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

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ABSTRACT

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Onondaga Lake, NY, has been described as the most polluted lake in the United States. This medium size (surface area of 12 km² 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.

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Setting/Hydrology

Onondaga Lake has a surface area of 12.0 km², a volume of 131 x 10⁶ m³, 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 km². The major hydrologic inputs to the lake are Ninemile Creek, Onondaga Creek, the Metropolitan Syracuse Sewage Treatment Plant (METRO), and Ley Creek (Fig. 1).

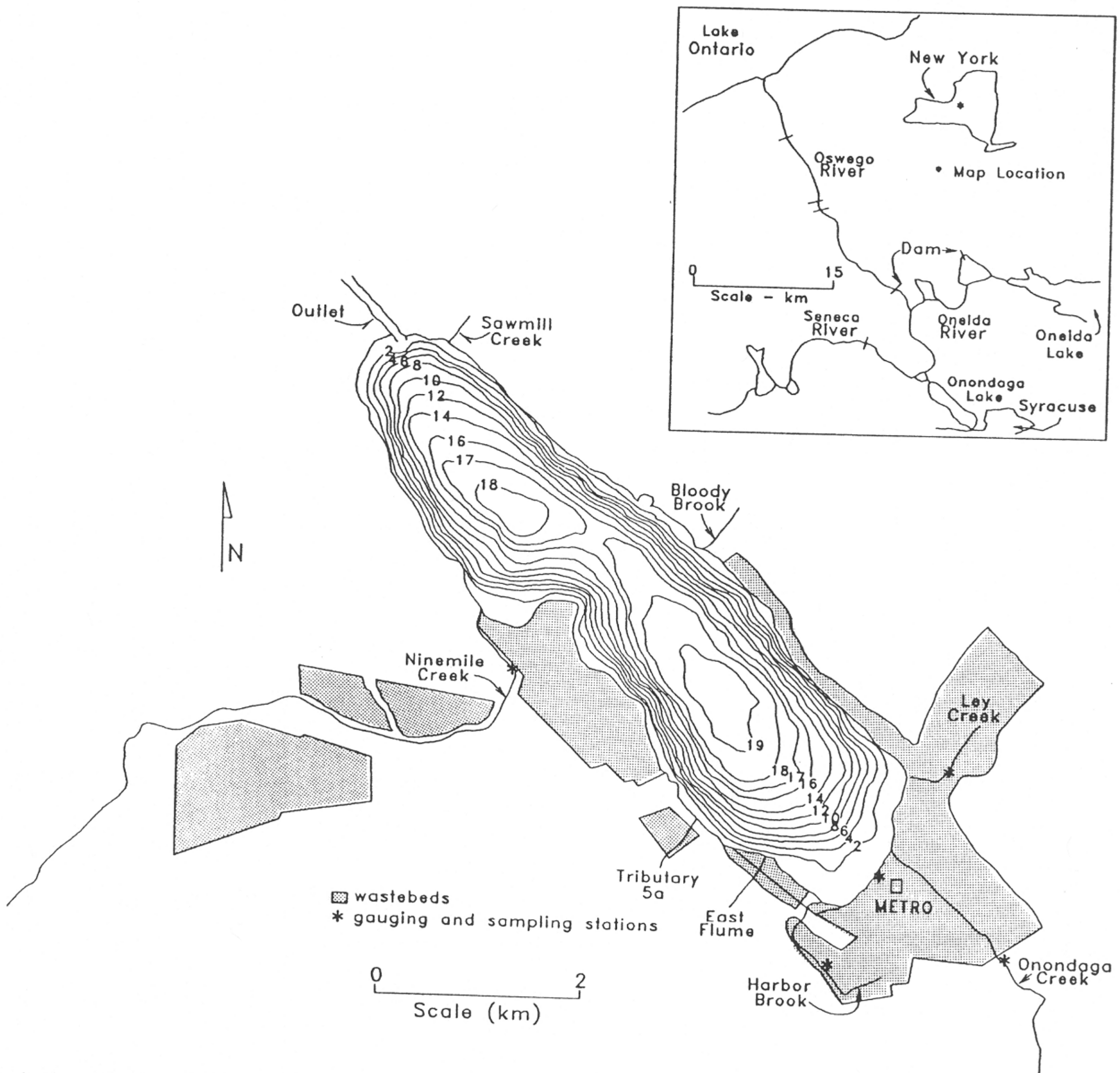

Figure 1.–Onondaga Lake bathymetry and setting.

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) Average	Std. Dev.	Std.Dev./Average	% Contribution to Total Inflow 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

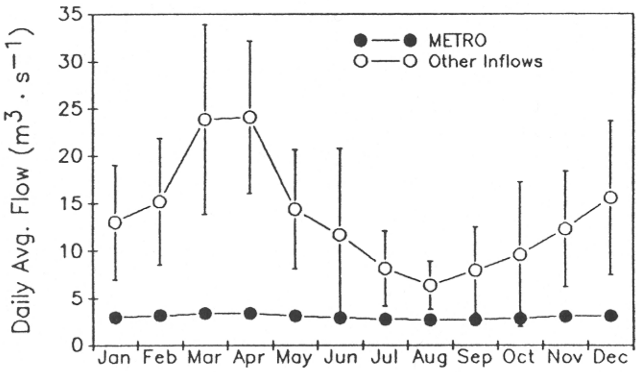

Figure 2.–Seasonality in surface flows to Onondaga Lake; average monthly total tributary and METRO inflow for period 1971-1989, with ± 1 standard deviation bars.

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 ($\geq$ 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

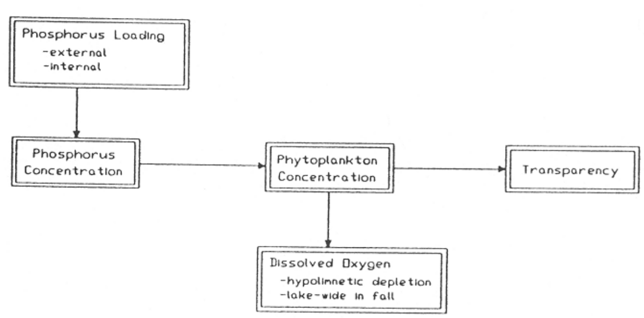

Figure 3.–Interplay between phosphorus loading and manifestations of cultural eutrophication.

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.

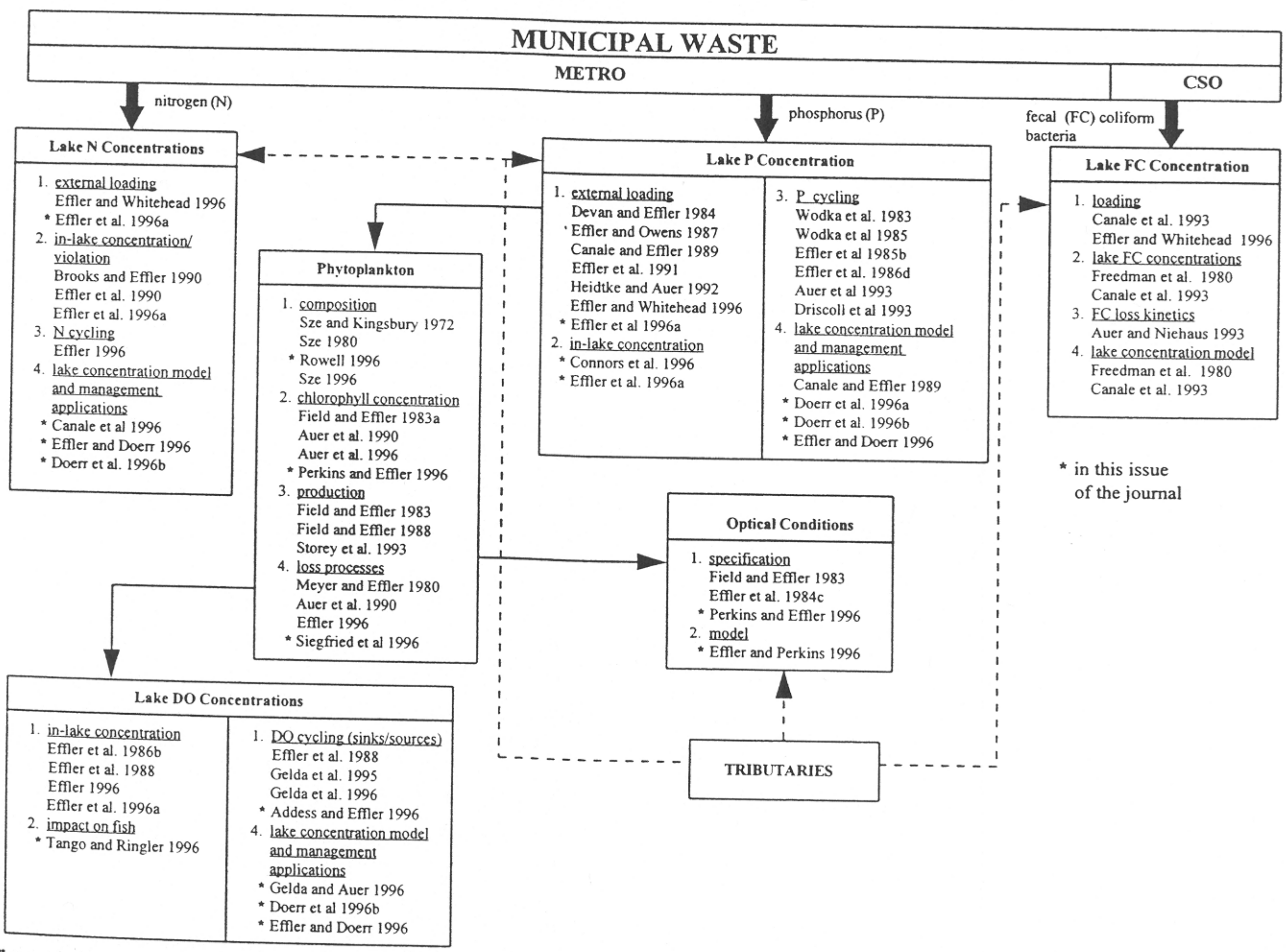

Figure 4.–Scope and design of Onondaga Lake research since the mid-1970s, related to the impacts of municipal wastes; literature citations presented.

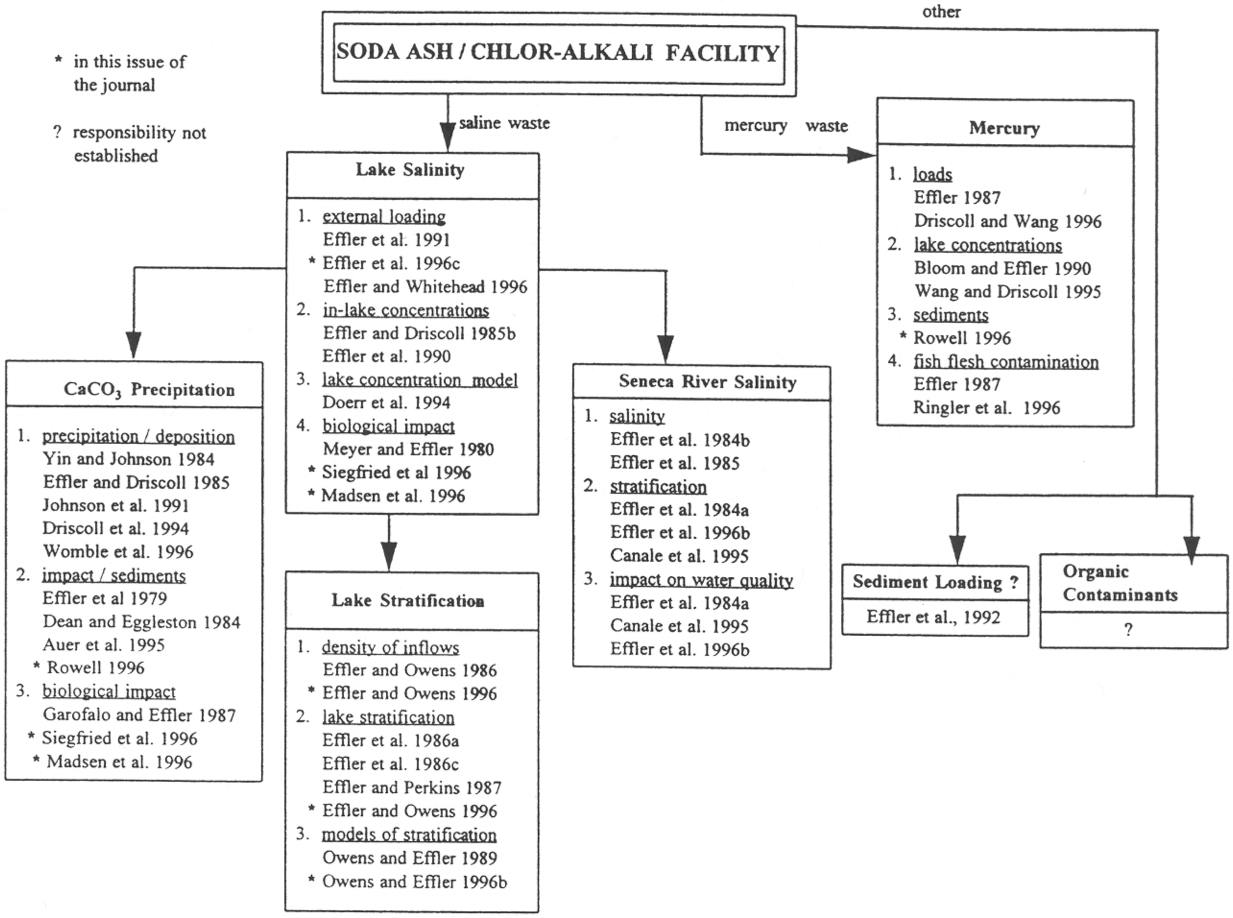

Figure 5.–Scope and design of Onondaga Lake research since the mid-1970s, related to the impacts of wastes from the soda ash/chlor-akali facility; literature citations presented.

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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