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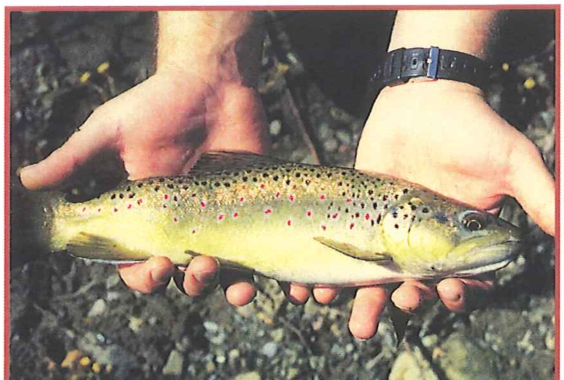
Ecological Status of Onondaga Creek in Tully Valley, New York — Summer 1998

Onondaga Creek flows through the Tully Valley (fig. 1) and supports a cold-water fishery (brook trout and brown trout) along its length. Several unusual hydrogeologic features cause the water quality of the creek to deteriorate as it flows northward. Mudboils, which are found in the central part of the valley, discharge artesian-pressured freshwater, brackish water, and fine-grained sediment to the land surface and to Onondaga Creek. Several mudslides (the latest in 1993) have exposed brackish-water springs that also discharge to the Creek. The result is a further degradation of water quality and possible adverse effects to stream biota. Even though remedial efforts in the mudboil area have decreased sediment loading to the creek (from 30 tons per day in 1992 to less than 1 ton per day in 1998), the discharge of brackish water is a concern to local citizens as well as to State and Federal agencies.

An ecological survey of the creek was made by the New York State Department of Environmental Conservation (NYSDEC) and the U.S. Geological Survey (USGS) in July and August 1998. Fish populations were sampled at eight sites and macroinvertebrate populations were sampled at nine sites in the upper 5 miles of the Onondaga Creek watershed (south of U.S. Route 20). The resulting data were correlated with streamflow and water-quality data collected by the USGS at 10 locations in the same reach to evaluate the ecological status of the creek and serve as a baseline for future study and for comparison of the effects of remediation projects within this part of the Onondaga Creek watershed.



Brown Trout — *Salmo trutta*

Physical Setting

The Tully Valley is a north-south-trending glacial trough which is about 6 miles long and a mile wide. The valley walls consist of till (compact soils) over weathered bedrock, and the valley floor overlies more than 400 feet of glacial deposits (gravel and sand grading upward to silt and clay at land surface) and the floor slopes gently from the valley walls toward the center of the valley. Onondaga Creek begins in the southern uplands of the Tully Valley and flows northward toward Syracuse, where it drains to the Seneca River and eventually flows to Lake Ontario. Land use in the valley is agricultural and low-density residential, and a brine-mining operation at the southern end of the valley was active for nearly a century (1889-1986).

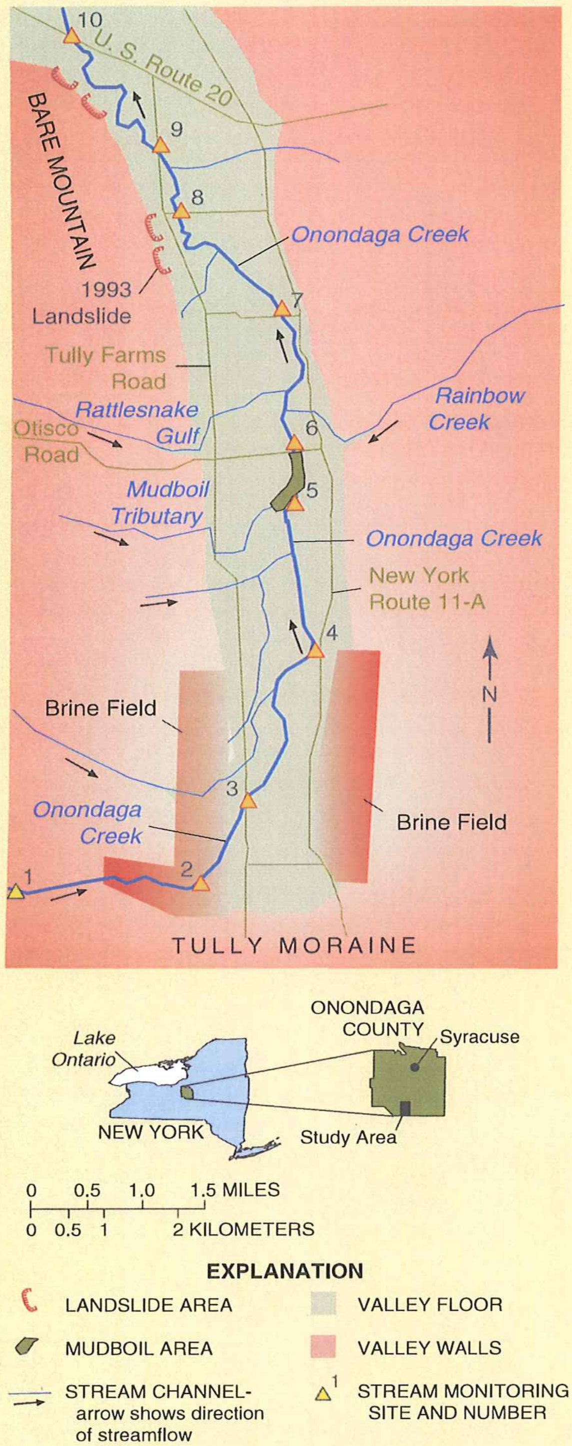


Fig. 1. Principal hydrologic features and locations of sampling sites in Tully Valley, N.Y.

Brook Trout — *Salvelinus fontinalis*

Discharge and Water Quality

The discharge measurements made along Onondaga Creek in July 1998 indicate that streamflow is supplemented by springs discharging from the Tully Moraine at the southern end of the valley, by streams along the flanks of the valley (primarily Rattlesnake Gulf and Rainbow Creek), and by springs discharging from the mudslide areas along the base of Bare Mountain. Little if any flow comes from the valley floor, except from mudboils, or from wells drilled around the mudboil area to lower the local artesian pressure.

The chemical quality of Onondaga Creek changes at each inflow point (table 1). Specific conductance (a measure of dissolved-solids concentration) ranged from 500 to 600 μS/cm (microsiemens per centimeter) upstream from the mudboils but increased to 1,400 μS/cm just downstream from the mudboil tributary. The specific conductance was lowered slightly by inflow from Rattlesnake Gulf and Rainbow Creek but increased to 2,000 μS/cm downstream from the 1993 landslide area and to 2,250 μS/cm downstream from the northernmost landslide areas at the base of Bare Mountain. Dissolved oxygen concentration was fairly constant (7.00 to 7.92 mg/L) along the creek, but was near 6.0 mg/L in the mudboil tributary and at site 10 at U.S. Route 20. pH varied only slightly (8.4 to 8.6 units) along the creek, but was about 7.5 in the mudboil tributary. Chemical concentrations were relatively stable along the creek except for sodium chloride (halite/salt) and calcium sulfate (gypsum), which increased as a result of discharges from mudboil and mudslide areas. Water temperature increased downstream, but this change was related to the time of day at which the temperature was measured.

A similar but less rigorous water-quality study of Onondaga Creek was done by the New York State Department of Health (NYSDOH) in December 1981 in response to reports of excessive turbidity in the creek at that time. The values of specific conductance and pH upstream from the mudboil tributary then were similar to those measured in 1998, but specific conductance downstream from the mudboils was less than a third of the 1998 value. The turbidity resulting from mudboil discharges in 1981 was described as "hyper-turbid" and was probably much greater than at present. No other water-chemistry measurements on Onondaga Creek were made in 1981, but the lower specific conductance measured then indicates that the halite and gypsum concentrations were probably much lower than at present.

Fish-Survey Results

Onondaga Creek, like many central New York streams, is home to several species of trout and a variety of smaller, native fish species such as suckers, chubs, and dace. The abundance and diversity of fish in a stream are affected by habitat conditions and by water quality. Ten species of fish were found within the surveyed section. The number of species at each survey site ranged from four (site 1) to as many as eight (sites 4 and 6), although most sites were dominated by two or three species. Fish diversity, based on the Shannon-Wiener diversity index, ranged from 1.05 to 1.76 (see fig. 2). (A diversity index combines information about the

Table 1. Discharge and water quality data of Onondaga Creek within Tully Valley, Onondaga County, N.Y., July 20, 1998

ft^3/s = cubic feet per second; °C = degrees Celsius; µS/cm = microsiemens per centimeter; mg/L = milligrams per liter, Analyses by USGS.

Location and source of flow	Time	Dis-charge (ft^3/s)	Dissolved oxygen (mg/L)	Specific conduct-ance (µS/cm)	pH	Sodium, as Na (mg/L)	Chloride, as Cl (mg/L)	Calcium, as Ca (mg/L)	Sulfate, as SO_4 (mg/L)
Onondaga Ck. at Woodmancy Road - Site 1 (On west valley wall, in headwaters above waterfalls)	0745	3.26	7.11	490	8.41	18.2	28.4	70.5	11.0
Onondaga Ck. at Tully Farms Road - Site 3 (Entering valley, additional flow from moraine springs)	0945	7.09	7.73	456	8.48	13.6	21.2	59.8	12.2
Onondaga Ck. at NYS Route 11A - Site 4 (East side of valley, additional flow from moraine springs)	1015	10.4	7.37	554	8.44	34.2	38.6	59.9	17.2
Onondaga Ck. above mudboil area - Site 5 (Central valley floor, limited side-wall tributary inflow)	1030	11.4	7.92	604	8.59	52.6	50.7	58.0	18.6
Mudboil Tributary to Onondaga Creek (Valley floor, flow from mudboils and depressurizing wells)	1215	0.728	6.04	6,940	7.50	1,230.	2,100.	160.	250.
Onondaga Ck. at Otisco Road - Site 6 (Valley floor, downstream of mudboil and well discharges)	1330	12.0	7.55	1,410	8.50	185.	286.	68.4	50.4
Onondaga Ck. at Nickols Road - Site 7 (Valley floor, below Rattlesnake Gulf and Rainbow Creek)	1415	14.1	7.00	1,160	8.44	174.	268.	68.9	49.9
Onondaga Ck. at Webster Road - Site 8 (Valley floor, below 1993 mudslide springs)	1430	18.3	7.25	2,010	8.35	295.	468.	84.1	73.1
Onondaga Ck. at Bear Mt. Road - Site 9 (Valley floor, below east-valley-wall tributary)	1530	18.8	7.05	1,970	8.39	290.	456.	83.5	71.7
Onondaga Ck. at US Route 20 - Site 10 (Valley floor, below 2 northern slide area springs)	1600	17.5*	5.90	2,250	8.17	340.	525.	86.0	91.5

*Streamflow measurement at Route 20 affected by upstream beaver dam, which diverted flow from stream channel number of species present with the relative abundance of those species to indicate how strongly the community is dominated by one or more species.)

The uppermost 3 miles of Onondaga Creek (not shown on the map) above site 1, contains relatively poor habitat for cold-water fish (brook trout and brown trout) because of the low streambed gradient (about 22 ft/mi), warm water, and unfavorable habitat conditions. The creek plunges over a series of waterfalls to the valley floor just upstream from site 1. The gradient of the creek from site 1 to site 3 is about 140 ft/mi, which provides the fast-moving, clean-bottom habitat required for trout. This reach also receives cold inflow from several spring-fed tributaries flowing northward from the Tully Moraine. The density of brook trout in five of these tributaries is high (9,800 to 37,000 fish per acre of streambed), according to previous NYSDEC fish surveys. The unique habitat of these small tributaries may be endangered, however, by recent gravel mining on the Tully Moraine, which could cause increases in turbidity and(or) water temperature in the tributaries.

Brown trout have become naturalized (successfully reproduce) since they were introduced in the past century and are the dominant fish predators in Onondaga Creek. They have out-competed native brook trout along the main stem, confining the brook trout to the small tributaries in which the water is too cold for brown trout. Only site 2 was inhabited by an appreciable number of brook trout; this site represents the 1.5-mile reach in which most of the small moraine tributaries enter Onondaga Creek upstream from Tully Farms Road. Even at this site, however, brown trout biomass was 7 times that of brook trout. The only other main-stem site with brook trout was site 3, also near Tully Farms Road; here the brown trout biomass exceeded the brook trout biomass by a factor of 230. Site 3 also contained the largest biomass of brown trout in the surveyed stream system — an estimated 113 lb/acre. Reproduction of trout in this reach is adequate

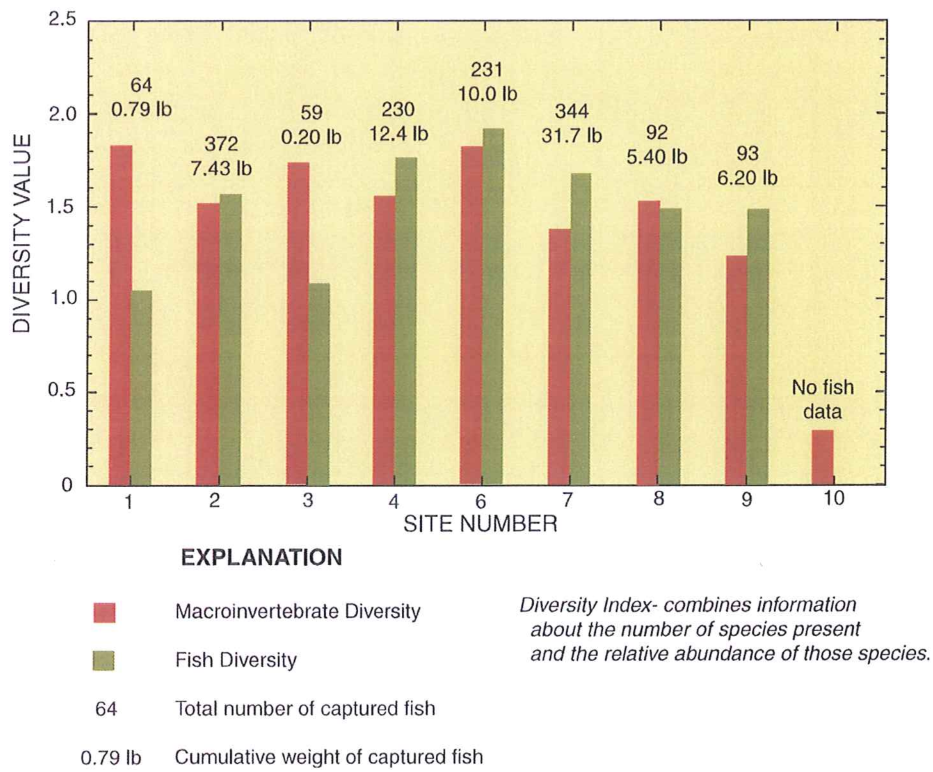


Fig. 2. Diversity of macroinvertebrates and fish at sites along Onondaga Creek, July and August 1998. No biological data were collected from Site 5 and no fish data were collected from Site 10. (Site locations shown on fig. 1)

to fill the available habitat throughout the creek because conditions in the lower reaches do not support natural reproduction.

Water temperature from site 1 to site 9 was low enough to support trout, even during summer hot spells, but competition from non-trout species and changes in water quality (primarily increased turbidity from the mudboil tributary) probably decrease trout density. Brown trout biomass decreases downstream, in the vicinity of the mudboil tributary. The average brown trout biomass at four sites above the mudboil discharge was 53 lb/acre, but at sites downstream of the mudboils, it was about 16 lb/acre. White suckers are found in greater numbers in the turbid waters below the mudboil tributary, where the stream gradient decreases to about 20 ft/mi. Although the change in fish species composition and diversity occurs just downstream of the mudboil tributary, the composition of fish species above and below the mudboil area indicate that habitat availability may be more important to fish community structure than water quality. Also, an increase in one species is generally offset by a decline in another because biological systems support a finite biomass. The changes in fish-population composition and species abundance noted in this survey, and comparison of results with those of previous NYSDEC surveys, indicate that Onondaga Creek is at or near its carrying capacity for trout.

Invertebrate Survey Results

Macroinvertebrates (mostly aquatic insects) are an integral part of any stream ecosystem. They form the major component of fish diets and are a link between fish and the lower end of the food chain. Macroinvertebrates also are indicators of a stream's environmental condition because they are less mobile than fish; thus, their abundance and distribution reflect local conditions.

Nine sites along Onondaga Creek (sites 1-4, 6-10) were sampled for macroinvertebrates in July 1998; eight of these sites corresponded to the fish-sampling locations (sites 1-4, 6-9). Sixteen invertebrate taxa or groups (mostly insects) were found in the survey. Site 10 had the fewest taxa (5), and site 3 had the most (13). Invertebrate diversity generally decreased downstream from the headwaters (site 1) to sites 9 and 10, near U.S. Route 20 (fig. 1). The number of individual invertebrates found in each sample generally exceeded 100, but the number per sample at site 10 was less than 30. The composition of the invertebrate community changed along the length of the creek, but midges were the most common at all sites. Downstream from the headwaters, the next most dominant taxa changed in the following sequence: stonefly, mayfly, true flies, beetle, caddisfly, and worm. This sequence indicates a change from good to poor environmental conditions, and the changes in predominant taxa downstream from the mudboil tributary indicate a shift from intolerant groups to tolerant groups; a similar change was measured during the NYSDOH survey of the creek in 1981. The change in macroinvertebrate community composition along the measured reach of the creek indicates that habitat is probably more important to the invertebrate-community structure than changes in water quality.

Site 2, upstream from Tully Farms Road, had the highest diversity of macroinvertebrates but a low number of individuals (about 60 per sample). This site had the highest density of predatory fish (brown trout and brook trout), which probably accounts for the low number and high diversity of macroinvertebrates. A 1981 survey of invertebrates in Onondaga Creek by NYSDOH also revealed an absence of mayflies below the mudboils and the dominance of worms (oligochaetes) in the most downstream areas. That study also indicated a lower prevalence of midges, and a greater range in stoneflies, than was found in this study. Collection locations and analytical methods differed from those used in this study, however; thus, rigorous comparisons are infeasible.

Conclusions

Downstream changes in fish and invertebrate assemblages and in water quality along the 5-mile surveyed reach of Onondaga Creek can be attributed to physical, chemical, and habitat changes along the stream. Stream gradient is flatter (about 15 ft/mi), and streamflow is slower, just downstream of the mudboil tributary than above it. The mudboil discharge strongly affects water quality and fish-population composition along the stream, but the effects of inflows from the mudslide areas, further downstream, are difficult to quantify.

Fish and macroinvertebrate diversity values change along the surveyed reach of Onondaga Creek in response to changes in both stream morphology and water quality. Fish diversity increases downstream from site 1 to site 4 but decreases below the mudboil tributary (sites 6-9). The predominant species above the mudboils are brown trout, brook trout, and mayflies, whereas those below the mudboil tributary are suckers, dace, and caddisflies. In the transition area below the mudboil tributary, the defining species were suckers, sculpin, and beetles. Species unique to the upstream sites can successfully compete in (and require) a fast-flowing, clean-bottom habitat, whereas species downstream from the mudboils include those that are tolerant of degraded environmental conditions. Although the change in species composition and diversity is greatest just downstream of the mudboil tributary, the similarity of species assemblages above and below the mudboil area indicate that habitat availability may be more important to species structure than water quality. The restricted range of stonefly occurrence in this survey may indicate a sensitivity to the increased concentration of halite discharged from the mudboil tributary. The changes in turbidity since the 1981 DOH invertebrate survey have had little effect on the invertebrate groups. The 1998 survey provides a baseline for future study and comparison as investigations of the stream, mudboil, mudslide, and watershed-remediation projects continue.

Sources of Technical Information

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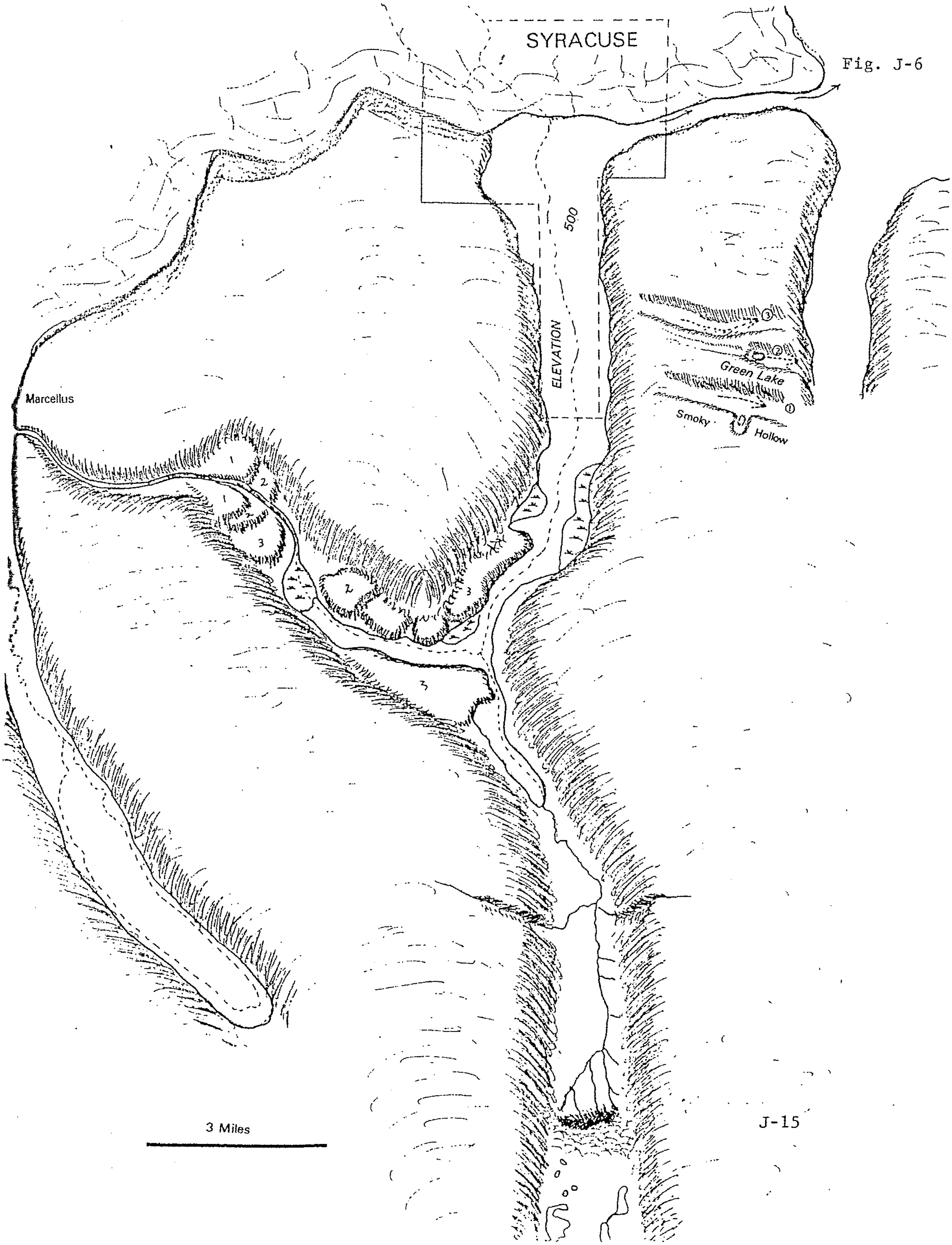
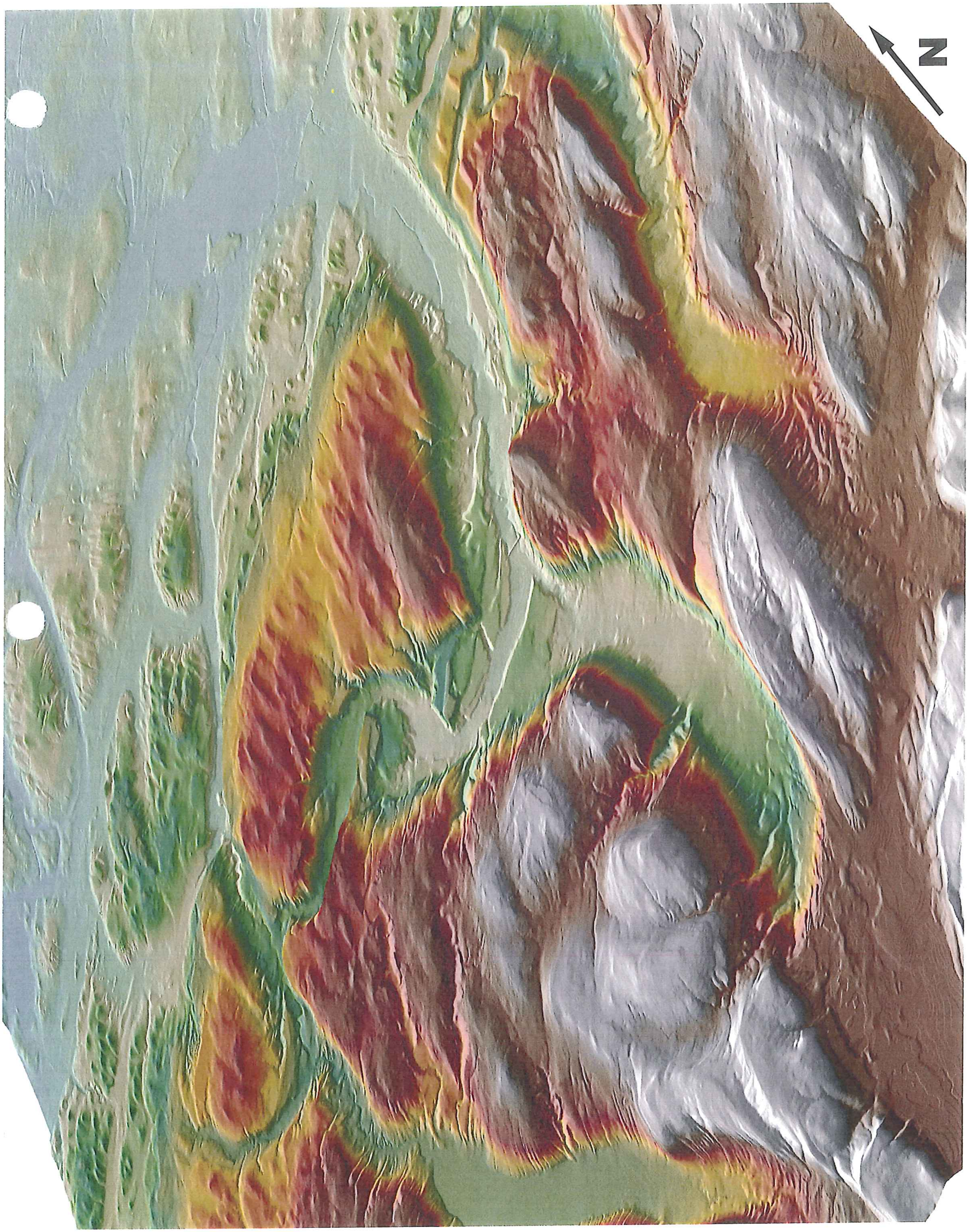
Lakes, Deltas, and Drainage in the Onondaga Valley

According to Grasso, 1970

Fig. J-6

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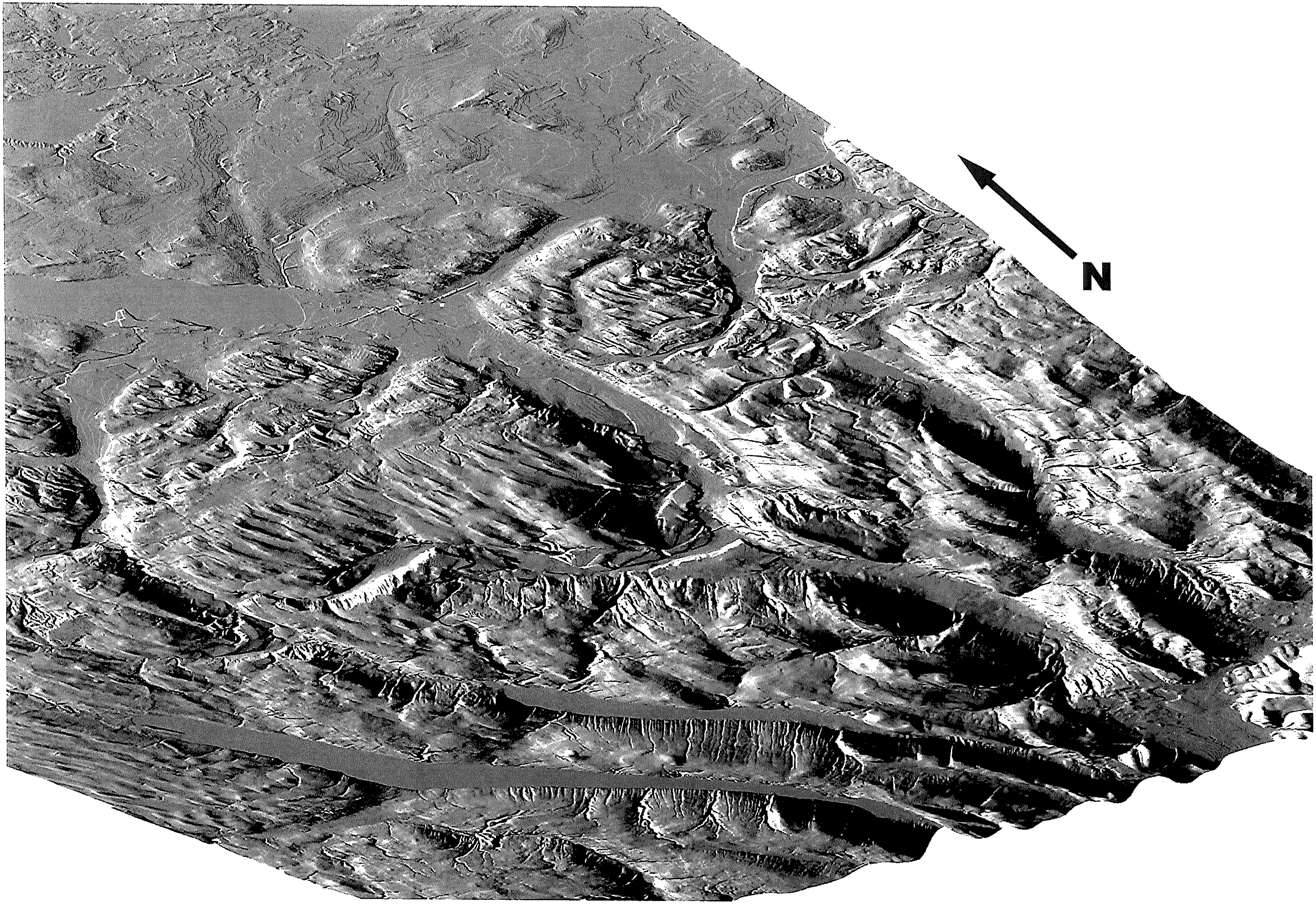
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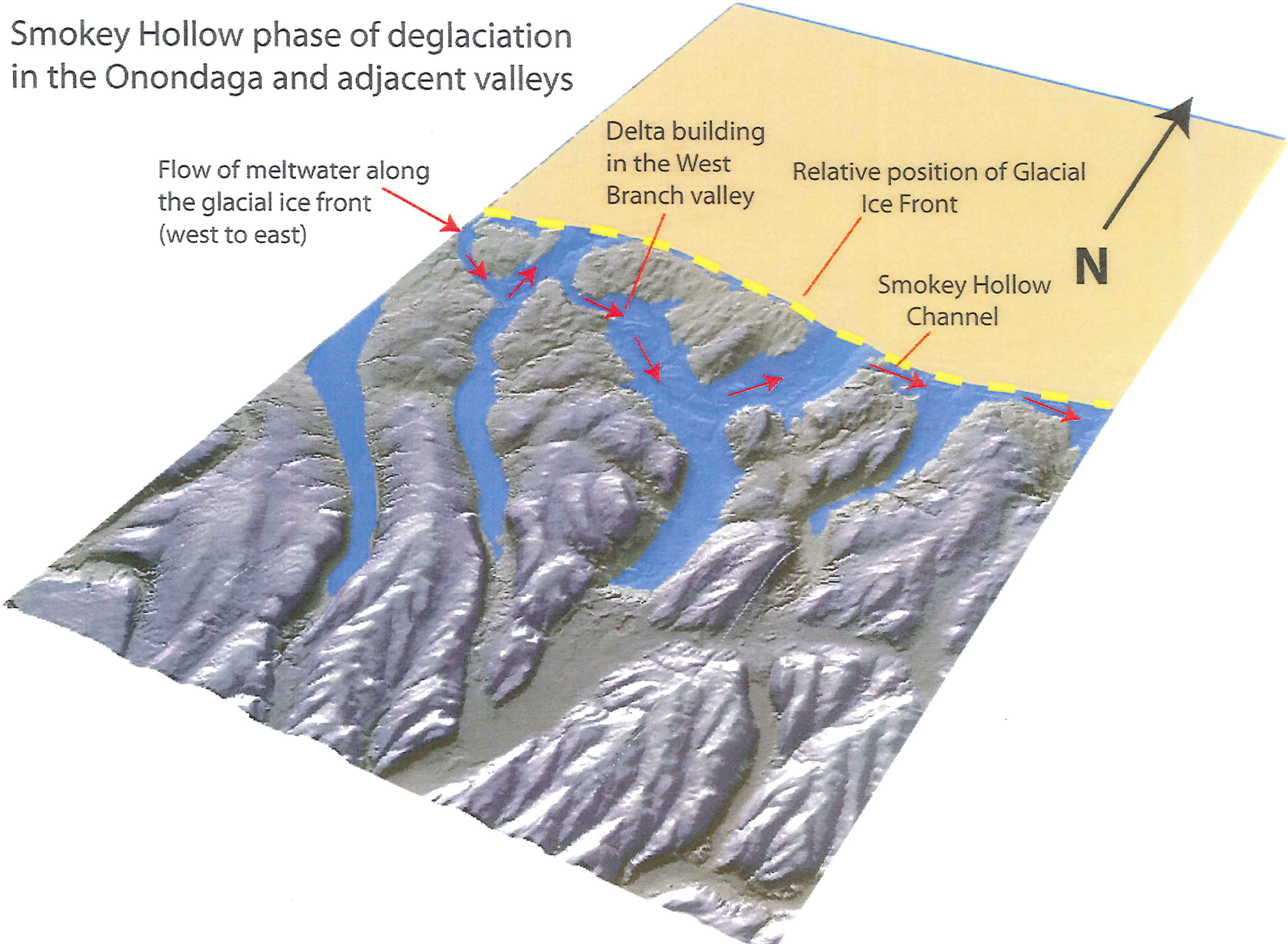
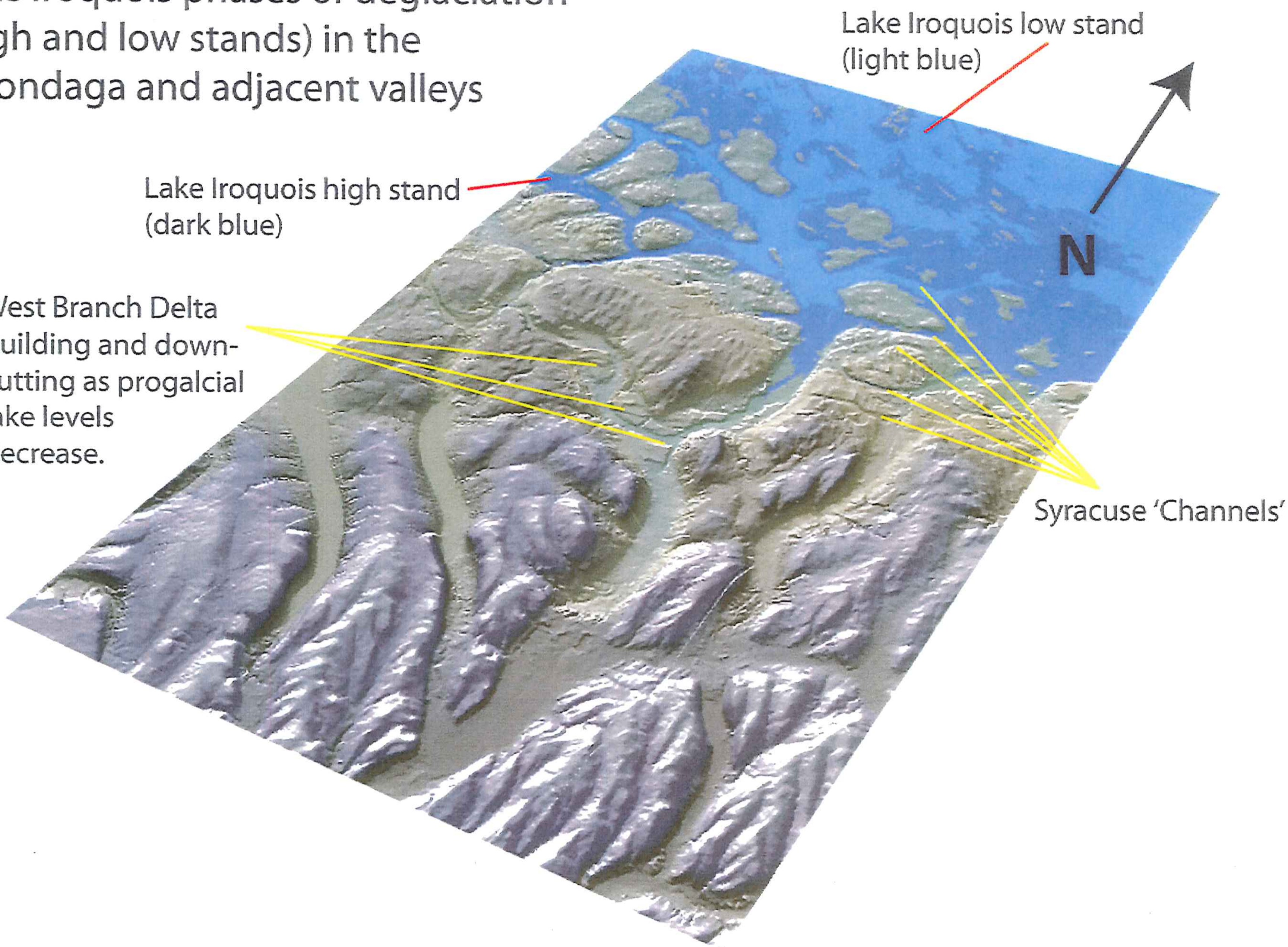
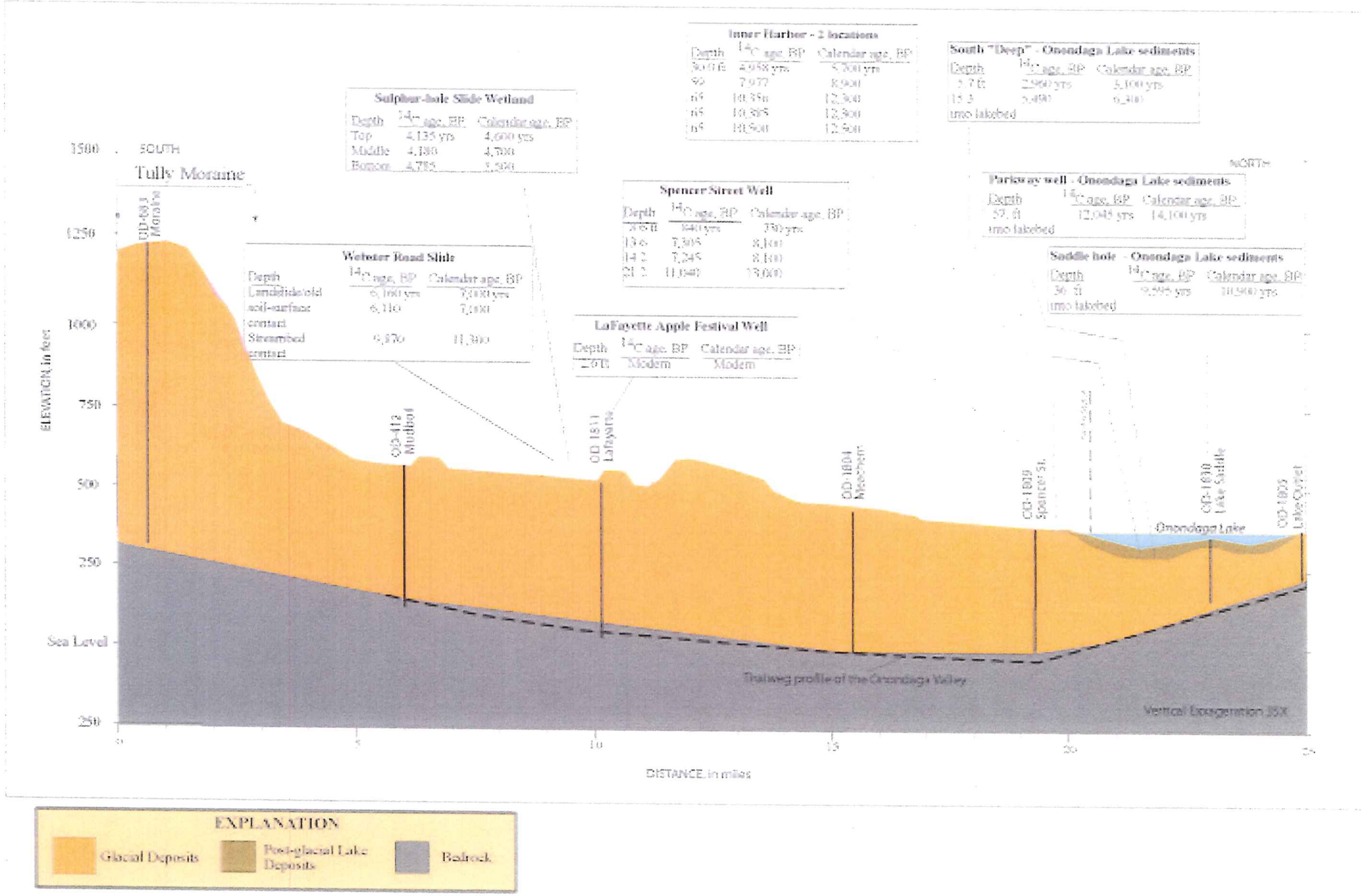
Smokey Hollow phase of deglaciation in the Onondaga and adjacent valleys

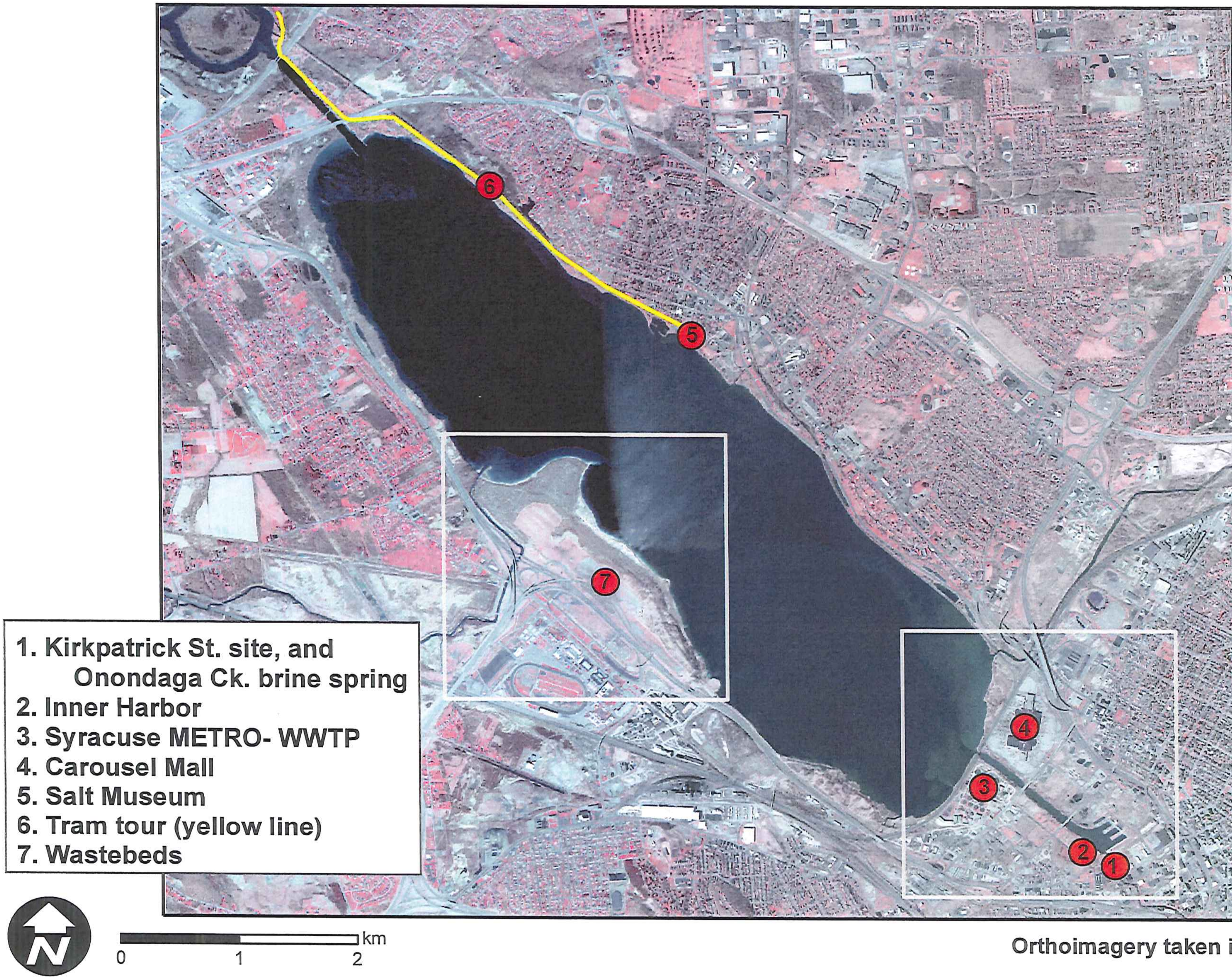


Lake Iroquois phases of deglaciation (high and low stands) in the Onondaga and adjacent valleys



RESULTS OF CARBON-14 ANALYSES FROM SPLIT-SPOON SAMPLES AND OUTCROPS IN THE ONONDAGA VALLEY





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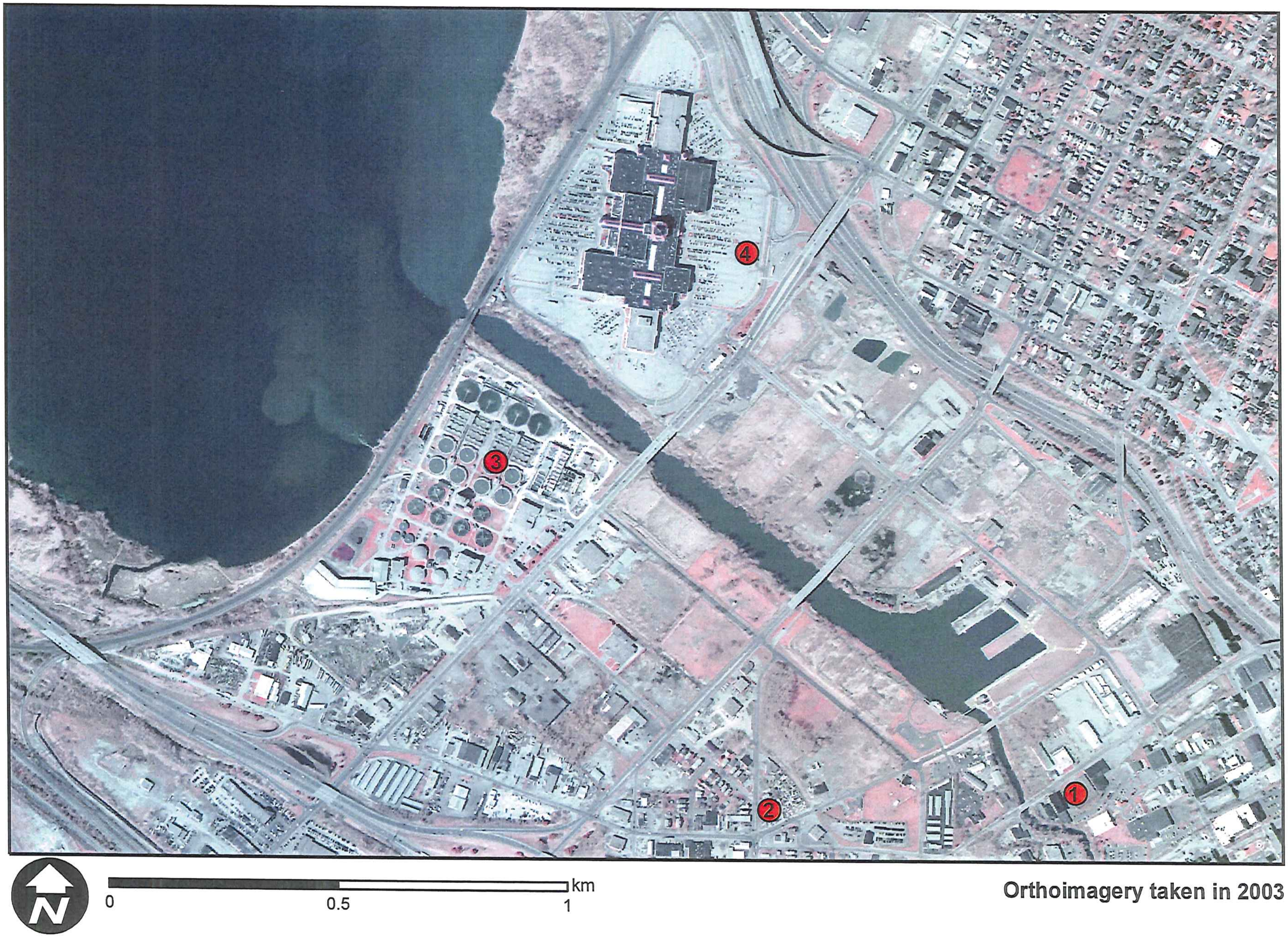

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Kirkpatrick Street Pump Station Addition Excavation: Small Project, Big Twist

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ABSTRACT: This case history describes the engineering design and construction for the Contractor of a 35-ft-deep excavation for an 800-square-foot addition to an existing sewage pump station. The site posed unexpected geotechnical complications that included deep gravelly soil, a history of local construction difficulties, groundwater consisting of heavy salt brine, and the need to underpin the existing pump station. The project took an interesting twist when the Owner issued a change order limiting the dewatering discharge to a fraction of that required to lower the water table. This documents the interesting circumstances of this job and documents the unusual subsurface conditions in the Syracuse, NY Lakefront area.

I INTRODUCTION

The Onondaga Lake lakefront area has significant community value for Syracuse, New York. The lake has survived years of pollution from various sources and is the subject of a major clean up and several planned developments. A small portion of the clean up effort was the construction of a sewage pump station addition for Onondaga County that required an unusual effort because of the geologic environment. This case history describes the excavation means and methods from the Contractor's perspective.

II BACKGROUND

A below-grade pump station was constructed at an unknown date but perhaps as early as 1930 in the lowland area of Syracuse on the south side of Kirkpatrick Street and on the banks of Onondaga Creek as shown in Figure 1. The facility boosted sewage to the Onondaga County Metropolitan Sewage Treatment facility located about 1 mile to the northwest on Onondaga Lake. Details of the original construction were long lost and unavailable for the current project.

The pump station was replaced around 1975 with a larger and more modern facility. The 1975 construction was known to have encountered construction difficulties, but details were unavailable. The only records available during bidding consisted of old structural drawings depicting the existing approximately 3000 sq ft footprint of the pump station and log of a 40-ft-deep test boring with standard penetration test data. The pump station structure consisted of two 35-ft-deep wet wells and a 10-ft-wide by 20-ft-long by 25-ft-deep screen room that connected them as shown in Figure 2.

The 2002 addition was to be approximately square in plan and nestled between the two wet wells and against the screen room. The addition was to be about 800 sq ft in plan and required excavation about 35 ft deep. This excavation would extend about 10 ft deeper than the screen room, and would be just slightly shallower than the two existing wet wells shown as in Figure 3.

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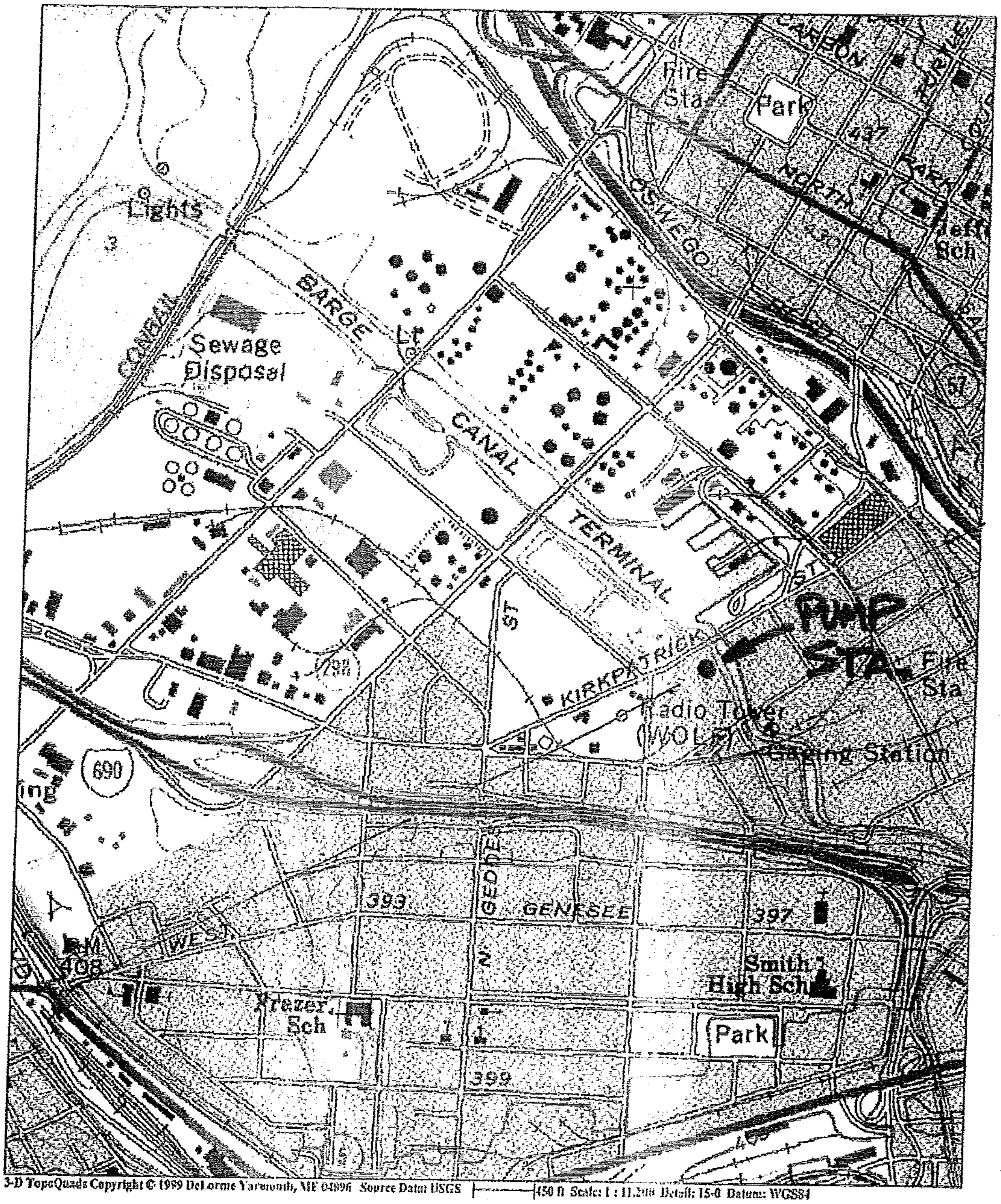

Figure 1: Site Location Plan

After successfully bidding the work and being awarded the contract, the Contractor's team obtained old test borings and a second-hand account of the previous construction. It seems that the original construction must have been about the same depth as the 1975 construction. No records were available, but the original construction seems uneventful. According to second hand reports, the

1975 construction encountered some abandoned interlocked shallow-arch steel sheetpiling. We later surmised that the shallow arch sheets were installed to impede the flow of water into the excavation and may have been long enough to be keyed into a deep thin layer of low permeability.

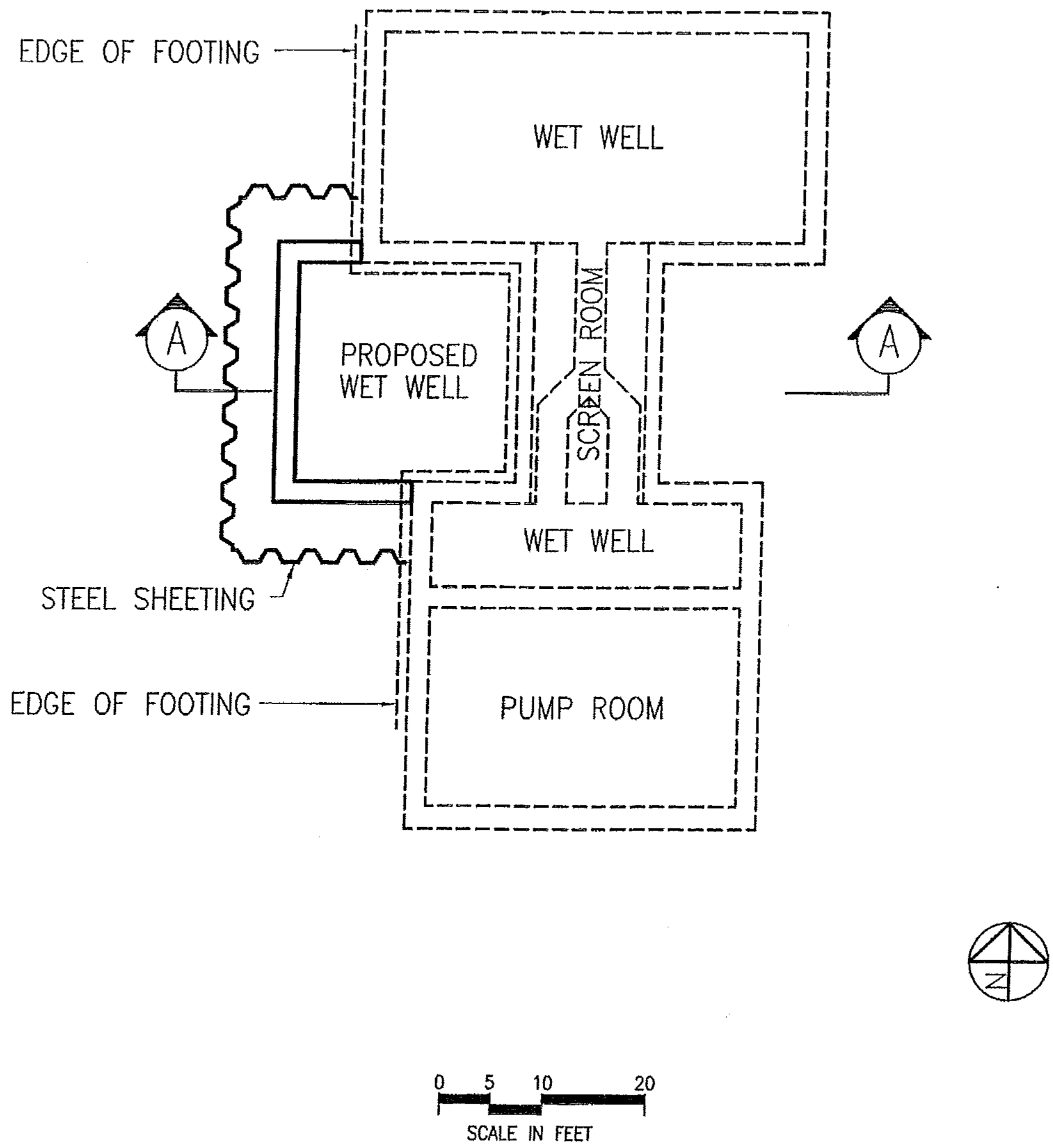

Figure 2: Pump Station and Addition Plan

The 1975 construction required heavy dewatering by several deep wells. Apparently this had been unanticipated and eventually culminated in a large construction claim lawsuit. Although nobody seemed to know for sure, the writers suspected that the old records may have been lost in the shuffle of records that goes with litigation.

Sketchy details of the 1975 construction were available second-hand from the recollection of a local engineer with a good memory. The 1975 dewatering apparently was performed for an excavation that was enclosed entirely within interlocked steel sheetpiling. The most germane aspects of the construction were the dewatering volume and quality.

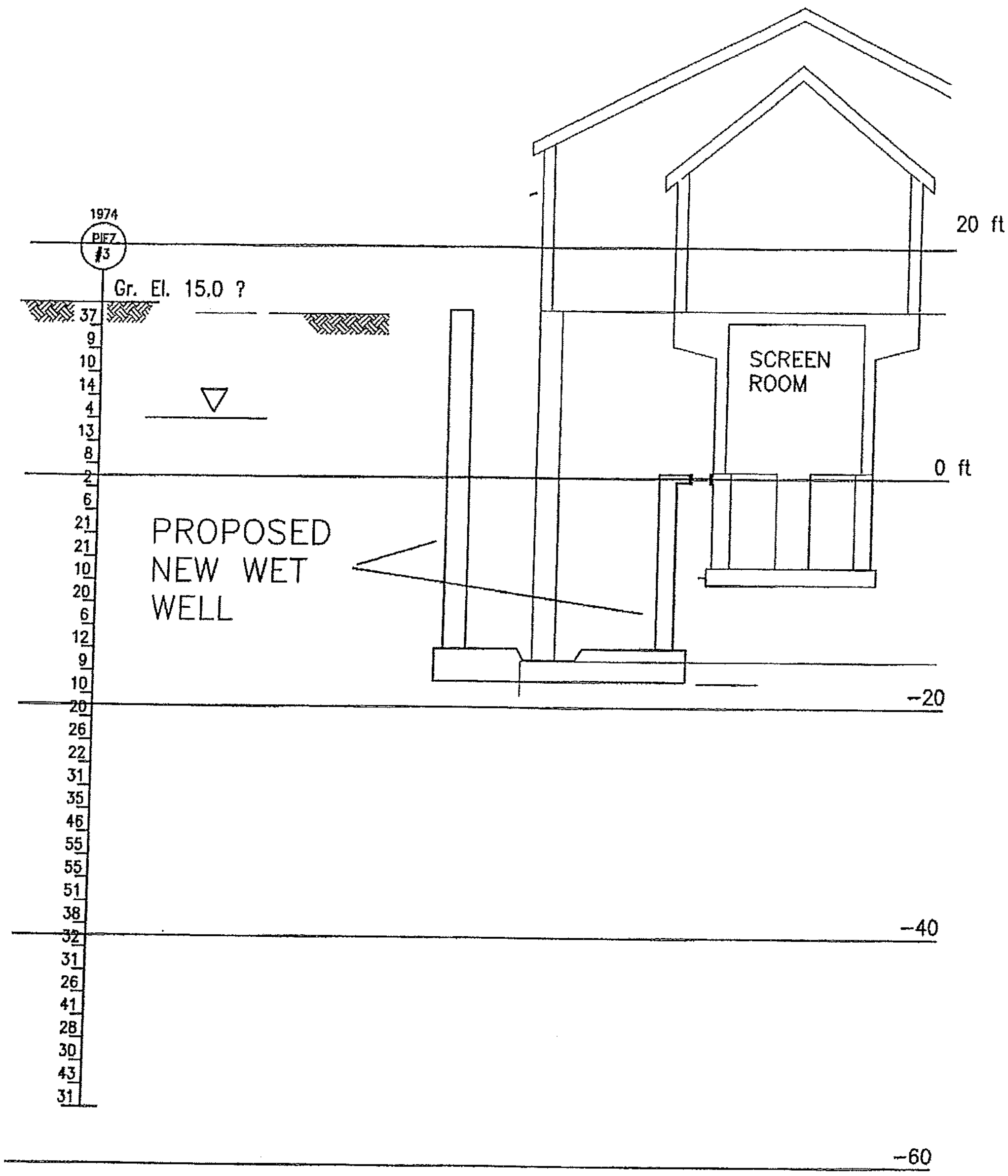

Figure 3: Pump Station Section

In 1975, thousands of gallons per minute (gpm) were pumped from the deep dewatering wells installed inside the excavation. With that volume of water, the effluent was checked for suspended solids by burning off the water and weighing the residue. Oddly enough, these tests showed high solid content in the essentially clear discharge. It was thought that significant fines were being removed from the ground that could cause settlement or collapse. Consequently, the job was shut down for several months for investigation and eventually led to a large construction claim.

The job did not resume until the late geotechnical engineer B. K. Hough determined that salt brine had been drawn up through the pumps. The solids in the brine were not suspended solids, but dissolved solids that posed no threat for ground settlement or collapse.

III GEOLOGIC ENVIRONMENT

Several factors combined to make this an unusual and interesting site, as the following geological description illustrates.

The area had natural artesian salt brine springs that were well known to native Americans and to the herds of native bison that roamed the area in the 1600's and 1700's. Salt was produced commercially throughout the area during the 1800's. Over 10 million cubic yards of salt were extracted from brine wells. In those days, this area was one of the few commercial domestic sources of salt. The economic importance prompted study and documentation of the geology by New York State.

Deep wells drilled in the 1800's determined that the site is in a glacial trough in the shale bedrock that has been filled with about 400 ft of post-glacial sediments (Stewart, 1933). The trough underlies Onondaga Lake and extends at least 20 miles south of Syracuse. The south end of the trough and up to about 1 mile south of the lake is filled mostly with permeable sand and gravel that seems to be derived from gravel terrace relics about 10 miles south of Syracuse. The gravel constitutes most of the valley fill northward to the Kirkpatrick site where it begins to thin so that the northern portion of the trough is filled with lacustrine silts and clays overlying progressively thinner cohesionless soil.

Although the shale bedrock has small pockets of salt and gypsum, old geologic studies concluded that the source of the brine was most likely Silurian halite deposits about 20 miles south of the site. These deposits were dissolved by groundwater and flowed through permeable glacial deposits in the valley bottom. Since the source of the brine was approximately 100 ft higher than the lakefront area, the brine had significant Artesian pressure until the commercial operations relieved it. Being heavier, the brine sank below a layer of fresh water.

Up until recently, the brine extraction was believed to have nearly depleted the natural salt brines. Well sampling showed declining salt content into the mid 1900s, at which point interest in the brines seems to have been lost. It was hypothesized that the salt brine had accumulated over geologic time but that there was no longer significant active accumulation.

In the wake of lake clean up efforts and the planned developments, there has been renewed geologic interest in the Onondaga Valley in the past few years. The USGS has lead the way with several studies including one by Kappel (2000) wherein evidence was presented that the brines were being recharged. Prior to beginning pump station construction in 2002, the USGS noted several flowing salt springs in the banks of Onondaga Creek (Kappel, 2002). Salt content from the spring water was approximately 2 times that of sea water.

The rejuvenation of the brines was suspected by many scientists of being a significant contributor of chlorides to Onondaga Lake. Chloride chemistry of the lake is important to the cleanup because it affects leaching of buried chemical waste on the lake bottom.

After construction began and the salt springs were noted, the USGS coincidentally drilled an exploratory boring within a few hundred feet of the Kirkpatrick Street Pump Station. The 6-inch-diameter vibro-sonic core boring retrieved a continuous sampling of the valley fill and the bedrock below (Kappel, 2003). Figure 4 shows a log of the boring and Figure 5 shows an interpreted geologic cross-section through the valley at the pump station. Of particular interest in Figure 4 is the salt content of the pore fluid that shows salt content increasing with depth, but also that the salt content of the deep water is more than 4 times that of sea water.

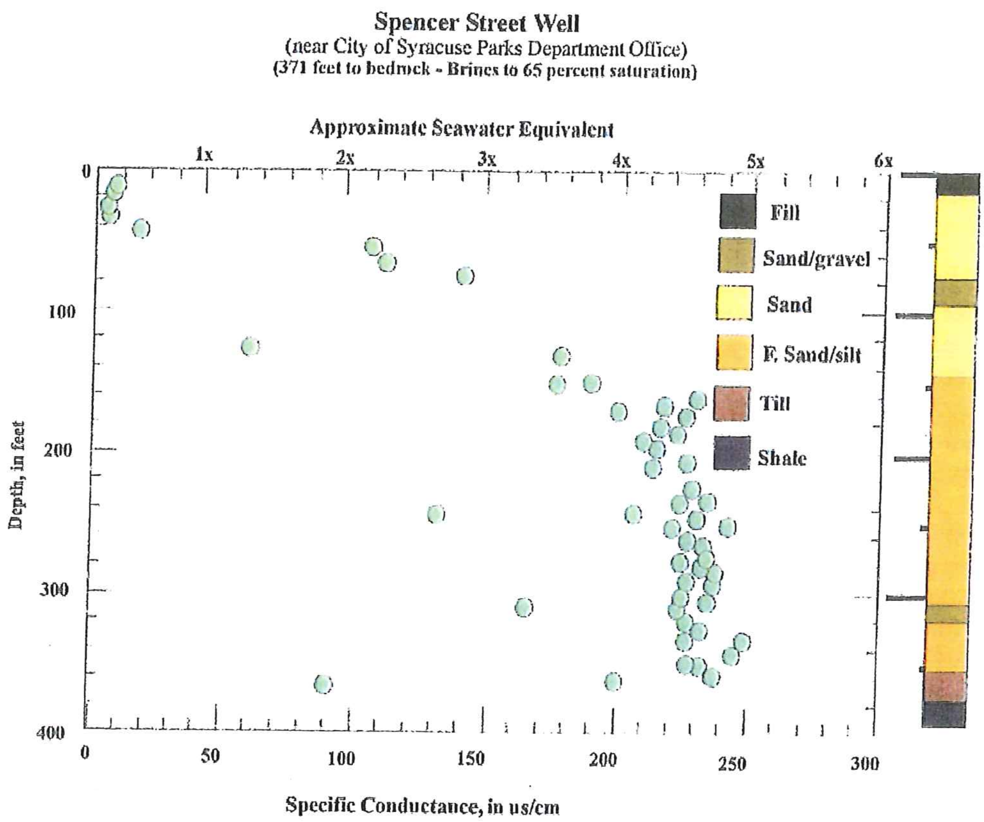

Figure 4: Nearby Well Log (Kappel, 2003)

Project borings and old test borings showed that the site was underlain by about 15 ft of old fill. The water table was about 10 ft below grade. The natural soils consisted of sands and gravels to depths of more than 60 ft. The USGS boring indicated that the deeper soils had seams with greater sand and silt content than the shallower soils.

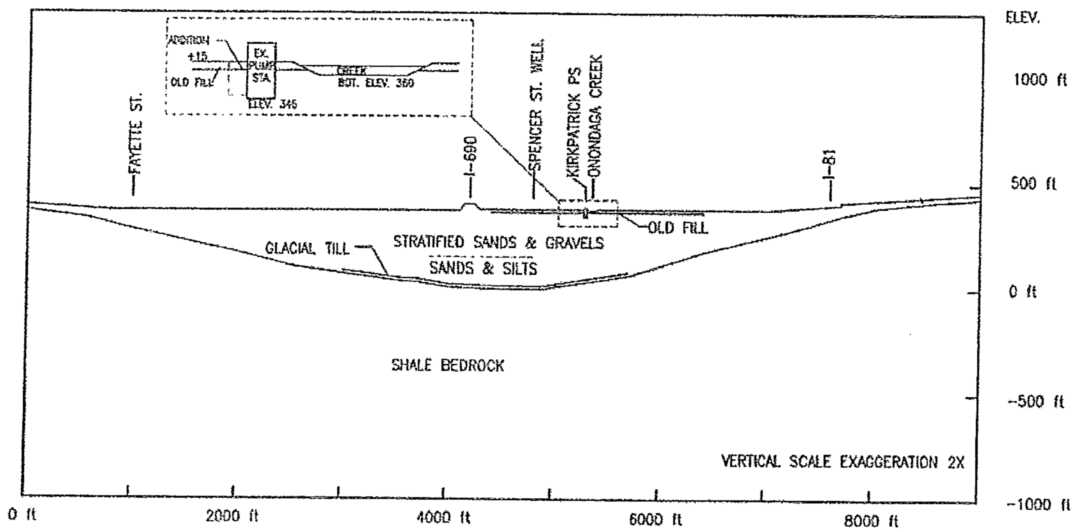

Figure 5: Geologic Cross-section at Pump Station

IV PROJECT DESCRIPTION

The project required excavation about 35 ft deep and about 25 ft below the water table. The soils consisted of deep permeable soil that was most likely hydraulically connected to the adjacent creek. A portion of the existing structure would require underpinning in cohesionless sand and gravel well below the water table.

Based on the previous experience at this site, an estimate of dewatering effort was made for an enclosed sheetpiled excavation based on the soil texture indicated on the test boring logs and procedures suggested by Mansur and Kaufman (1962). These procedures yielded estimates of between 2,000 and 5,000 gpm, which was quite significant for an 800 sq ft excavation.

The estimated dewatering volume was uncertain, but the actual conditions were more severe than those on which the estimate was based. It was not possible to close interlocked sheeting around the excavation because of piping that needed to remain in service throughout the construction and the odd geometry. Furthermore, it was anticipated that the pump station was constructed on a porous crushed stone pad. This pad would act as a collector and conduct ground water and creek water toward the excavation. Consequently, the dewatering load for the addition would be much greater than for the previous construction.

To evaluate the required dewatering effort, a pump test was performed in a test well installed next to the pump station with results as shown in Figure 6. Back evaluation of the pump test by Continental Placer (2002) indicated that dewatering would require 10,000 to 15,000 gpm.

The required dewatering had several practical limitations including the pumping cost and installing enough well capacity in the small project area. Furthermore, it was uncertain if contamination on an adjacent site would be drawn in.

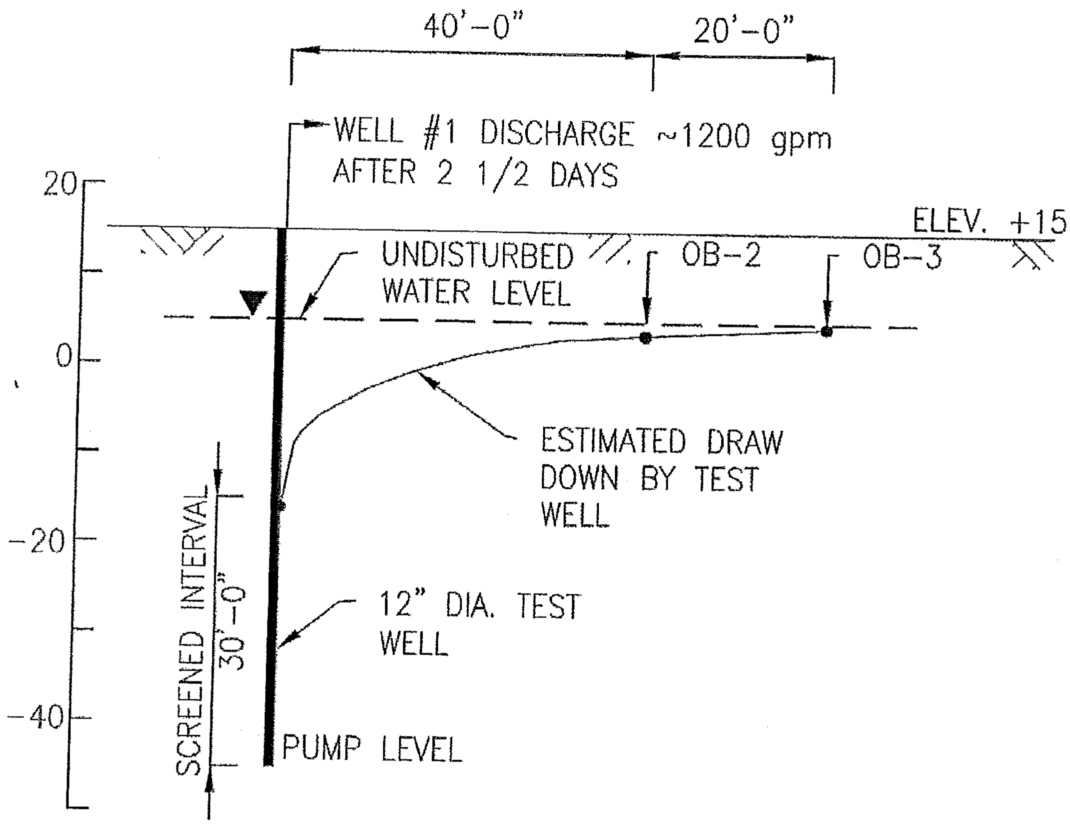

Figure 6: Pump Test Result

The most important problem that dewatering posed, however, was the environmental concern of disposing of the groundwater that was several times saltier than sea water. Scientists studying the lake during the 3-day pump test detected a significant spike in chlorides. Since the construction would require about 2 months of pumping at about 10 times the test rate, dewatering was not acceptable. The Owner subsequently added a big twist to the project by issuing a change order to construct the excavation by dewatering at a rate less than 100 gpm.

The Contractor and the Owner explored options to move the pump station addition so that less dewatering effort was required, but there was no other place.

V EXCAVATION DESIGN

Although underpinning the screen room was an important project consideration, limiting dewatering discharge was the main concern. In the gravelly soils, this could be accomplished only by sealing the soil in advance of excavating by a combination of sheeting, grouting and/or freezing.

Although sheeting could not be used to provide a seal all around the excavation it was the most practical and economical method on the three accessible sides. Grouting was less expensive and more practical than ground freezing for constructing the bottom and side seals and for accomplishing the underpinning. Since the soils with variable silt content could not be reliably grouted by permeation methods, the jet grouting method was selected. Chemical testing verified that the saline groundwater was compatible with jet grouting.

The bottom seal needed to be thick enough to resist the buoyancy of the open excavation that would extend below the water table by about 20 ft. The existing structure was not relied on to resist uplift on the bottom seal because of its eccentricity and the need to resist its own buoyancy. It was prudent to limit the risk of shifting the structure if load was transferred to it. As a consequence, the bottom seal needed to be stable without contribution from the existing structure.

The bottom seal thickness was determined to be about 25 ft, based on unit weight of the jet-grouted soil-crete mass of 110 pcf, unit weight of salty groundwater of 68 pcf and a safety factor of 1.2 against the design high ground water level.

Such a thick soil-crete mass constructed by jet grouting was expensive. A thinner seal could be constructed if it was supplemented with hold-down anchors as shown in Figure 7. The only practical way to fasten the bottom seal to the anchors was by bond. Consequently the hold down anchors would be passive because it was impractical to post-tension them.

Evaluation showed the most economical seal would be attained with the minimum seal thickness and as many hold down anchors as required. The bottom seal thickness needed to be sufficient to effect a reliable seal and to provide bond length for the hold down anchors. Based on Hayward Baker's experience, a minimum 6-ft-thick bottom seal would be required to provide a reliable seal. Using a design bond stress of 80 psi in the soil-crete mass and practical anchor size and capacities, a 10-ft-thick bottom seal was required for bonding the anchors. Therefore a 10-ft-thick bottom seal was selected.

To provide the necessary hold down capacity, seventeen 75-kip design pressure-grouted ground anchors were designed using the cylindrical shear method with k=2, phi=32 degrees and vertical stress corresponding to the full excavation. The center of gravity of the anchors corresponded to the center of gravity of the bottom seal to avoid eccentricity that could cause movements or load concentrations. The 1-1/4 inch diameter anchor bars were oversized to reduce potential movements from elastic stretching of the passive anchors. Anchors were also checked for cone pullout as a group corresponding to the full excavation level.

Sheeting was braced according to apparent earth pressures based on phi = 33 degrees, total and buoyant soil weights of 120 pcf and 52 pcf, surcharge load of 300 psf, and high water table at 8 ft below ground surface. The bottom seal was assumed to be essentially unyielding for sheeting design.

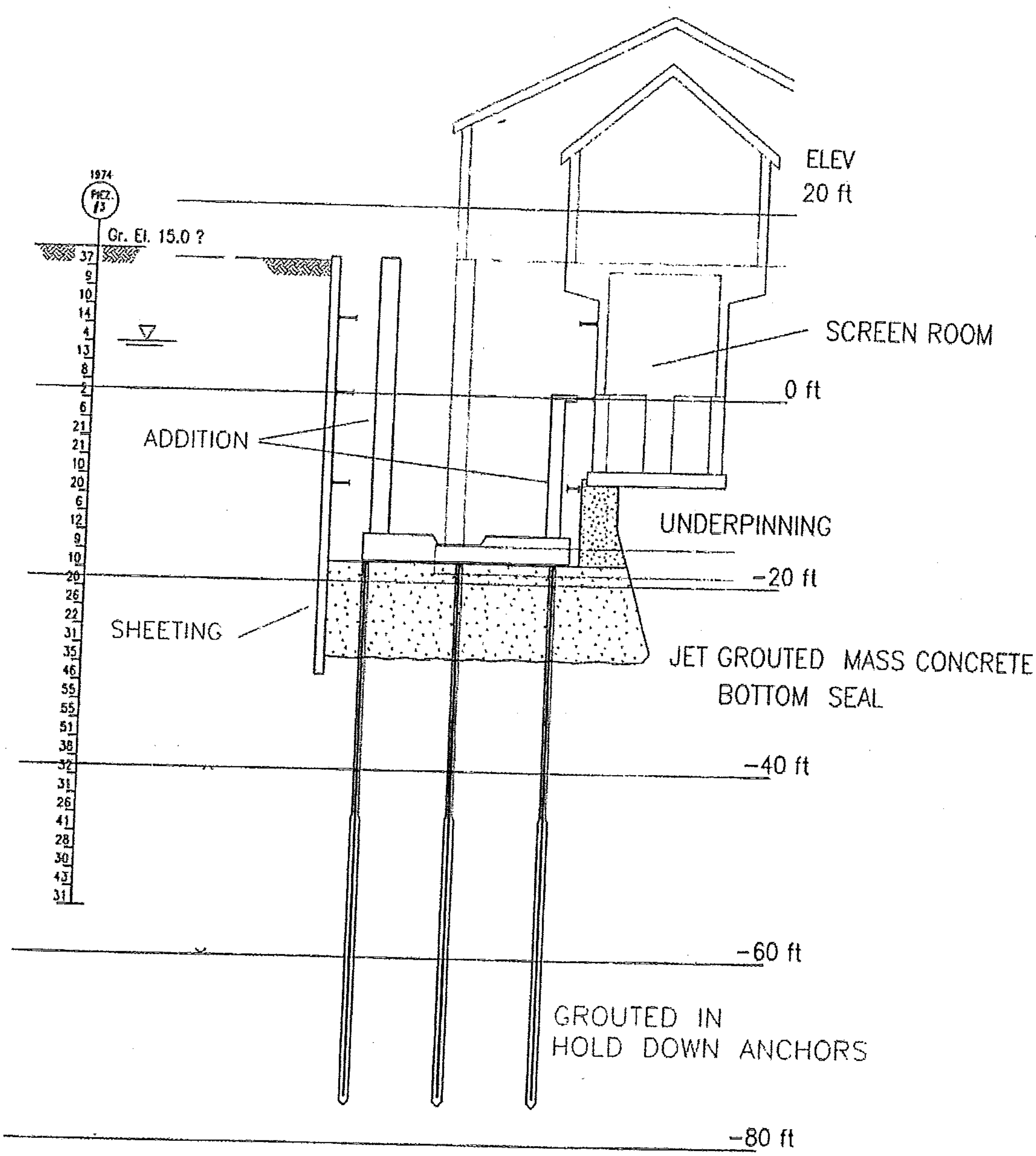

Figure 7: Excavation Cross-section

Jet grouting limits were extended to underpin the screen room. The jet grout mass was proportioned so that it would act as an unreinforced concrete mass having unconfined compressive strength of at least 500 psi. The underpinning was widened to provide flexural resistance for the horizontal loads based on the stresses allowed by the ACI Code for plain concrete. Jet grouting also provided side seals between the sheeting and the structure.

VI CONSTRUCTION AND PERFORMANCE

The first step was driving interlocked hot-rolled steel sheetpiling on the three sides of the excavation that were accessible. Sheeting extended to the bottom of the proposed bottom seal.

The next step was to construct a test anchor and a few jet grout test columns to confirm the procedures and equipment. The test columns were cored and demonstrated the grout was of good quality. The cores showed thin silty layers and significant proportion of large pieces of gravel and small cobbles. The test anchor confirmed the design bond stress in the native soil.

The existing structure was then underpinned by jet grouting. The building was never undermined by more than 1 fluid column within 15 ft. After the underpinning grout set up overnight, additional columns were installed. Concurrently, jet grout columns were installed to construct the bottom seal. The jet grout column plan was as shown on Figure 8. Figure 9 shows installation of a battered jet grout column for underpinning the screen room.

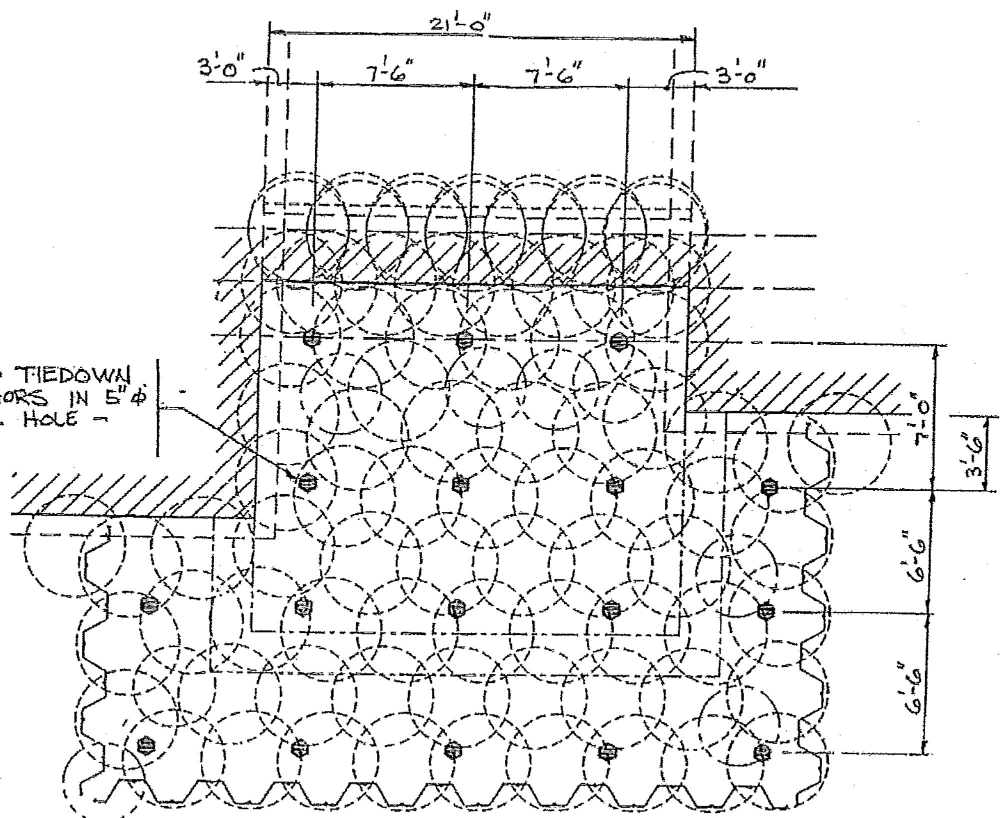

Figure 8: Jet Grout Plan

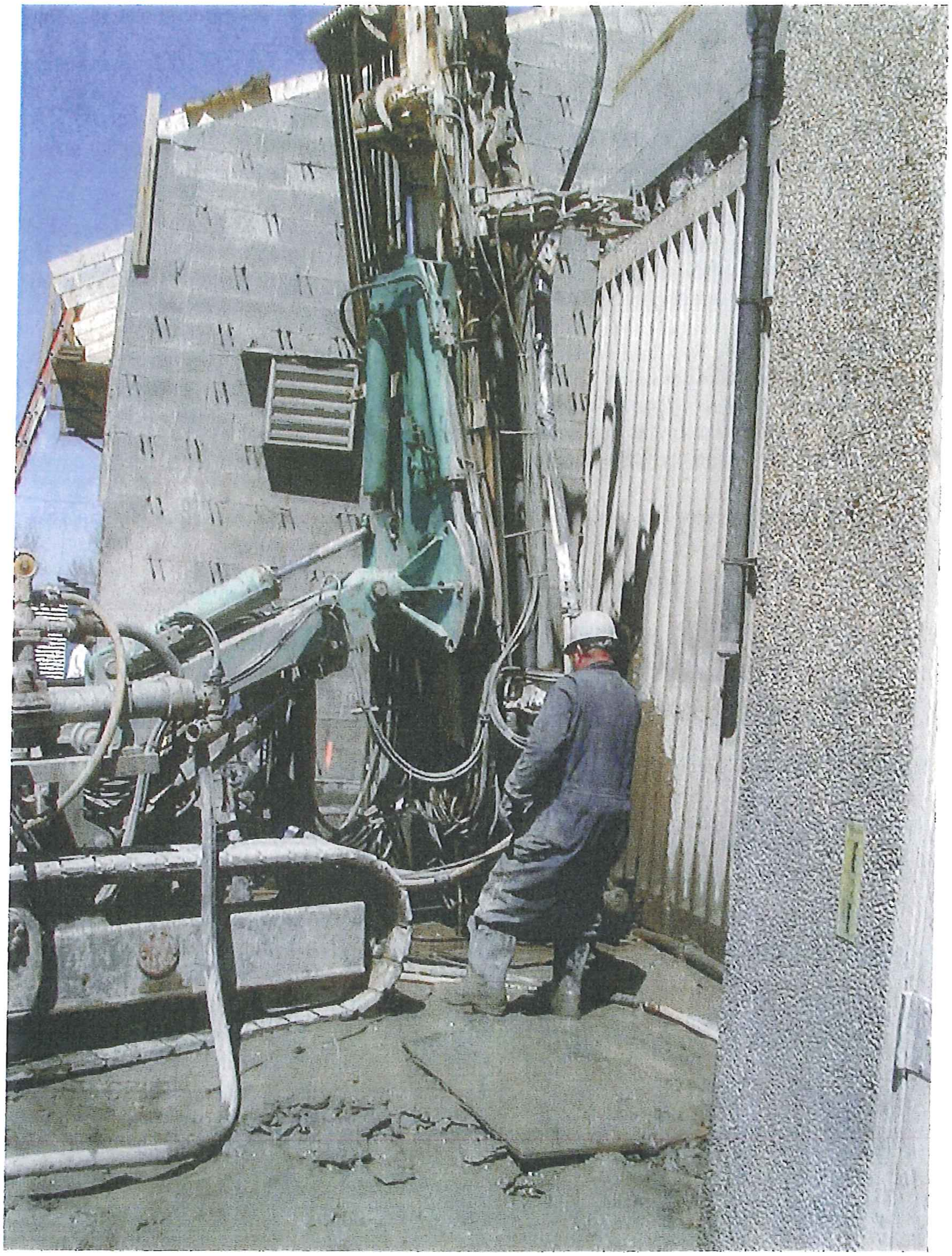

Figure 9: Installation of jet grout column to underpin screen room

The underpinning operation encountered a thin concrete diaphragm at the face of the screen room. Its presence was not anticipated, but drilling measurements allowed its geometry to be estimated as shown in Figure 10.

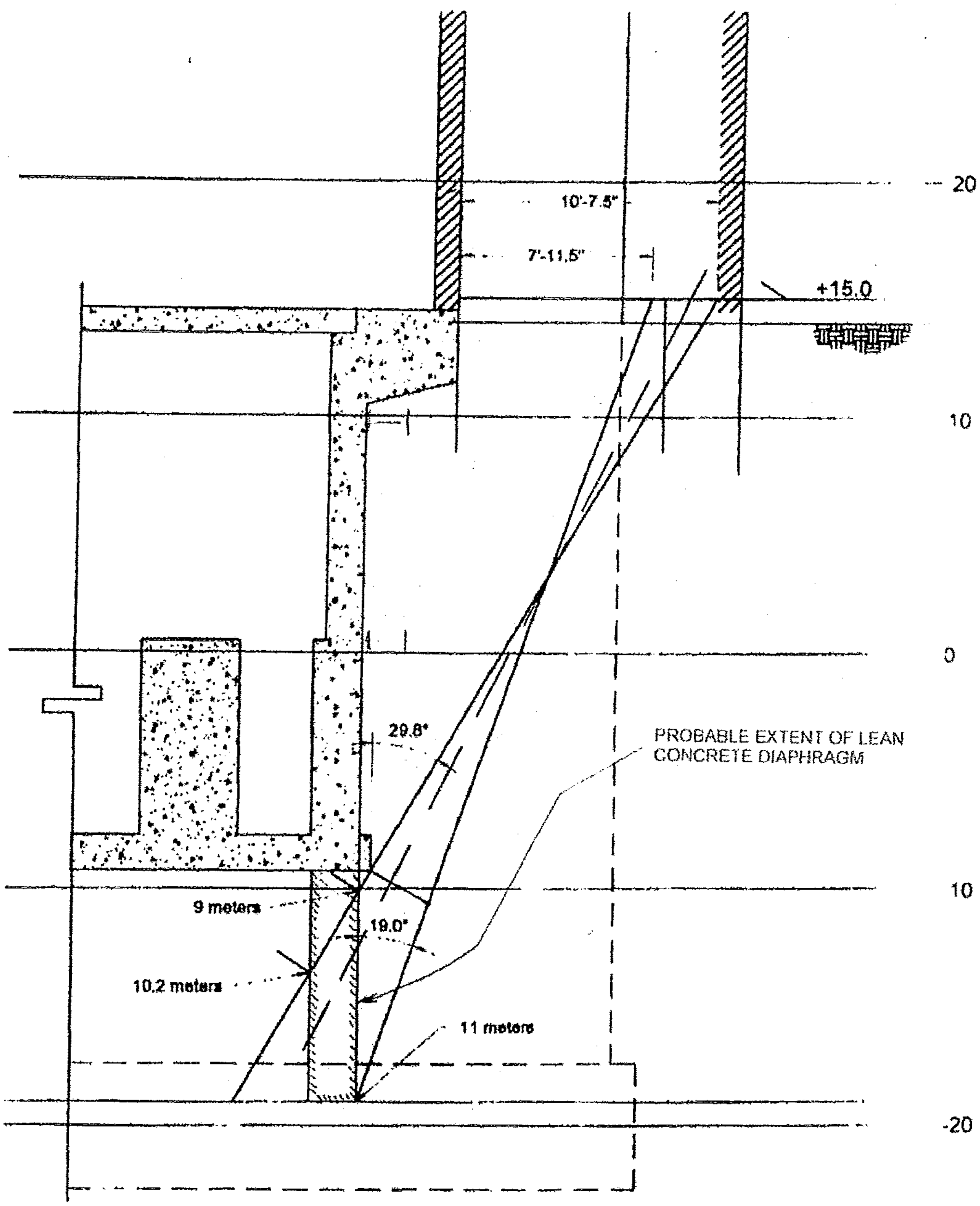

Figure 10: Unanticipated Concrete Diaphragm Below Screen Room

Evaluation showed that the diaphragm was inadequate for underpinning. It also showed that it was risky to jet grout behind it. If cobbles or large gravel clogged the drill hole through the diaphragm, high pressure could build beneath the existing structure and potentially shift it. Therefore the underpinning could not be constructed as wide as designed and it would require reinforcing to prevent bursting under the imposed water pressure.

It was impractical to reinforce the underpinning by installing reinforcing from the ground surface because the existing structure had a 3 ft overhang. Therefore, supplemental measures would be required from inside the excavation near the level of the screen room, and this was deferred until the excavation was advanced to the bottom of the screen room.

After constructing the underpinning and bottom seal by jet grout columns, the third step was to install the ground anchors. Ground anchors were drilled by the duplex casing method from the ground surface through the bottom seal and approximately 50 ft below the bottom seal. The first anchor encountered heaving sands near the anchor bottoms. To prevent significant ground loss, the drilling means and methods were modified by installing the casing the full length before drilling out the contained soil. Anchor bars were terminated only a few feet above the bottom seal.

After the last anchors were installed, excavation began and bracing was installed, as shown in Figure 11. Below the screen room, the underpinning needed to be reinforced to carry the horizontal loads from water and earth. This was accomplished manually by installing 6-inch-diameter micropile soldier piles into holes cored in the jet grout. The coring was done with a small manual coring machine and the holes filled with grout before installing the casings.

The final element of the excavation support was installed to brace the top of the micro-soldier piles against the sheeting before the excavation was finished.

The work was completed without further complications. During the work, no movement of the existing structure was detected. According to analyses, the passive anchors would stretch about 0.5 inch and it was thought that some movement would be detected. The design did not, however, include the effect of skin friction on the sheetpiling that must have contributed significant resistance.

The maximum dewatering discharge was about 20 gpm and well within the requirements set by the Owner. Most of the water entered through a single localized leak in the side seal at the sheeting. It is likely that sheeting flexure under the earth pressure loads caused a slight separation from the jet grout mass. Nevertheless the leakage was essentially insignificant.

VII CONCLUSION

This case history demonstrated the feasibility of combining a jet grout bottom seal and underpinning with hold down anchors and steel sheeting to limit dewatering effort. It also showed that even relatively small projects can pose interesting geotechnical complexities.

Figure 101: Excavation

VIII ACKNOWLEDGEMENTS

The writers wish to acknowledge the professional contributions to this project by Mr. Kenneth Chadwick, and Dr. Geetha Mathiyalakan; and the background information provided by Mr. Kenneth Kauffmann. Site work was completed under the direction of field engineer Michael L. Grant, P.E. and superintendent John Willet of CATOH, a Division of Hayward Baker, Inc. and Hayward Baker, Inc., respectively.

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Onondaga Lake, New York: Legacy of Pollution[1]

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ABSTRACT

Effler, S. W. and R.D. Hennigan. 1996. Onondaga Lake: legacy of pollution. Lake and Reserv. Manage. 12(1):1-13.

Onondaga Lake, NY, has been described as the most polluted lake in the United States. This medium size (surface area of 12 km^2 and mean depth of 10.9 m), rapidly flushed (average of 3.9 flushes/y), urban lake has received large quantities of domestic and industrial waste associated with development of the Syracuse area. Selected features of the history of development of the area, including municipal and industrial inputs to the lake, are reviewed. Presently about 20% of the inflow to the lake is municipal wastewater effluent. Standards for dissolved oxygen, fecal coliform, free ammonia, nitrite, clarity, and mercury concentration in fish flesh are violated routinely in the lake, a state guidance value for total phosphorus concentration is exceeded annually, and the lake's stratification/mixing regime and littoral zone have been impacted. Enforcement actions, now underway against the primary sources of municipal and industrial waste, are described. The design of the research program for the lake is reviewed, and the role subsequent articles in this issue play in developing a management strategy for remediation is described.

Key Words: pollution, industrial pollution, municipal wastewater, hydrology, history, enforcement action, violations of standards, research program.

Onondaga Lake is severely polluted as a result of the input of large quantities of municipal and industrial wastes from the surrounding urban area for more than a century (Effler 1987, 1996). Despite mandated reductions in external loading of pollutants, and reductions associated with the closure of a chemical manufacturing facility, Onondaga Lake remains arguably the most polluted lake in the United States (Effler 1996, Hennigan 1991, U.S. Senate Committee on the Environment and Public Works, Sub-committee on Water Resources, Transportation and Infrastructure 1989). The lake's extremely polluted state is testimony to the failure of regulatory programs for this system. This system is deserving of special attention because of the severity and complexity of its problems, and the challenge it presents to remediation.

A series of research investigations have been conducted to document the lake's condition, identify and quantity key phenomena and processes, and develop credible models to guide effective management of the lake. The findings of a number of these studies are reported in this special issue. This paper presents valuable background material to support the following manuscripts in this issue; specifically it

1. describes the setting and hydrology of the lake,
2. reviews the recent history of the lake, including the development of the surrounding area, the treatment of municipal wastewater, and the operation and discharges of an adjoining chemical plant,
3. characterizes the present polluted state of the lake, within the context of numerical standards, and its degraded habitats,
4. identifies enforcement actions underway against the two primary polluters, and
5. outlines the overall strategy of the research program for Onondaga Lake, and identifies the key position the findings reported in this issue plays in the overall body of scientific work on the lake.

[1]Contribution No. 148 of the Upstate Freshwater Institute.

Setting/Hydrology

Onondaga Lake has a surface area of 12.0 km^2, a volume of 131 x 10^6 m^3, a mean depth of 10.9 m, and a maximum depth of 19.5 m (Fig. 1). The lake is oriented along a northwest - southeast axis (Fig. 1), and has a length along its major axis of 7.6 km and a maximum width of 2 km. Outflow from the lake, to the Seneca River, is via a single outlet at its northern end (Fig. 1). The Seneca River, which drains the Finger Lakes region of New York, combines with the Oneida River to form the Oswego River, which flows north, entering Lake Ontario at the City of Oswego (Fig. 1).

Onondaga Lake is located (lat. 43 06'54", long 76 14'34") immediately north of the City of Syracuse, in the center of the most urbanized area of central New York State; 28% of the landuse in the lake's watershed is urban. The lake is surrounded by commercial, industrial and residential land uses. The watershed supports a population of ~450,000. Onondaga County owns 78%, or 15.3 km, of the shoreline; the rest is in private ownership. The lake is surrounded by high speed traffic arteries on all sides and a railroad track. There is a county park and trail system which starts at Ley Creek and continues in a counter-clockwise direction around the east side and north end and down the west side to Ninemile Creek (Fig. 1). The lake's watershed is almost wholly contained within Onondaga County.

The Onondaga Lake watershed is 642 km^2. The major hydrologic inputs to the lake are Ninemile Creek, Onondaga Creek, the Metropolitan Syracuse Sewage Treatment Plant (METRO), and Ley Creek (Fig. 1).

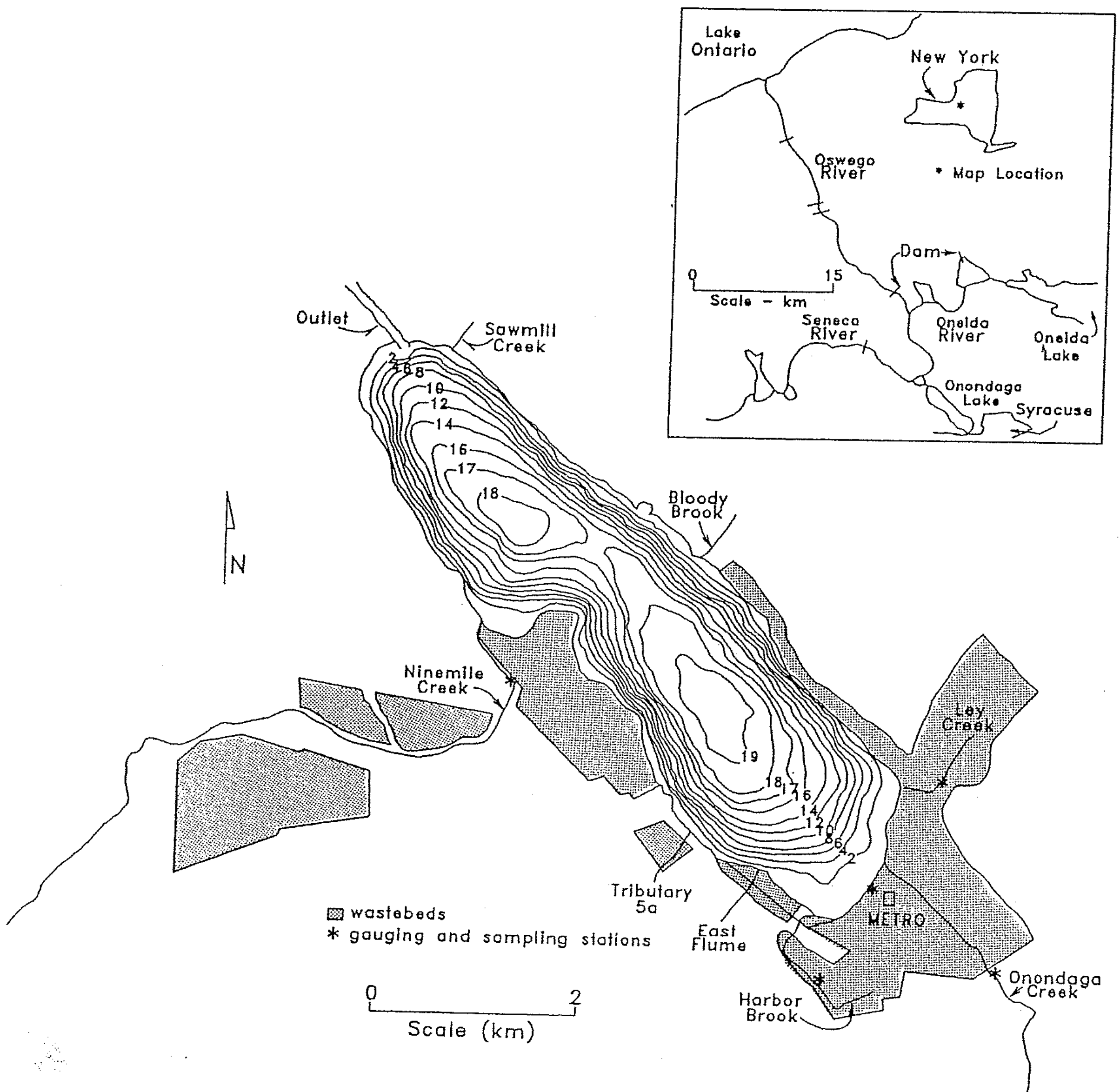

Figure 1.–Onondaga Lake bathymetry and setting.

Table 1.–Annual flow conditions for surface inflows to Onondaga Lake, and contributions to total inflow, for the period 1971 - 1989.

Tributary	Annual Flow (m^3/s)			% Contribution to Total Inflow	
	Average	Std. Dev.	Std.Dev./Average	Average	Range
Ninemile Cr.	5.05	1.72	0.25	30.4	23.7-34.1
Onondaga Cr.	5.22	1.31	0.25	31.4	27.6-34.1
METRO	2.99*	0.33	0.11	18.9	11.7-28.3
Ley Cr.	1.28	0.33	0.26	7.7	5.9-9.5
Harbor Br.	0.38	0.15	0.38	2.2	1.6-3.6
Others**	1.56	0.51	0.32	9.3	7.3-13.4
total	16.48				

* does not include by-pass discharges that occur during certain rainfall events; average value of 0.059 m^3/s over the period 1986-1990.
** sum of Bloody Brook, Sawmill Creek, Tributary 5A and the East Flume (ungauged).

Minor inflows include Harbor Brook, Bloody Brook, Sawmill Creek, Tributary 5a and the East Flume (Fig. 1). The configurations of the lower reaches of Ninemile and Onondaga Creeks have been altered, in the first case associated with disposal of waste by a soda ash/chlor-alkali manufacturer, and in the later case associated with the development of the City of Syracuse.

The United States Geological Survey (USGS) presently maintains nine continuous gauging stations in the watershed; three on Ninemile Creek, two on Onondaga Creek, two on Harbor Brook, one on Ley Creek, and lake level is monitored at the marina on the east shore (Fig. 1). A gauge is located proximate to the mouth of each of the gauged tributaries (Fig. 1); these have all been in service since the early 1970's. The discharge from METRO is also continuously gauged; most of this water comes from outside the lake's watershed.

The hydrodynamics and hydrology of the river system have been altered greatly over the years (e.g., dams, locks, intakes for power generating facilities) to support navigation and hydroelectric power generation. The level of Onondaga Lake is now regulated by control devices on each of the three rivers (Fig. 1), thus there is not a free flowing discharge from the lake to the Seneca River. This situation, in combination with the ionic enrichment of the lake, caused by industrial pollution (Doerr et al. 1994), causes irregular inflow (e.g., backflow) from the Seneca River into Onondaga Lake (Owens and Effler 1996a). The phenomenon apparently occurs mostly during low runoff periods (Owens and Effler 1996a). The estimated contribution of this inflow to the lake's hydrologic budget during the summer of 1991 (Owens 1993, 29%) probably represents a near-maximal case. The input from direct precipitation to the lake's surface is essentially in balance with evaporation in this region (Effler and Whitehead 1996). There is no evidence that exchange with the surrounding ground water system is a significant component of the lake's hydrologic budget.

The hydrologic loading conditions for the lake, exclusive of the river inflow contribution, have been estimated for the 1971-1989 period (Table 1). The annual average total inflow for the period was 16.5 m^3/s (Table 1). Substantial interannual variability in inflow, depicted by the standard deviation (Table 1), reflects the large year-to-year variations in precipitation common to this region. The largest sources of water annually to the lake are (by a wide margin) Ninemile Creek and Onondaga Creek. Together they represent about 62% of the surface inflow received over the 1971-1989 interval. The METRO effluent represented nearly one-fifth of the inflow over this period. The gauged inflows (including METRO) represented more than 90% of the total.

Although there are strong seasonal variations in hydrologic loading from the fluvial inputs, the METRO discharge remains relatively uniform by comparison (Fig. 2). The highest rates of tributary inflow generally occur in March and April (Fig. 2). The minimum usually occurs over the July-September interval (Fig. 2). Thus the METRO discharge contributes relatively more to total inflow during the critical water quality period of summer.

Onondaga Lake flushes rapidly. The average flushing rate for the 1971-1989 period (assuming a completely-mixed system, and exclusive of the inflow from the Seneca River) was 3.9 flushes/y; the range was 2.7 to 5.7 flushes/y. This high flushing rate has important implications for remediation efforts, as it

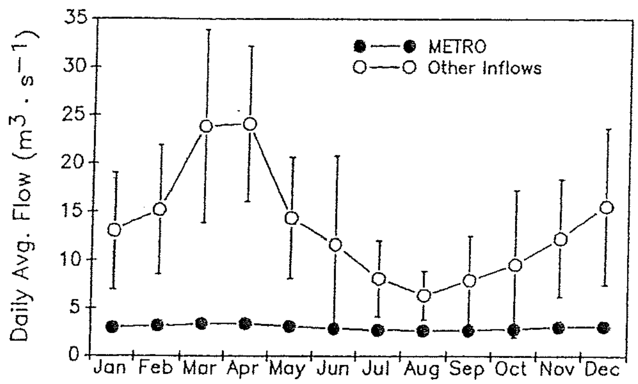

Figure 2.–Seasonality in surface flows to Onondaga Lake; average monthly total tributary and METRO inflow for period 1971-1989, with ± 1 standard deviation bars.

causes the response time (the time it takes to reach a new steady state) to be short (< 1 y; Effler and Whitehead 1996). On average, the lake flushes through more than once during the March-April interval. During the summer stratification period, the epilimnion is flushed through about 3 times under average flow conditions (Effler and Whitehead 1996).

History

General

The history of development of the surrounding area is important to understanding the lake's prevailing problems. The major impetus for development around Onondaga Lake was the salt (NaCl) industry, supported by salt springs found along the east side of the lake. The first large scale salt manufacturing operation was established in 1794. Later the brine was taken from shallow wells. The brine was boiled off or reduced by solar evaporation to produce salt. The industry peaked in 1862; by 1880 it had declined greatly, though remnants persisted to 1920. This activity was the original foundation for the economic growth and development of Syracuse and the County, and the first industrial pollution of the lake (Doerr et al. 1994, Rowell 1996).

The construction of the Erie Canal (1825), followed by the railroads (~1840), and then highways (1910 - date), fueled a steady growth in population and commercial and industrial activity. In 1822, a channel was cut (present lake outlet channel) to permit the lake's surface elevation to drop (0.6 m) to that of the Seneca River (Fig. 1). The canal ran along the east shore of the lake and became the prime supply and shipping route for the salt industry.

Local salt and limestone deposits provided the basis for the development of other important industries. Most notable was the establishment of soda ash production (by the Solvay Process) on the western shore of the lake in 1884, which initially utilized the salt wells adjoining the lake, and nearby limestone quarries. As the brine deposits were exhausted, salt production wells were developed about 35 km south of the lake in the 1880s. A more detailed description of the soda ash process and other activities at this chemical production facility are presented subsequently in this paper and elsewhere (Effler 1996).

A number of resorts were built along the northwest shoreline in the 1870s and 1880s. A successful commercial and recreational cold water (salmonid) fishery existed in the lake through this period, and stocking of fish was common (Schramm 1994). The "resort era" was short-lived, as it reached its peak around the turn of the century. The demise of the resorts, after World War I, was due to the mobility afforded by the automobile, and to the increasing pollution of the lake. During the decades from 1900 until the second World War, a number of additional manufacturing facilities developed within the lake's watershed. The county's park and salt museum were built along the abandoned canal, on the east shore, in the 1930s.

By the turn of the century, sewage and industrial pollution had already had a profound impact on Onondaga Lake. By the late 1890s the lake had lost its coldwater fishery. Particularly noteworthy was the disappearance of the whitefish, a commercially important cold water species (Lipe et al. 1983). In 1900 ice harvesting was banned for health reasons. Despite installation of interceptors in Syracuse and early domestic waste treatment efforts, the lake was increasingly recognized as degraded. Swimming was banned in 1920 for public health reasons. A study by the New York State Health Department (1951) acknowledged the lake was grossly polluted. The same year the U.S. Department of Justice initiated legal action against the soda ash facility to reduce discharge of mercury to the lake, fishing was banned because of the contamination of fish flesh with mercury (Kilborne 1970). The lake was reopened to angling in 1986, but fish from the lake are not to be eaten, according to a directive of the state regulating agency. The reopening represented a shift in regulating policy (e.g., not coincident with improving trend in fish contamination). Limited monitoring indicated the fish of the lake are also contaminated with other potentially toxic substances. In 1994 the sediments of Onondaga Lake and some of its tributaries, and certain areas in proximity to the lake, were added to the superfund National Priority List (NPL), entitling the sites to special attention concerning the release, or potential release, of hazardous substances.

Municipal Wastewater

The City of Syracuse was originally served by small privately owned water systems, drawing water from wells, springs, and local creeks. Publicly owned water supplies were established by the early 1900s. This ushered in a new era, privies were outlawed and the city went to inside plumbing for water supply and wastewater service. The wastewater infrastructure was primitive, consisting of street storm sewers discharging to Onondaga Creek and Harbor Brook, and later also to Ley Creek (Fig. 1). These same storm sewers were then used for sanitary waste, which caused multiple local nuisances. The first strides to treat sewage were taken in 1907 with the creation of the Syracuse Intercepting Board, which constructed two trunk sewers paralleling Onondaga Creek and Harbor Brook. The interceptor sewer system was completed in 1922. The sewage was discharged to Onondaga Lake following screening and disinfection.

One hundred and twenty (presently 66) overflows were maintained as part of the interception system. During storms these overflows ("combined sewer overflows", CSOs) released an admixture of storm water and sanitary waste to adjacent streams and thence to the lake. A primary sewage treatment facility was completed in 1925 by the City of Syracuse, located on the lake shore just west of Onondaga Creek (Fig.1). The effluent was discharged to the lake and the sludge was pumped to the Solvay Process waste beds (Fig. 1), where it was mixed with industrial waste and deposited.

The Onondaga County Sanitary Sewer and Public Works Commission was formed in 1933. The commission built the Ley Creek sewage treatment plant in 1936 to serve residents on the east side of the lake (Fig. 1). This facility was an activated sludge plant, which discharged to Ley Creek and thence to the lake. The City's treatment facility adjacent to the mouth of Onondaga Creek was shut down for four years in the early 1950s, due to the lack of sludge treatment, resulting in the discharge of raw sewage to the lake over that period. Due to overloading, the facility was inefficient when it reopened.

In 1960, Onondaga County took over the interceptors and treatment responsibilities from the City of Syracuse, and constructed a new primary plant (METRO) at the same site on the southeastern shore of the lake. METRO was designed to treat 2.19 m^3/s (50 million gallons/d (MGD)) of sewage. According to the original plans for the facility, the METRO effluent was to be pumped around the lake, combined with the Ley Creek plant effluent, and discharged to the Seneca River (Fig. 1). Later a lake discharge was selected for METRO instead, and justified as a cost saving measure. A subsequent report (SURC 1966) apparently represented the scientific justification to permanently reject the diversion concept. The report concluded little beneficial effect would be realized for the lake. Further, it concluded that diversion would eliminate the diluting effect of the domestic waste effluent on the ionic waste discharge from the Solvay Process facility. This last feature exemplifies the confounding effect the simultaneous discharge of domestic and Solvay Process wastes to the lake has had on lake reclamation efforts. By the early 1970s, METRO was hydraulically overloaded, with related manifestations of poor performance (USEPA 1974).

Major upgrades of METRO were made in the late 1970s and early 1980s. Secondary treatment, by the contact stabilization modification of activated sludge, was added in 1979. The design was not intended to achieve any significant level of nitrification. In fact the continued occurrence of potentially toxic concentrations of free ammonia in the lake following this upgrade was considered a distinct possibility (USEPA 1974). Advanced, or tertiary, treatment (aimed at removal of phosphorus (P)) was added in 1981. By design, precipitation of P was achieved by addition of calcium-rich Solvay Process waste (Effler et al. 1996c) supplied by the soda ash manufacturer. This utilization of the soda ash waste enabled the manufacturer to avoid compliance with the Clean Water Act, representing yet another example of the unfortunate interplay between the municipal and industrial waste problems in clean-up efforts for the lake. The formation of carbonate deposits within METRO, as a result of the acceptance of the calcium-rich waste, caused extensive operational problems. This facility was designed to treat an average flow of 3.51 m/s (80 MGD). The effluent standard for P to be met, established for facilities of this size in the Great Lakes watershed, is 1.0 mg/L. The effluent continues to be discharged to the southern end of the lake.

Discharge of METRO effluent to the Seneca River was dismissed at the time of the METRO upgrades because the river's assimilative capacity was judged to be inadequate (USEPA 1974). However, a credible water quality model for the river did not exist to support such a conclusion. It was concluded that discharge to Lake Ontario would not significantly impair that system, but it was considered to be too expensive (USEPA 1974). The Ley Creek plant was closed in 1980, with the flow being diverted to METRO for treatment. The closure of the soda ash manufacturer in 1986 required the development of an alternate P treatment methodology. Phosphorus is presently removed by precipitation with ferrous sulfate.

In the late 1980s Onondaga County undertook a rehabilitation program for the combined sewers to limit overflows. This resulted in reducing the incidence of overflows by about 90%. By 1991, 45 CSO's discharged to Onondaga Creek, 19 to Harbor Brook, and 2 to Ley Creek (Fig. 1). Presently, combined sewage (dilute raw sewage) is discharged to these tributaries and thence the lake about 50 times a year.

Soda Ash/Chlor-Alkali Facility

The chemical plant on the western shore of the lake, originally named the Solvay Process Co., subsequently part of Allied Chemical Co., and finally part of Allied Signal Co., has had a profound impact on Onondaga Lake (Effler 1987, 1996). The plant was originally built to produce sodium carbonate (Na_2CO_3), commonly referred to as soda ash. Diversification at the facility lead to the manufacture of more than 30 chemicals over the plant's 102 y tenure (1884-1986). The impacts of soda ash and chlor-alkali production have received the most attention to date, thus the facility is described here as the soda ash/chlor-alkali facility. The impacts of the operation of this facility on Onondaga Lake have been greater than those of the other industries in the watershed.

Soda ash was produced by the Solvay Process over the entire tenure of the facility. The simple overall reaction for the process is

$$CaCO_3 + 2NaCl \rightarrow Na_2CO_3 + CaCl_2 \qquad (1)$$

The abundance of the reactants in the Syracuse area in the form of limestone, and NaCl brines and deposits, and the proximity of the lake for disposal of wastes and as a source of cooling water, made the shores of the lake an ideal location for the production of soda ash. In 1971 there were eleven Solvay Process soda ash production facilities in the United States. The Syracuse facility was the last operating facility. Large quantities of waste were produced from soda ash manufacturing. A waste slurry (5-10% suspended solids), containing $CaCl_2$, excess CaO, unreacted $CaCO_3$ and NaCl, and lime impurities, was pumped to waste beds (Fig. 1), where the soluble fraction (waste bed overflow) drained off and entered the lake. The waste bed overflow was enriched in Cl^-, Na^+, and Ca^{2+}. According to the USEPA (1974), for each kg of soda ash produced approximately 0.5 kg of NaCl and 1.0 kg of $CaCl_2$ were released. Estimates of the loading of this ionic waste to the lake before the closure of the facility, and lingering inputs following closure, are presented by Effler et al. (1996c).

The solid phase waste left behind after drainage of the wastebed overflow is described as Solvay waste. Wastewaters and waste slurries were discharged directly to the lake until the early 1900s. In response to pressure from the state, the practice of direct discharge of waste slurries was terminated, and additional land was acquired to support expansion of the Solvay waste beds. The present areal distribution of this material is shown in Fig. 1. This waste surrounds about 30% of the lake; the most recent (≥ 1944) waste beds are located along Ninemile Creek (Fig. 1). More than 2000 acres (8.1 km^2) are covered with the waste. The depths of these deposits vary greatly. The more recent beds are about 21 m high (e.g., along Ninemile Creek); the older beds around the southern shore are as shallow as 2 m. No impermeable material was used to line the waste beds.

Water for process cooling was taken from the lake from shallow (epilimnion) and deep (hypolimnion) intakes. Withdrawal from the hypolimnion was preferred in summer because of the lower temperature, though poor water quality (e.g., high concentrations of hydrogen sulfide) limited the practice. Heated water was discharged directly back to the lake via the East Flume (Fig. 1), and to Ninemile Creek, upstream of the USGS gauge, via the West Flume (until 1980). The thermal discharges were discontinued in the late 1970s, in favor of a multi-port diffuser discharge to the lake's epilimnion.

The products of the chlor-alkali (an electrolysis) process at the facility were chlorine gas and NaOH. Mercury was used as the cathode and was recirculated in the process. However, there were losses due to leakage and dumping, as the cells were cleansed or replaced. Mercury waste was released from the chlor-alkali facility at the Allied Chemical plant to Onondaga Lake from 1946 to 1986. The load of Hg to the lake was estimated to be approximately 10 kg/d (USEPA 1973) when the U.S. Department of Justice took legal action against the facility in the summer of 1970. It was estimated that approximately 75,000 kg of Hg were discharged to the lake by Allied Chemical over the 1946-1970 interval (Effler 1987). Loading reductions of more than a factor of 20 were subsequently achieved through process modification.

The chemical company also operated (1917-1947) a benzene production facility on the site. Related wastes were lagooned on site. Some of this material has entered, and continues to enter, the lake via the ground water (Perkins and Romanowicz 1996). Tar-like substances and hydrocarbons of benzene origin have been found in the shoreline sediments in the southwest corner of the lake, adjoining the facility.

The Polluted State of Onondaga Lake

The historic and on-going use of the lake and bordering environs for the disposal of municipal and

Table 2.–Violations/exceedance of numerical standards/guidance value for state of New York, in Onondaga Lake.

Constituent/Attribute	Resource/ Use	Standard/Guideline	References
free ammonia (NH_3)	fishing	toxicity; standard function of pH and temperature; differ for salmonid and non-salmonid fisheries	Effler 1996, Effler et al. 1990
nitrite (NO_2^-)	fishing	toxicity; < 100 μg NO_2^-/L for non-salmonid, 20 < μgNO_2^-/L for salmonid	Brooks and Effler 1990, Effler 1996
dissolved oxygen (DO)	fishing	≥ 5 mg/L, daily average; ≥ 4 mg/L minimum within a day	Effler 1996, Effler et al. 1988
mercury (Hg) in fish flesh	fishing	FDA standard of < 1 ppm	Effler 1987, Ringler et al. 1996
clarity (Secchi disc transparency, SD)	swimming	standard for opening a public bathing beach; ≥ 4 ft (or 1.2 m)	Auer et al. 1990, Perkins and Effler 1996
fecal coliform (FC) bacteria	swimming	log mean ≥ 200 FC/100 ml over 5 days, single observations < 1000 FC/100 ml	Canale et al. 1993
total phosphorus (TP)	swimming	guidance value; epilimnetic summer average ≤ 20 μg/L	Effler et al. 1996a

industrial waste has severely degraded Onondaga Lake and the Seneca River. An impressive list of numerical standards, intended to protect the fishing and contact recreation resources of surface waters, were, and continue to be, violated (Table 2). Standards to avoid the potentially toxic effects to fish of nitrogen species, and to provide adequate oxygen for fish survival, are routinely violated in the lake and river (Table 2). Fish from the lake cannot be eaten due to contamination of fish flesh, and the lake is often not fit for contact recreation (Table 2). A number of these problems are addressed in more detail in subsequent manuscripts of this issue, or elsewhere (see subsequent treatment), and thus are considered only briefly here.

The total phosphorus (TP) criterion (Table 2) is a "guidance value" (New York State Department of Environmental Conservation (NYSDEC) 1993) instead of a standard, and thus is not subject to regulatory enforcement. The lake's problems of high TP and low DO concentrations and low clarity (Table 2) are primarily manifestations of cultural eutrophication (i.e., anthropogenic inputs of P). The interplay between these features of water quality and external P loading (e.g., Fig. 3) has been described widely in the literature. The lake-wide DO depletion in the lake's upper waters to concentrations that violate state standards, observed in most years with the approach to fall turnover, is a particularly severe manifestation of cultural eutrophication (Addess and Effler 1996, Effler et al. 1996a, 1988).

Free ammonia (NH_3) and nitrite (NO_2^-) standards are violated in the upper waters of the lake (and often by a wide margin) for much of the summer period (Brooks and Effler 1990, Effler et al. 1990, 1996a). Despite reductions in the level of mercury contamination of fish flesh since the 1970 ban, violations of the fish flesh concentration standard continue (Table 2). More than 95% of the legal sized (30.5 cm) smallmouth bass collected from the lake in 3 of 4 years during the 1987-1990 interval exceeded the FDA Standard (Table 2).

The fecal coliform bacteria standard(s) for swimming usage, intended to protect against the transmission of disease organisms, is violated in the upper water's of the lake's south basin following significant runoff events, and lake-wide following major storms. These violations are a result of the irregular discharge of dilute untreated sewage from the CSO system to lake tributaries (particularly Onondaga Creek) that enters the south basin in response to runoff events. Application of a validated fecal coliform model for Onondaga Lake (Canale et al. 1993) indicated a major reduction in external loading of fecal coliforms would

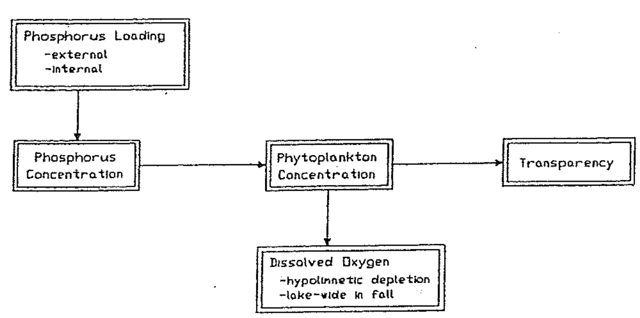

Figure 3.–Interplay between phosphorus loading and manifestations of cultural eutrophication.

Table 3.– Features of degradation of Onondaga Lake and Seneca River related to discharges of the soda ash/chlor-alkali facility.

Feature	Implication	References
elevated salinity	reduction of biological diversity; depressed zooplankton grazing, thereby exacerbating lake clarity problems	Effler 1996, Meyer and Effler 1980, Remane and Schleiper 1971, Siegfried et al. 1996
artificial vertical cycling of spent cooling water	enhanced internal loading of phosphorus	Effler and Owens 1987
plunging inflow	alterations to stratification/mixing regime, e.g., salinity stratification, failure of spring turnover; exacerbation of lake's DO problems	Effler 1996, Effler et al. 1986a, Effler and Perkins 1987, Effler and Owens 1996, Owens and Effler 1989
enhanced rate of sedimentation of $CaCO_3$	elevated rate of net sedimentation	Driscoll et al. 1994, Effler and Driscoll 1985a, Rowell 1996
formation of unusual $CaCO_3$ concretions in near-shore zone	discourages development of normal littoral community	Dean and Eggleston 1984, Madsen et al. 1992, 1996
contamination of sediments with Hg	uncertain, potential contamination of biota, probably ameliorated by burial	USEPA 1973, NYSDEC 1990, Effler 1987, Rowell 1996
salinity stratification in adjoining portions of the Seneca River	violations of DO and free ammonia water quality standards	Canale et al. 1995, Effler 1996, Effler et al. 1984a

be necessary to assure avoidance of violations (Effler 1996). For example, about a 90% reduction in fecal coliform loading would be required, for a one-year return frequency storm and critical environmental conditions, to meet the related public health standard (Table 2; see Effler 1996).

The extent of the degradation of Onondaga Lake is not fully depicted by its status with respect to numerical standards (Table 2). Certain of the impacts are not amenable to simple quantification. In particular, discharges from the soda ash/chlor-alkali facility have degraded habitats within the lake and adjoining portions of the Seneca River (Table 3). The ionic waste discharges from the facility (Effler et al. 1996c) exacerbated the lake's problems of poor clarity and low DO concentrations, greatly altered it's natural stratification/mixing regime, and impacted the littoral zone (Table 3, Effler 1996). Some of these problems have been ameliorated by reductions in ionic waste loading that accompanied the closure of the facility. However, impacts continue because of the continuing, albeit lower, waste loading (e.g., Effler 1996, Effler et al. 1996c, Effler and Owens 1996). Note that impacts associated with the occurrence of salinity stratification in adjoining portions of the Seneca River (Table 3) would not have been manifested, or at least, would have been greatly ameliorated, in the absence of the ionic pollution from the soda ash/chlor-alkali facility. The salinity stratification in the river extends Onondaga Lake's problems into the river (Effler 1996). It continues, albeit diminished, because of the continuing ionic waste inputs from the Solvay waste beds (Effler 1996).

Testimony to the U.S. Senate described Onondaga Lake as one of the most polluted lakes in the United States; perhaps the most polluted (U.S. Senate Committee on the Environment and Public Works, Sub-committee on Water Resources, Transportation and Infrastructure 1989). Hennigan (1991) described the lake as the nations's "dirtiest". In reality there is no widely accepted basis to quantitatively rate and compare the degree of pollution of different lakes. However, it can be said that the impact of of municipal and industrial wastes on Onondaga Lake has been profound. The ecology of the lake has been severely impacted, and use of the lake for fishing and swimming has been lost (Tables 2 and 3, Effler 1987, 1996).

Enforcement Actions

Enforcement actions are presently underway against the two primary polluters of the lake, Onondaga County for METRO and CSOs, and Allied Signal, Inc. (Allied) (Effler 1987, Effler 1996) for the residual impacts of its soda ash/chlor-alkali operations.

In January of 1989 a Judgment on Consent was entered in federal court against Onondaga County based on METRO exceeding its permitted effluent limits and CSO discharges to the lake. The Judgment requires the county to complete and implement a Municipal Compliance Plan (MCP) to correct these violations. In April, 1995, Onondaga County was assessed $189,000 in fines for continuing to violate effluent limits at METRO. A deadline of January, 1996 has been set by the parties to this lawsuit for completion of the MCP.

In July, 1989, New York State sued Allied under the federal "superfund" legislation. The state alleges pollution of the lake from Allied's facilities including mercury, calcium carbonate, calcium chloride, sodium chloride and chlorinated benzene. In January, 1992 Allied agree to conduct a Remedial Investigation and Feasibility Study (RI/FS) of the impact of its activities on the lake and its environs. The purpose of the RI/FS is to evaluate what affect Allied's discharges had and continue to have on the lake and to assess the feasibility of remedial options to address those impacts. Because the RI/FS has not yet been completed, the data and results of a number of the studies being conducted by Allied's consultants are protected by rules of legal confidentiality and therefore are not yet available to the public.

Research on Onondaga Lake

It is perhaps not surprising that research of this extremely polluted lake has lagged behind efforts on other highly impacted systems. The first comprehensive limnological and water quality study of the lake was not conducted until the late 1960's (Onondaga County 1971). This effort provided the first documentation of the degraded conditions of the lake, and related it to loadings of domestic and industrial wastes. Funded study of the lake thereafter, until the late 1980s, was largely limited to an annual (and on-going) monitoring program administered by one of the primary polluters of the lake (Onondaga County 1971-1996). The paucity of independent research, and funding to support such work, undoubtedly contributed to the perpetuation of the status quo.

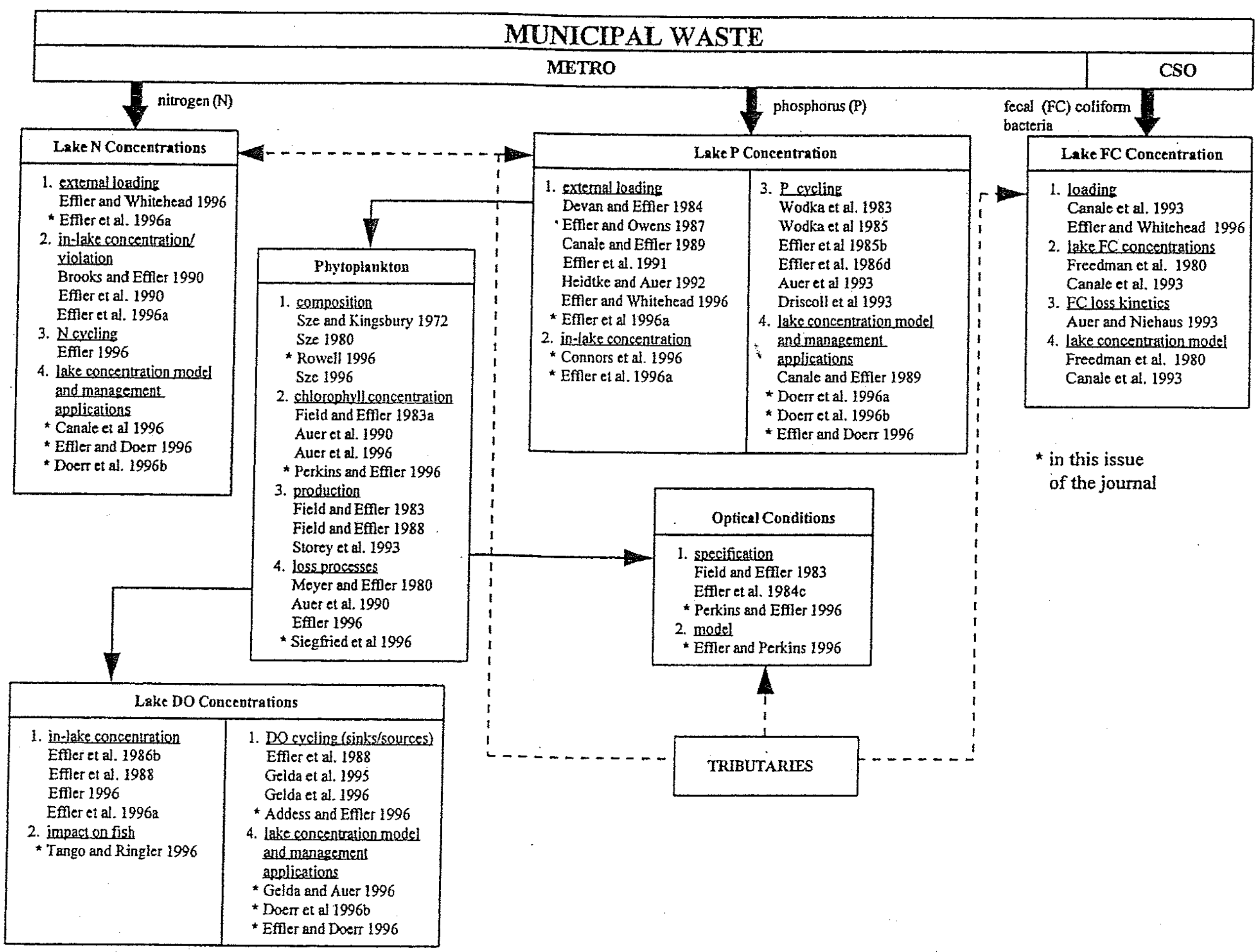

Figure 4.–Scope and design of Onondaga Lake research since the mid-1970s, related to the impacts of municipal wastes; literature citations presented.

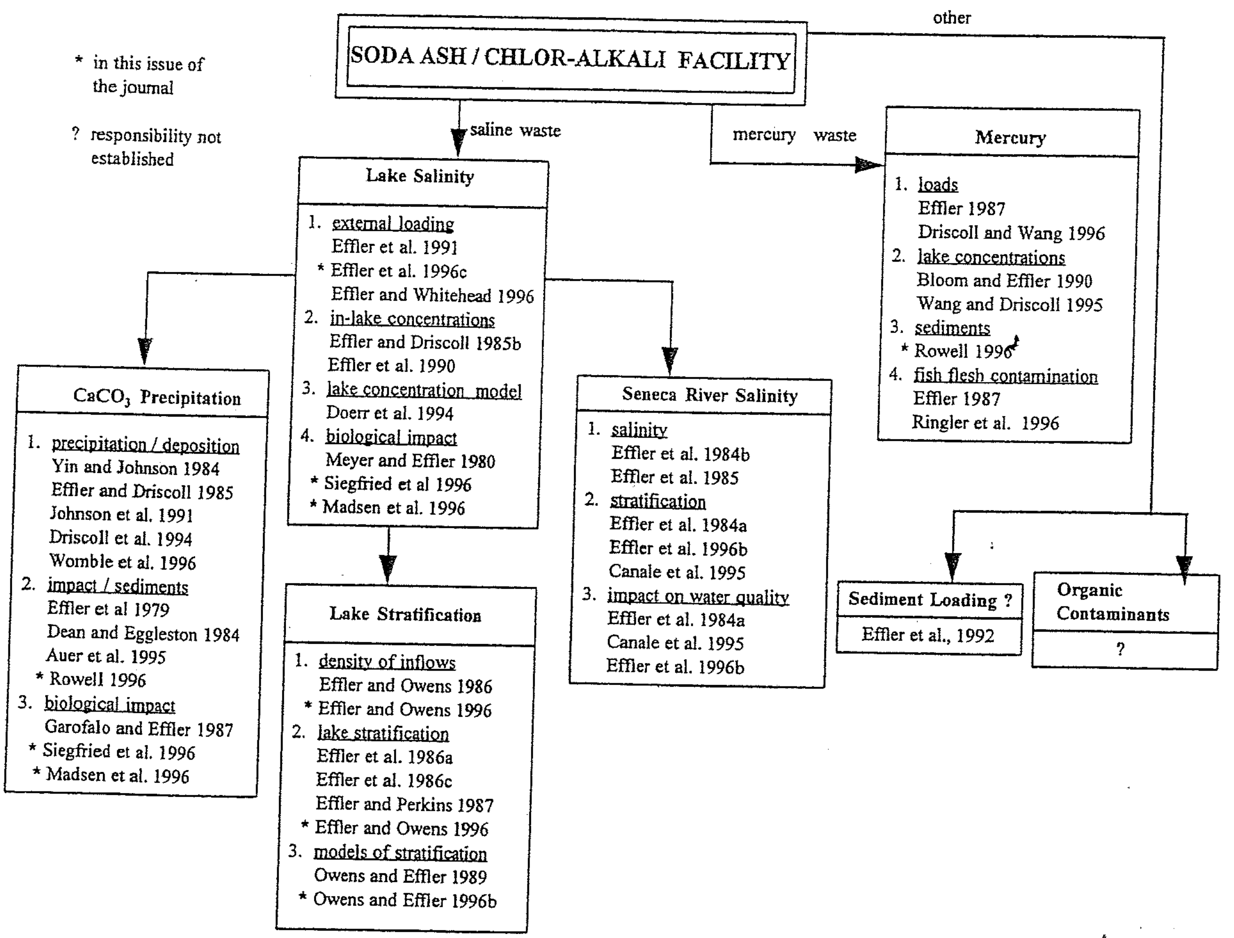

Figure 5.–Scope and design of Onondaga Lake research since the mid-1970s, related to the impacts of wastes from the soda ash/chlor-akali facility; literature citations presented.

Starting in 1987, under funding provided by Onondaga County, intensive research studies were initiated to support the development of mechanistic water quality models that were to be used to guide the remediation of certain of the lake's problems. Federal funding (starting in 1989), administered by the State of New York, supported the continuation of this program. The Onondaga Lake Management Conference, formed by the U.S. Congress in 1990, has supported additional, and more broad-based, research of the lake and the Seneca River.

Here the scope and design of the research program for Onondaga Lake (since the mid-1970s) is presented within the context of the impacts of the lake's primary sources of pollution, municipal waste inputs (Fig. 4), and discharges from the soda ash/chlor-alkali facility (Fig. 5). The respective flow diagrams (Figs. 4 and 5) are necessarily simplifications. Further there are interactions between the municipal and industrial pollution problems (Effler 1987, 1996) that are not depicted. There are, of course, alternate ways to organize the components of the program (e.g., disciplines and sub-disciplines, lake processes, etc.), but the adopted scheme (Figs. 4 and 5) is particularly valuable from the lake management perspective. Manuscripts that address the various manifestations of pollution in the lake and the Seneca River are identified in these diagrams. An array of valuable interdisciplinary (e.g., physical, chemical and biological limnology, hydrodynamics, paleolimnology, and mathematical modeling) findings have emerged from this research program (Figs. 4 and 5). Selected portions of these findings are presented in this special issue of the journal.

While the entire myriad of the lake's problems, cannot be addressed here, this collection of manuscripts (see Figs. 4 and 5) provides critical input to the difficult management deliberations for this system. Systematic changes in the loading of important pollutants, associated with remediation efforts and changes in industrial activity, are reviewed. The impacts of these loadings on selected physical, chemical, and biological features of the lake are documented, including the status of the system with respect to water quality standards. Key processes influencing the lake's response to pollution and the cycling of important constituents are identified and quantified. The development and testing of hydrodynamic, optical, and water quality models are documented. The models, in particular, provide a strong basis for effective management of this polluted system. These management tools are applied to simulate the response of the lake to selected management alternatives presently under consideration for the lake.

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