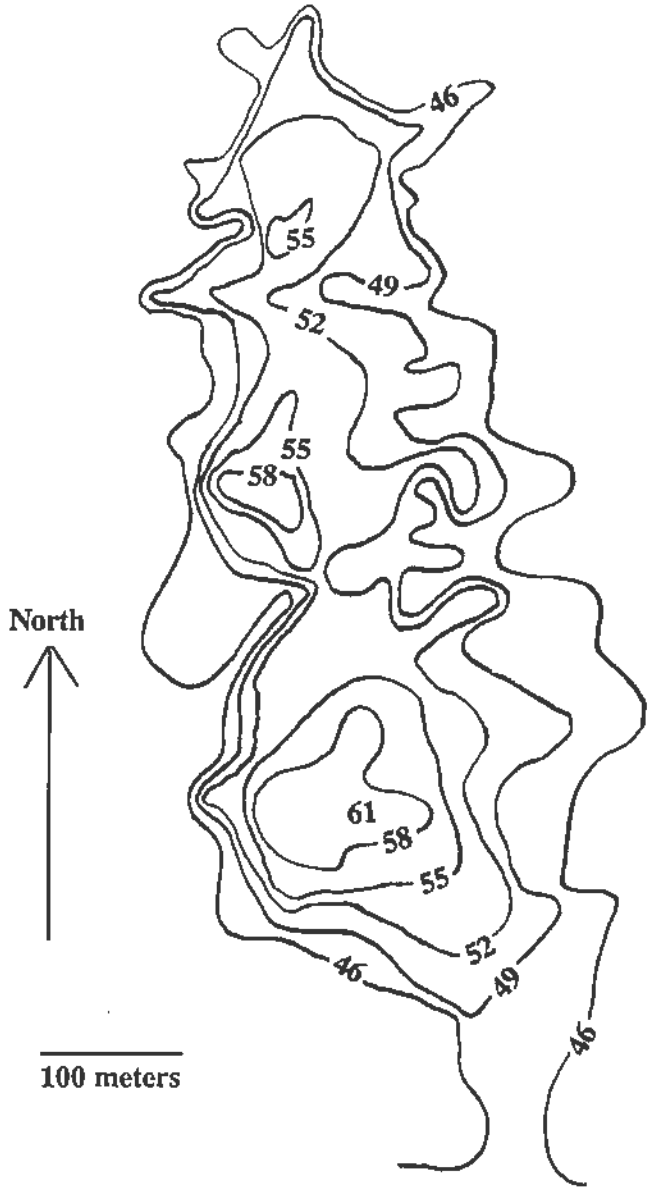

Fig. 13. Bathymetry of Belhurst Castle Hole (depths in meters). The deepest part of the hole (61 m) is at 42°49.95'N, 76°57.95'W.

Pooling of saline water in a topographic depression in Seneca Lake—The bottom of Seneca Lake is topographically irregular. A depression in the lake floor at 42°49.95'N, 76°57.95'W (known locally as the Belhurst Castle Hole) has been observed on occasion to contain water with up to twice the conductivity of the rest of the lake below its sill depth of 46 m (Figs. 13 and 14). Sediments in the hole are saline (Seneca cores 8, A, E) but not significantly more so than those of other cores at this end of the lake. It would appear that the morphology of the hole prevents mixing of water below its sill with the rest of the lake. This phenomenon is transient. It persists for at least a few weeks at a time in summer or autumn but can suddenly disappear. Seneca Lake is known to undergo internal waves and seiches with amplitudes of tens of meters (Ahrnsbrak 1974). Such events are pre-

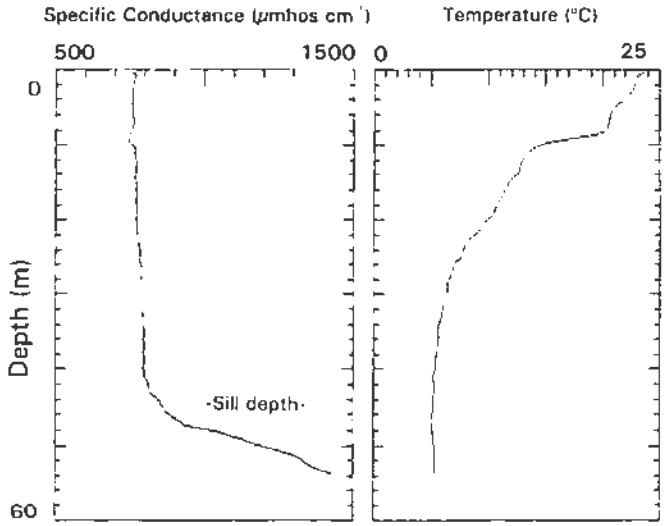

Fig. 14. Water-column conductivity/temperature/depth profile at the Belhurst Castle Hole. Sill depth is ~46 m.

Table 3. Sediment interstitial water concentrations of chloride, total alkalinity, sodium, calcium, magnesium, and potassium (ppm) in selected sediment cores.

Depth (cm)	Cl^-	Alk.	Na^+	Ca^{2+}	Mg^{2+}	K^+
			Seneca I			
0	4,380	250	2,670	323	123	10
44	7,100	200	4,520	475	200	11
84	9,120	200	6,010	661	269	18
124	9,970	200	6,250	651	266	17
164	13,350	250	8,040	842	334	22
204	15,730	200	9,640	918	361	33
244	15,750	200	9,740	929	362	34
			Seneca A			
0	1,700	400	1,240	150	60	13
41	2,700	500	1,800	180	90	5
82	3,400	600	2,220	210	120	5
123	4,300	700	2,920	240	150	7
164	5,200	1,000	3,450	280	180	5
205	6,300	800	4,080	330	220	7
246	7,400	800	5,210	400	280	8
287	8,600	550	5,300	380	280	8
			Seneca E			
0	7,650	100	5,500	1,290	410	34
78	11,100	100	8,050	1,160	510	52
156	13,250	150	10,140	1,300	560	74
234	15,400	250	10,950	1,400	510	78
312	16,600	200	10,420	1,510	500	80
390	16,350	200	10,320	1,290	480	81
468	16,000	200	9,680	1,160	440	80
546	16,600	200	9,910	1,160	450	82

sumably sufficient to flush the hole of its salt-enriched water.

Conclusions

Whether the model of Effler et al. (1989) is accurate for Cayuga Lake, it entirely fails to balance the salt budget of Seneca Lake without a significant input of salt from within the lake's basin. Seneca Lake and Cayuga Lake each exhibit large regions of highly saline groundwater within 3 m of the sediment–water interface and a bottom-up conductivity-chloride gradient in the water column consistent with large-scale intrusion of saline groundwater into the water column. For Seneca Lake, no source other than saline groundwater intrusion can account for the high chloride levels. The field data strongly suggest that the same process occurs on Cayuga Lake, albeit to a lesser extent.

In his discussion of salt in the Finger Lakes, Berg (1963, p. 203) wrote of the saline groundwater hypothesis: "This suggests a dimension in regional limnology that has not received much attention in the literature—the possibility that the chemistry of a lake can be affected significantly by the deep-lying strata intercepted by its basin as well as by the surficial lithology of its watershed." Three decades later, this "dimension" is still underappreciated.

References

AHRNSBRAK, W. F. 1974. Some additional light on surges. J. Geophys. Res. **79:** 3482–3483.

———. 1975. A saline intrusion into Seneca Lake, New York. Limnol. Oceanogr. **20:** 275–278.

BERG, C. O. 1963. Middle Atlantic states, p. 191–237. *In* D. G. Frey [ed.], Limnology in North America. Univ. Wisconsin.

EFFLER, S. W., M. T. AUER, AND N. A. JOHNSON. 1989. Modeling Cl concentration in Cayuga Lake, U.S.A. Water Air Soil Pollut. **44:** 347–362.

GROTZINGER, J. P. 1979. The diffusion of chloride in Seneca Lake sediments. B.S. thesis, Hobart College. 87 p.

HARRISS, R. C. 1967. Silica and chloride in interstitial waters of river and lake sediments. Limnol. Oceanogr. **12:** 8–12.

LIKENS, G. E. 1974. Water and nutrient budgets for Cayuga Lake, New York. Cornell Univ. Water Resour. Mar. Sci. Center Tech. Rep. 82.

MULLINS, H. T., AND E. J. HINCHEY. 1989. Erosion and infill of New York Finger Lakes: Implications for Laurentide ice sheet deglaciation. Geology **17:** 622–625.

MURPHY, C. B., JR. 1978. Onondaga Lake, p. 223–365. *In* J. A. Bloomfield [ed.], Lakes of New York State. V.2. Academic.

OGLESBY, R. T. 1978. The limnology of Cayuga Lake, p. 1–120. *In* J. A. Bloomfield [ed.], Lakes of New York State. V.1. Academic.

RICKARD, L. V., AND D. W. FISHER. 1970. Geologic map of New York. Finger Lakes sheet. New York State Museum Sci. Serv. Map and Chart Ser. 15.

SCHAFFNER, W. R., AND R. T. OGLESBY. 1978. Limnology of eight Finger Lakes: Hemlock, Canadice, Honeoye, Keuka, Seneca, Owasco, Skaneateles, and Otisco, p. 313–470. *In* J. A. Bloomfield [ed.], Lakes of New York State. V.1. Academic.

VON ENGELN, O. D. 1961. The Finger Lakes region: Its origin and nature. Cornell Univ.

WETZEL, R. G., AND G. E. LIKENS. 1991. Limnological analyses, 2nd ed. Springer.

Submitted: 4 March 1994
Accepted: 23 November 1994
Amended: 25 January 1995