Contaminated sediment in the Buffalo River area of concern–historical trends and current conditions

K.N. Irvine[1]*, K.M. Frothingham[1], M.C. Rossi[2], S. Pickard[3],
J. Atkinson[4], T. Bajak[4]

*[1]Department of Geography/Planning and Great Lakes Center, State University of New York, College at Buffalo, 1300 Elmwood Ave., Buffalo, NY 14222, U.S.A. *irvinekn@bscmail.BuffaloState.edu*
[2]Erie County Department of Environment and Planning, 95 Franklin St., Buffalo, NY 14202, U.S.A.
[3]U.S. Army Corps of Engineers, Buffalo District, 1776 Niagara St., Buffalo, NY 14207, U.S.A.
[4]Department of Civil, Structural, and Environmental Engineering and Great Lakes Program, State University of New York, Buffalo, NY 14260, U.S.A.

Keywords: Great lakes area of concern, contaminants, aquatic organisms, sediment quality, water quality

Introduction

The Great Lakes is the largest freshwater lake system in the world and an invaluable natural resource, but impairment of its water quality has been documented since the 1800s (IJC, 1987; Rossi, 1995). Most recently, management and remediation initiatives for the lakes have been focused through programs such as Remedial Action Plan (RAP) development for Areas of Concern (AOCs) and Lakewide Management Plans (LaMPs).

Areas of Concern are designated by the IJC because they fail to meet the general or specific objectives of the U.S.-Canada Great Lakes Water Quality Agreement and as such, exhibit some type of beneficial use impairment. Beneficial use impairments may include restrictions on fish and wildlife consumption, fish tumors or other deformities, eutrophication, beach closings, or restrictions on

Sediment Quality Assessment and Management: Insight and Progress
Edited by M. Munawar

Aquatic Ecosystem Health & Management Society

dredging activities, amongst others (IJC, 1987). Under the U.S.-Canada Great Lakes Water Quality Agreement, a RAP must be developed for each AOC. In brief, the RAP process identifies: the environmental impairments of an AOC; the potential sources of the impairments; approaches for remediation of the impairments; lead agencies responsible for remediation; and a timeline for remediation.

The RAPs have identified contaminated sediment as a problem at the majority of AOCs. In the United States, several of these AOCs also are federally-designated navigable channels and the contaminated sediment has hampered the ability of the U.S. Army Corps of Engineers (USACE) to maintain adequate depths for navigation. Annex 14 of the 1987 Protocol to the U.S.-Canada Great Lakes Water Quality Agreement called for an identification of the nature and extent of the sediment pollution of the Great Lakes system (U.S. EPA, 1994). The ARCS (Assessment and Remediation of Contaminated Sediment) Program was implemented under the auspice of the U.S. EPA to conduct a five year study and initiate a series of demonstration projects relating to the control and removal of toxic compounds from bottom sediments in the Great Lakes (U.S. EPA, 1994). It was intended that this program would provide information and tools for RAPs, in particular, to help identify options for contaminated sediment remediation.

The Buffalo River, NY, was identified as one of five demonstration sites for the ARCS program. Various ARCS-sponsored projects were conducted in the Buffalo River AOC, including a mass balance study (Atkinson et al., 1994; DePinto et al., 1995; Pratt et al., 1995), bed sediment sampling (SAIC, 1996), physical habitat and aquatic organism survey (Singer et al., 1995); and baseline risk assessments for both human health (Crane, 1993) and aquatic organisms (Passino-Reader et al., 1995). The ARCS studies provided extensive documentation of the recent condition of the Buffalo River, but they also utilized and were guided by previous studies on water and sediment quality (e.g. Symons, 1940; 1946; Hall, 1955; Parsons et al., 1963; Sweeney, 1970; Sargent, 1975; Black et al., 1980; Meredith and Rumer, 1987; Raggio et al., 1988; USACE, 1988; New York State Department of Environmental Conservation (NYSDEC), 1989; Aqua Tech, 1989a,b).

The Buffalo River AOC is a highly urbanized ecosystem that has experienced over a century of industrial and municipal impacts and port activities. In recent decades, industry has declined along the river and the city of Buffalo has ambitious redevelopment plans for the waterfront, including increased waterway access and recreational use. It is essential to consider the environmental conditions associated with the river as remediation and redevelopment plans are drafted.

Contaminated sediment is an important issue for the Buffalo River AOC and the broad objective of this paper therefore is to document changes in the

Buffalo River ecosystem as they pertain to temporal trends in sediment quality. To address this objective, we summarize several of our recently completed studies in an effort to draw a picture of sediment quality in the river, past and present. More specifically, this paper: 1) traces the historical relationship between the change in industrial activity along the Buffalo River and trends in sediment quality as reflected through sediment cores; 2) discusses results of aquatic organism risk assessment as they pertain to new sediment dredging guidelines developed by the USACE and the U.S. EPA; and 3) examines changes in sediment load within the AOC in relation to changes in industrial activity, changes in land use, and implementation of Best Management Practices (BMPs) within the upper watershed.

The Buffalo River watershed

The Buffalo River drains an area of 1,155 km^2 and Cayuga, Buffalo, and Cazenovia creeks are the three major tributaries within the watershed (Figure 1). The Buffalo River watershed occupies two physiographic regions. The northern and western portion of the watershed is within the Erie-Ontario Lake Plain Province, while the southern part of the watershed is within the Alleghany Plateau Province. The Erie-Ontario Province formerly was a glacial lake bed and therefore has limited relief. The watershed consists primarily of 21 different soil series, but the majority of soils texturally are a silt loam (U.S. Department of Agriculture, 1986). The slopes of these soil units range between nearly level

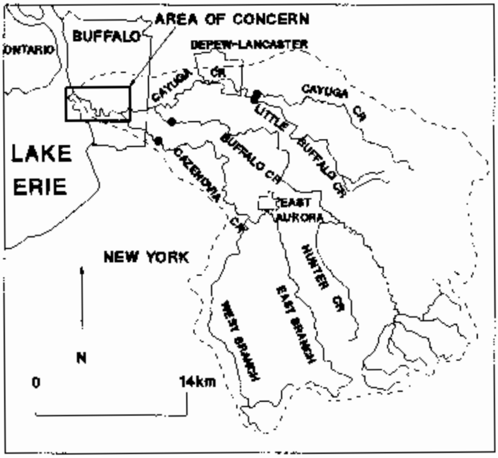

Fig. 1. The Buffalo River watershed. Suspended sediment sample locations near U.S. Geological Survey gauge stations are shown as (·).

and 0.50, while the drainage classification ranges from very poorly drained to excessively drained (U.S. Department of Agriculture, 1986).

The climate of the Buffalo area is classified under the Koppen system as humid continental with a mild summer (Dfb) (Gabler et al., 1997). Annual total precipitation at the Buffalo Airport averages 98 cm, with February being the driest month (5.9 cm of precipitation) and August being the wettest month (10.6 cm of precipitation). The lowest monthly mean flow recorded at U.S. Geological Survey (USGS) gauge stations on each of the tributaries (Figure 1) typically occurs in July and August when evapotranspiration is highest (Cayuga Cr. - 0.70 m^3 s^{-1} (24.6 cfs); Buffalo Cr. - 1.30 m^3 s^{-1} (45.8 cfs); and Cazenovia Cr. - 1.35 m^3 s^{-1} (47.8 cfs)). Highest monthly mean flow on the three tributaries typically occurs in March (Cayuga Cr. – 9.68 m^3 s^{-1} (342 cfs); Buffalo Cr. – 14.0 m^3 s^{-1} (495 cfs); and Cazenovia Cr. – 15.6 m^3 s^{-1} (551 cfs)) as the result of snowmelt and spring rainfall.

New York State water quality guidelines are based on the concept of "best use", that considers the past, present, and future uses of the waterway, including the disposal of sewage, industrial waste, and other wastes (NYSDEC, 1989). There are four "best use" categories, ranging from A (best water quality) to D (worst water quality). The best use for A class streams is drinking water; B class streams is swimming; C class streams is fish propagation; and D class streams is fish survival. The best use class for the Buffalo River AOC was upgraded from D to C in the early 1990s. The water quality classes for the tributaries range between A and C (NYSDEC, 1996). Although Sargent (1975) noted there were little data on most metals or organic contaminants prior to the 1970s, Irvine (1997) compared Pb levels in whole water samples collected in the Buffalo River and lower Cazenovia Creek, as reported by different studies between 1973 and 1997. Qualitatively, this comparison indicated a trend towards a decrease in concentration.

Land use within the watershed varies. Much of the upper portion of the watershed is characterized by woods and farmland, but prior to joining the Buffalo River the creeks also pass through several small communities and receive industrial, commercial, residential, and municipal discharges (Irvine and Pettibone, 1996). As noted, the lower Buffalo River historically has been highly industrialized (Sauer, 1979; Rossi, 1998) and this appears to be one of the principal reasons why only the lower 9.6 km of the river was designated an AOC by the IJC. The industrial history of the AOC is discussed in detail in the following section.

Much of the Buffalo River AOC is designated as a navigable channel and is maintained at a minimum depth of 7m by the Buffalo District USACE. This dredged reach is wider and deeper than the tributaries, but the bed slope is shallower. As a result of the changes in the hydraulic geometry, flow velocities within most of the AOC typically are less than those of the tributaries, producing local shoaling areas as sediment deposits. The Buffalo River Improvement Corporation (BRIC) was created in 1967 to supply industries along the Buffalo River with water for cooling and processing purposes. The water is pumped from Lake Erie and ultimately augments flows in the Buffalo River. The design operation of the BRIC system is 2.18 m^3 s^{-1} (77 cfs) and during its early years of operation often contributed 90% of the total river flow in the drier summer months (Sauer, 1979). As industry has declined along the river, so too has the BRIC pumping rate. Pumping rates during the past year averaged 0.66 m^3 s^{-1} (23 cfs).

Industrial history of the Buffalo River watershed and relationship to sediment quality

Buffalo exhibits a history of development similar to that of several other Great Lakes cities, including Cleveland, Chicago, Detroit, Milwaukee, and Toronto, which has been generalized in a descriptive urban model outlined by Paterson (1994). Following Paterson's (1994) model, all six cities shared common traits as initial settlements and were subjected to the same stimuli, primarily transportation related, that altered their respective landscapes. The cities, founded between 1815 and 1840, were situated initially at the mouth of a creek/river tributary to their respective lake. The sites characteristically were marsh environments first occupied by a military fort and/or trading post. From 1840, the physical characteristics of the cities evolved in response to transportation developments and the expansion of steel production. During the most recent time period (1950-1994), industries characteristically were located beyond the Central Business District due to increasing land costs, limited room for expansion in central cities, pollution and nuisance concerns. Beyond these generalizations made under the Paterson (1994) model, the six cities share commonalities with respect to environmental degradation. The Cuyahoga River in Cleveland, the Waukegan Harbor in North Chicago, the Detroit River, the Toronto waterfront, Milwaukee Harbor, and the Buffalo and Niagara rivers all have been designated as AOCs.

Buffalo's location on Lake Erie and the Niagara River led to its existence as a port. The Erie Canal (1825) not only propelled Buffalo into existence, but as the western terminus, it also gave the city unprecedented economic prosperity (Thompson, 1986). Supplementing Buffalo's success as a port was an extensive network of rail lines. Through the mid-1800s, Buffalo's economy was based on the commercial success it enjoyed as an inland port on the Great Lakes. However, lake and canal travel was not possible during the winter months due to ice and eventually the railroads replaced the canal as the preferred method of transportation.

Buffalo experienced a financial depression between 1857 and 1859, which inspired its leaders to contemplate manufacturing as a means to revitalize and redirect its "commercial" economy (Goldman, 1983). The locational advantages of the city were exploited as a means of attracting local and outside interest in manufacturing investment opportunities. The city retained its place as an inland port and water transportation continued to be supplemented by an expanding rail network. Hydroelectric power from Niagara Falls also became an important selling point to entice manufacturing interests to Buffalo. The first commercial transmission of Niagara Falls electricity occurred in 1895 and Buffalo was connected one year later (McIntyre, 1952). In fact, an 1853 prospectus cites the potential demand for electricity in Buffalo by manufacturing interests as justification for the initial cost of establishing the Niagara Falls Power Company (Adams, 1927). Subsequently, a number of corporations indicated the inexpensive and virtually unlimited supply of electrical power available as a primary reason for building or relocating their businesses in Buffalo (Goldman, 1983).

Six classes of industry offer a good representation of the manufacturing firms present in the city since the mid-1800s: tanning and leather; grain milling; petroleum refining; chemical production; iron and steel production; and metal working and machining. By the 1920s, Buffalo was the nation's second largest milling center (Hill, 1923). The largest dye plant in the nation was located on the Buffalo River when National Aniline merged with General Chemical Company and the Contact Process Company to form Allied Chemical and Dye Corporation (Kessel, 1923). Within the Bethlehem Steel conglomeration, the Lackawanna (south Buffalo) plant was second only to the Johnstown, Pennsylvania plant in steel ingot capacity. Rossi (1998) provided a more thorough documentation of the development, nature, and extent of these six industrial classes for the city of Buffalo.

Documenting industrial change along the Buffalo River

Several sources of information were used to create a database of industry at 10 year increments for the period 1929 through 1990 within the six sewer districts adjacent to the Buffalo River. The sewer district boundaries were used as the spatial delimitation because industries within these districts either would have discharged to the Buffalo River directly, or the effluent could enter the river during storms via combined sewer overflows. The Polk section of Buffalo's city directory was the principal source of information used to identify the industrial occupants on each of the appropriate streets and track changes in occupancy through time. The industrial inventory for Buffalo begins in 1929 because it was the first year that city directories contained a Polk section. Sanborn Fire Insurance Maps, dating back to 1881, also exist for the city. The original purpose of these maps was to provide detailed information to insurance companies pertaining to fire risks associated with various structures (Ristow, 1970). Commercial, residential, and industrial structures are depicted on the maps which also portray the placement, size, shape, construction materials and use of buildings, in addition to street patterns, lot lines and infrastructure. Sauder (1980) successfully used Sanborn maps to reconstruct the city of Boston's waterfront from 1867 to 1972, but there is not a locally available, complete set of Sanborn maps. In addition, the Buffalo maps have numerous "pasteovers" which were used to update the maps while simultaneously avoiding the cost of reproduction. These pasteovers often obliterate the original occupant, which reduced the utility of applying these maps for this study.

Based on distinctions in the Standard Industrial Codes (SIC) for New York State (MacRae's State Industrial Directory, 1991), 10 industrial categories were identified for south Buffalo and these are summarized in Table 1. For each 10 year period, the industry's name, address, and category were entered into a spreadsheet format that was then imported into MAPINFO, a desktop GIS package. For brevity, the years 1929, 1960, and 1990 are shown in Figure 2. Several trends are evident in examining the time series maps. Perhaps the most pertinent to this paper is the gradual reduction in the number of industries, although there are some instances of a small increase for each category at one time or another. Two factors account for the decrease in the number of industries over time. First, many early industries, particularly iron and steel and chemical, experienced mergers. The total number of industries therefore was reduced

Table 1. Industrial categories[1] in historical database.

Code	*Category*
1	Food and Kindred Products; Pet Food
2	Lumber; Wood; Non-metal Furniture
3	Chemical; Plastic; Soap; Pharmaceutical
4	Petroleum; Coal; Asphalt
5	Primary Metal
6	Fabricated Metal
7	Industrial Machinery and Equipment; Other Machinery
8	Transportation; Transportation Equipment
9	Auto Repair; Miscellaneous Repair
10	Miscellaneous; Unknown

[1] Based on SIC Codes (see MacRae's State Industrial Directory, 1991)

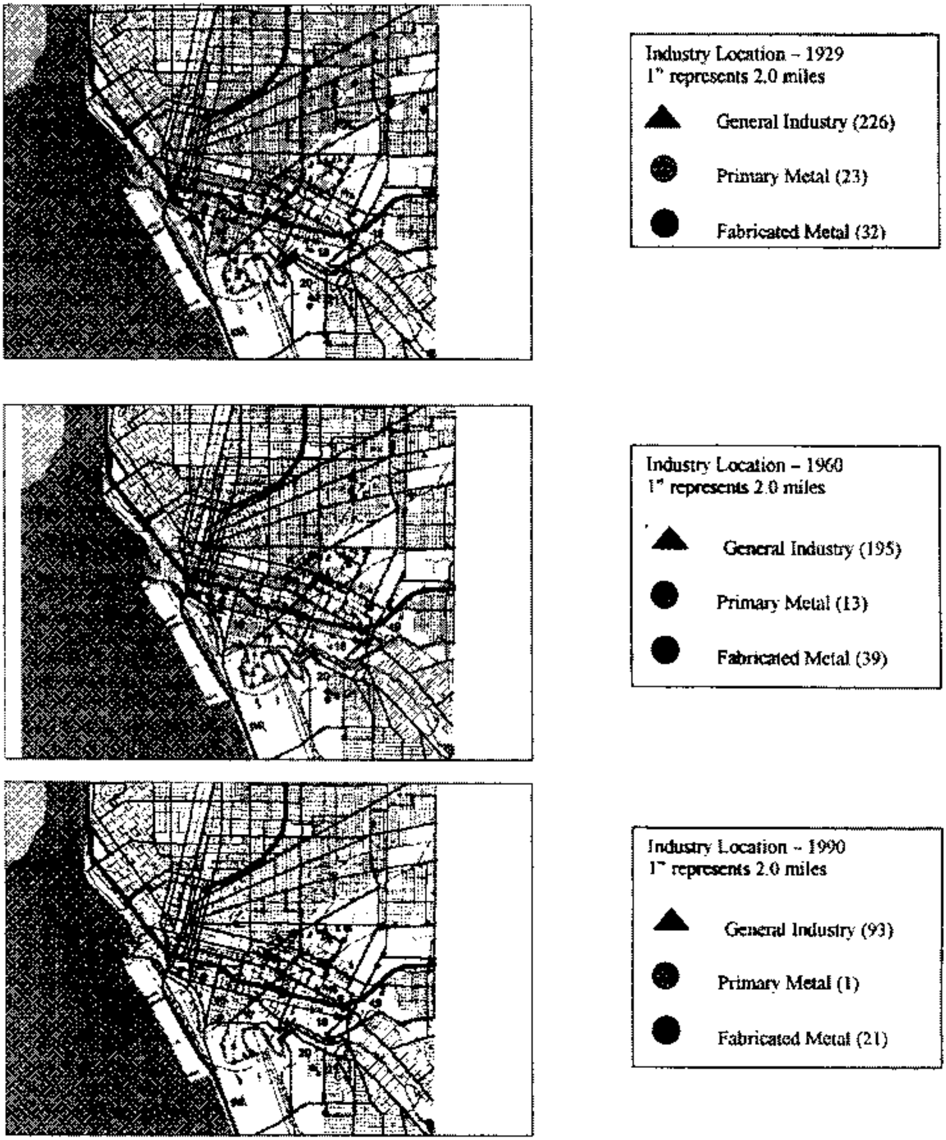

Fig. 2. Location of industry in sewer districts bordering the Buffalo River Area of Concern, 1929, 1960, 1990. The pink lines represent the boundaries between sewer districts 16 through 21.

while the size of the individual establishments increased. Furthermore, beginning in the 1960s and accelerating into the 1970s and beyond, industrial decline in the United States was reflected in the nation's trade imbalance and the impact of international trade on production by various industries (Ullman, 1988). Many factors, among them, foreign competition, corporate greed, labor union disputes, failure to modernize, and pollution control requirements contributed to the general decline in manufacturing (Strohmeyer, 1986; Stokoe, 1993).

Sediment core data

As part of the ARCS program, the U.S. EPA used a Vibrocorer to collect a total of 34 sediment cores from five locations within the AOC in August, 1991, following the methodology described by SAIC (1996). The majority of sediment cores were taken from areas outside of the dredged channel in an effort to obtain samples that were not disturbed by dredging operations. The cores ranged from depths of 75 to 500 cm and were analyzed for a variety of contaminants. For discussion purposes in this paper, we focus on the levels of Cr, Pb, and Zn. These metals were selected for examination because they are representative of industrial activities and past studies have indicated that levels in the sediment for various locations in the AOC represent some risk for aquatic organisms (Passino-Reader et al., 1995; SAIC, 1996). Maximum levels reported by SAIC (1996) for Cr, Pb, and Zn in sediment cores were 2,500, 3,400, and 6,400 μg g^{-1}, respectively.

Core samples from three areas were selected for the purpose of establishing a relationship between industrial change and sediment quality over time (Figure 3). The Hamburg St. area is adjacent to a sewer district that was characterized

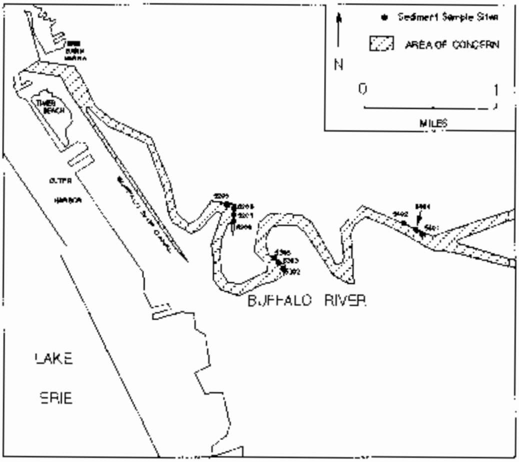

Fig. 3. Location of sediment core samples used for correlation with industrial discharge data. Cores 5201-5208 are located in the Hamburg St. area; cores 5302-5305 are located in the Blue Tower Turning Basin area; and cores 5401-5404 are located in the Mobil Oil area.

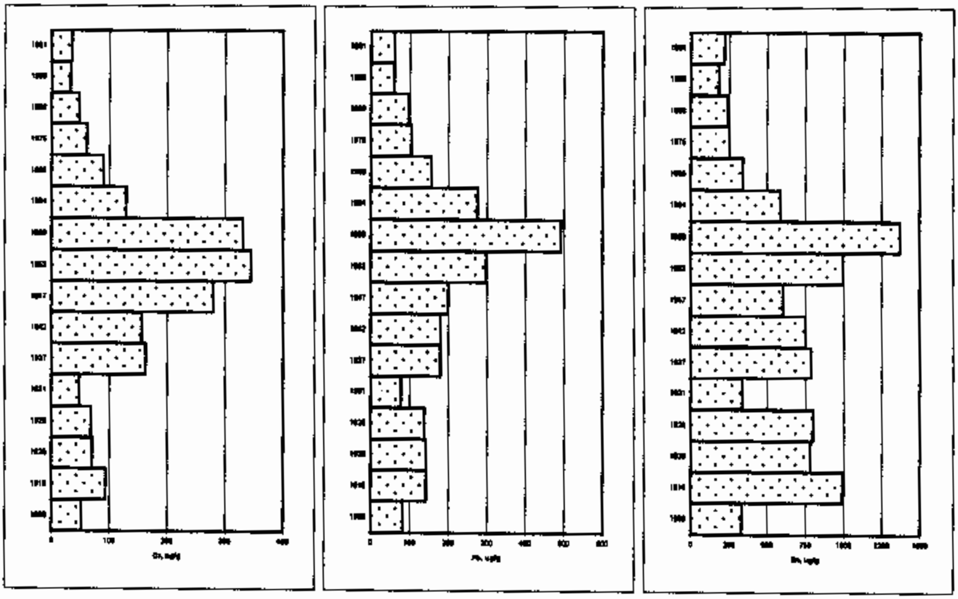

Figure 4a Metals Levels, Core 5208, Hamburg St. area.

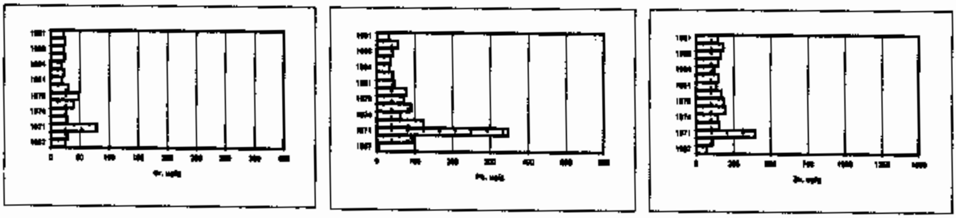

Figure 4b Metals Levels, Core 5401, Mobil Oil area.

Fig. 4. (a) Metals levels, sediment core number 5208, Hamburg St. area; and (b) metals levels, sediment core number 5401, Mobil Oil area.

by a concentration of iron and steel related industries from the late 1800s through the early 1900s. The Blue Tower Turning Basin was selected because of its proximity to Republic Steel, the city's largest iron and steel producer. The reach of river termed Mobil Oil provides an upstream location for comparison purposes. A total of 10 sediment cores were selected from the three river reaches, based on several criteria: 1) the cores were outside of the dredged channel; 2) each core offered a long record of accumulation; 3) seven cores were offshore from former areas of iron and steel production; and 4) three cores were upstream from areas of iron and steel production and provided levels of contamination for comparison.

Table 2. Shoaling rates for the sediment core sample areas.

Location	*Shoaling Rate, cm yr^{-1} (from USACE, 1988)*	*Adjusted (for Consolidation) Shoaling Rate, cm yr^{-1}*
Hamburg St.	6.1	4.6
Blue Tower Turning Basin	15.2	11.4
Mobil Oil	19.8	14.9

Unfortunately, none of the sediment cores were dated, so there is no direct information regarding the age-contaminant level relationship. It was therefore necessary to indirectly determine sediment age based on shoaling and consolidation calculations. Shoaling rates were determined for 15 representative cross sections by the USACE (1988) as part of its dredging evaluations for the river. The shoaling rates were calculated using the HEC-6 model (http://www.hec.usace.army.mil/software_distrib/hec-6/hec6program.html, accessed on 1/23/02) and the rates for cross sections within the three sediment core areas are shown in Table 2. Due to the hydraulic nature of the river, shoaling rates tend to increase in the downstream direction. Once sediment is deposited, typically it is subject to consolidation (Perrier and Quiblier, 1974). The process of sediment consolidation can be complex and variable. Factors affecting the rate and extent of consolidation include: type of sediment; age; rate of sedimentation and loading; abnormal pressure situations (e.g. coarse textured sediment overlying fine); transformation of minerals; and cementation (Perrier and Quibler, 1974). Consolidation data for the Buffalo River sediment are not available, but based on research by Bokuniewicz et al. (1977) and Vink and Winkels (1994), and considering the texture of Buffalo River sediment, it was estimated that a consolidation rate of 25% would be appropriate. The shoaling rate for each area, adjusted for consolidation, is shown in Table 2 and these adjusted rates subsequently were used to date the sediment cores.

Sediment core data representative of the Hamburg St. and Mobil Oil areas are shown in Figure 4. The temporal trend in metals levels for the Blue Tower Turning Basin was similar to that of the Hamburg St. area. The metals levels for the cores were not as high as the maximum levels reported by SAIC (1996). In general, metals levels were lowest at the upstream Mobil Oil site and were higher at the two downstream sites that were adjacent to iron and steel industry operations. There also was a general trend towards lower metals levels nearer the surface, suggesting that in recent years, metals contamination has declined.

The sediment age estimates presented in Figure 4 clearly will be influenced by the accuracy of the shoaling rate and consolidation estimates. The USACE

(1988) did not provide an evaluation of model accuracy. Raggio et al. (1988) also applied the HEC-6 model to the Buffalo River and found trap efficiencies estimated by the model were within 1-5% of those calculated using USACE bathymetric survey data. Our review of the literature cannot provide a good quantitative estimate of the error in the consolidation estimates. The important issue here, however, is that the sediment nearest the surface (i.e. most recently deposited) has lower metals levels.

We are not aware of metals data for the Buffalo River that would represent pre-industrial conditions. The USACE samples surface sediment in Lake Erie, about 1660 meters south west of Buffalo Harbor's south entrance, to determine the suitability of Buffalo River sediment for open lake disposal. In essence, this Lake Erie reference site is considered to reflect background conditions. Levels of Cr, Pb, and Zn for the Lake Erie reference site are 13-14 µg g^{-1}; 14-15 µg g^{-1}; and 69-71 µg g^{-1}, respectively (Engineering and Environment, 1996a). A comparison of the reference site levels with those presented in Figure 4 indicates that the metals in the river are enriched, even at the upstream (Mobile Oil) site. Enrichment is lowest near the surface at both sites as presented in Figure 4 and also at the Blue Tower site (not shown).

Relationship between metals levels in sediment cores and industrial activity

Data on industrial loadings of Cr, Pb, and Zn to the Buffalo River for the study period of interest were not available. However, industrial loading data for total Fe were available. Because Fe is an indicator metal, in particular for the iron and steel industry, total Fe loadings were used as a surrogate for industrial activity and discharge of the other metals. Total Fe loadings for the AOC were obtained from Sauer (1979) and were based on industrial discharge records or industrial production indices for times that discharge records were unavailable.

Table 3. Industrial loadings of total Fe to the Buffalo River AOC (from Sauer, 1979).

Time Period	*Total Fe (metric tons day^{-1})*
1900-1909	1.32
1910-1919	3.46
1920-1929	5.28
1930-1939	4.10
1940-1949	8.34
1950-1959	8.24
1960-1969	6.78
1970-1977	1.49

The total Fe loadings were calculated by Sauer (1979) generally for 10 year increments between 1900 and 1977 and are shown in Table 3.

Qualitatively, the levels of Cr, Pb, and Zn in the cores for the lower two areas (Blue Tower Turning Basin and Hamburg St.) corresponded to the total Fe loadings, increasing, peaking, and declining over time. Spearman Rank Correlation was calculated between the levels of Cr, Pb, and Zn and total Fe loadings for the Hamburg St. sediment cores. The correlation calculations could not be done for the Blue Tower Turning Basin or the Mobil Oil sites because the sediment cores were too short and as a result there was not a sufficient time span for reliable correlation analysis. The results of the correlation analysis are shown in Table 4. In all cases there was a positive correlation although the strength of the relationships varied by site and metal. Sediment cores 5201 and 5208 exhibited the strongest correlations and these two cores came from adjacent sample sites that were in a protected inlet and as such were shielded from perturbation due to storm events and ship traffic.

Surficial sediment quality analysis through the USACE Navigational Dredging Program

As part of its regular sediment quality assessment program on the Buffalo River navigation channel, the USACE collected surface sediment samples with a petite ponar grab sampler from 12 sites in the lower 8.9 km of the river in 1989 and 1996 (Figure 5). These samples were subjected to chemical (PAHs, PCBs,

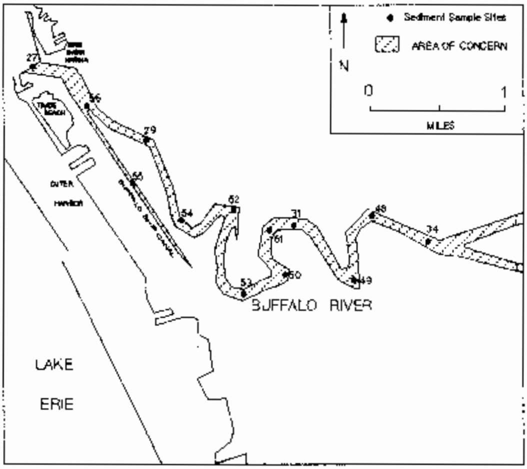

Fig. 5. Location of surficial sediment grab samples collected for the USACE.

Table 4. Spearman rank correlation between metals levels in sediment cores and total Fe loadings, Hamburg St. sample area.

Sediment Core Number and Metal	*Spearman Rank Correlation*
5201 – Cr	0.943
5201 – Pb	0.829
5201 – Zn	0.314
5205 – Cr	0.257
5205 – Pb	0.543
5205 – Zn	0.371
5206 – Cr	0.543
5206 – Pb	0.657
5206 – Zn	0.200
5208 – Cr	0.762
5208 – Pb	0.905
5208 – Zn	0.595

pesticides, metals) and particle size analyses by Aqua Tech (1989a) and Engineering and Environment (1996a). Past studies have indicated that PAHs may pose a risk to aquatic organisms (Black et al., 1980; Passino-Reader et al., 1995). But interestingly, except for Site 48, Figure 6 shows that the total concentration of 16 priority pollutant PAHs has declined throughout the reach of the navigation channel by 27 to 72 percent over the seven year period, 1989-1996. The notable increase in total PAHs at Site 48 between 1989 and 1996 appears attributable to offloading operations and possible groundwater contamination near the Mobil Oil dock located immediately upstream of this site. In addition, a 1981 sediment survey of many of the same sites showed a mean detectable total PAH concentration of 64,774 $\mu g\ kg^{-1}$ (U.S.EPA, 1983), which is much higher than the 1989 mean of 8,032 $\mu g\ kg^{-1}$ (Aqua Tech, 1989a) and 1996 mean of 4,403 $\mu g\ kg^{-1}$ (Engineering and Environment, 1996a). The overall decrease in total surface sediment PAHs appears to be associated with stricter discharge regulations and reduced industrial activities on the river, including the closing of the Republic Steel plant (1984) and the Mobil Oil refinery (1981). A similar attenuation in PAH levels was noted in Black River, Ohio, sediment samples collected between the years 1980 and 1987. This decline coincided with the closure of a local coking plant and a reduced incidence of liver tumors in brown bullhead catfish (*Ameriurus nebulosus*) (Baumann and Harshbarger, 1995). Pathology studies by Black (1983) showed elevated neoplasm frequencies in *A. nebulosus* collected at the PAH-contaminated mouth of the Buffalo River in 1980/1981. However, we are unaware of any follow-up studies to verify a reduction in the incidence of neoplasms in this species following the downscaling of industry on the river. In addition to the reduced PAH contamination, the analytical results for Fe in the Buffalo River sediment samples showed a decline in surface concentrations generally throughout the channel, evidenced by a reduction of mean concentrations from 28,767 mg kg^{-1} in 1989 to 25,500 mg kg^{-1} in 1996 (Aqua Tech, 1989a and Engineering and Environment, 1996a). Significant changes in surface concentrations of the metals As, Ba, Cd, Cu, Pb, Ni, Se, Hg and Zn were not evidenced from these data.

Bioavailability and biological effects of contaminants near the Buffalo River sediment surface

The USACE performed a study to ascertain the bioavailability of contaminants in resuspended surface sediments relative to resuspended subsurface sediments (McFarland, 1997). The premise of this study was that contaminants resuspended as a result of routine maintenance dredging processes were no more bioavailable than those resuspended at the sediment-water interface by natural processes in the same area. For this study, a benthic sled was used to obtain surface sediment and a one-meter long corer was used to obtain subsurface samples from a contaminated river site (Engineering and Environment, 1996a). To obtain the sediment samples, the benthic sled was dragged from a Boston Whaler boat

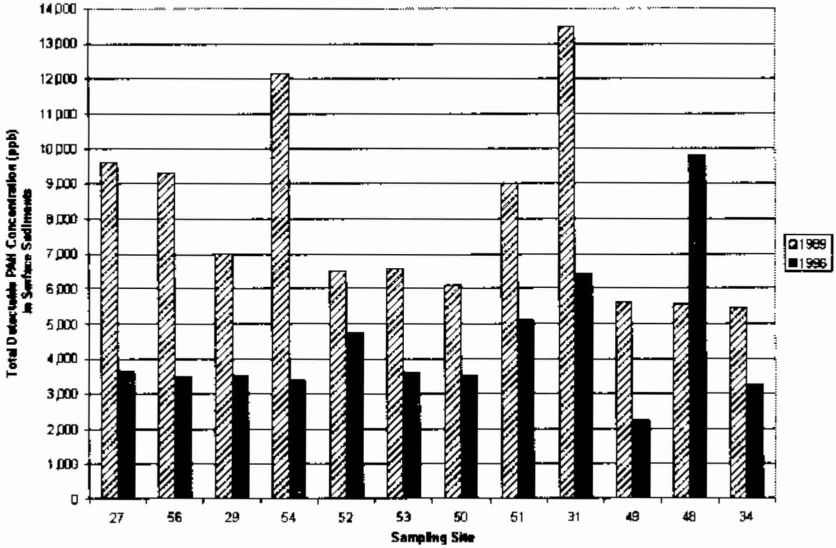

Fig. 6. Levels of total PAHs in surficial grab samples collected for the USACE, 1989 and 1996. Sample sites are arranged from downstream (site 27) to upstream (site 34).

Table 5. Comparisons of metal concentrations (μg kg^{-1}, dry weight) in surficial and core sediment samples from a contaminated site in the Buffalo River, and corresponding 28-day resuspended exposures of *C. fluminea.*

Metal	*Sediment mean (SE)* *(3 replicates)*		*C. fluminea mean (SE)* *(8 replicates)*	
	Surface	*Core*	*Surface*	*Core*
Arsenic	6,200±321.5	5,800±200.0	1,688±47.95	1,662±77.78
Lead	37,667±3,756	56,000±2,887	297[1]±	ND
Mercury	ND[2]	ND	ND	ND
Nickel	29,333±1,202	28,333±881.9	ND	ND
Zinc	113,333±6,667	130,000±5,773	18,875±854.3	20,125±548.9

[1] mean based only on three measurements (the remaining five replicates showed concentrations of lead below the MDLs of 250-300 μg kg^{-1})

[2] not detected in any sample at the respective MDL (mercury sediment – 180-190 μg kg^{-1}; mercury tissue – 200 μg kg^{-1}; nickel tissue – 1600-2000 μg kg^{-1}; lead tissue – 250-300 μg kg^{-1})

SE – standard error

Other MDLs – arsenic sediment – 540-560 μg kg^{-1}; arsenic tissue – 500-590 μg kg^{-1}; lead sediment – 270-280 μg kg^{-1}; nickel sediment – 1800-1900 μg kg^{-1}; zinc sediment – 1800-1900 μg kg^{-1}; zinc tissue – 1600-2000 μg kg^{-1}.

along the river bottom for an approximate distance of 6 meters, and the boat-mounted corer was driven approximately 0.6 meters into the bottom sediment via gravity. Historic data (Aqua Tech, 1989a) suggested that the selected sampling site (31) had the most contaminated surface sediments within the navigation channel. These samples were subjected to 28-day bioaccumulation experiments that exposed the sediments to the non-native filter-feeding clam *Corbicula fluminea*, a test species often employed as a surrogate because of its high filtration rate. *C. fluminea* also frequently is employed as a subject in bioaccumulation studies (e.g. Inza et al., 1997). These experiments were conducted in laboratory aquaria provided by the Flow-through Aquatic Toxicology Exposure System (FATES) (McFarland et al., 1985; 1994). Based on the results of the chemistry on the sediment samples, it was decided that the *C. fluminea* tissues would be analyzed for only five metals: As, Pb, Ni, Hg and Zn.

Table 5 compares the mean concentrations of these five metals in replicates from the surface and core sediment samples, and in the corresponding replicate *C. fluminea* exposures (Engineering and Environment, 1996 a, b). Lead was the only metal that showed significantly higher concentrations in the core sediment sample in comparison to the surface sample ($t=-3.87$; $P \leq 0.0180$). The concentrations of Hg and Ni in the tissue replicates were below the method detection limits (MDLs). Lead, As and Zn were measured above the MDL in some or all of the replicates, but only the concentrations of As and Zn permitted statistical analysis. ANOVAs and pairwise comparisons showed no significant difference between the bioaccumulation of metals in the surficial and core sediment samples. This study demonstrated that contaminants resuspended by routine maintenance dredging are no more bioavailable than contaminants in sediments resuspended by natural processes in the same area (McFarland, 1997). Perhaps more importantly, it also indicated that the bioavailability of contaminants in resuspended near-surface or surficial sediments is a fraction of the sediment concentration, and is limited or undetectable. The bioavailable vs. sediment concentrations of As and Zn, for example, were on a ratio of less than 0.29 and 0.17, respectively.

The majority of the surficial sediment samples collected from the Buffalo River in 1989 by Aqua Tech (1989a) also were subjected to bioassays employing the test species fathead minnow (*Pimephales promelas*), a water flea (*Daphnia magna*), and mayfly nymph (*Hexagenia limbata*). These bioassays applied the 96-hour, solid phase procedures prescribed by Prater and Anderson (1977 a,b). Using mortality as the measurement endpoint, the results of the bioassays showed no toxicity to *P. promelas* (0% mortality), and generally moderate toxicity to the latter two test species (10-40% mortality) (Aqua Tech, 1989b). These results appear consistent with the results of Nelson et al. (1993) as reported by Passino-Reader et al. (1995). Nelson et al. (1993) exposed Buffalo River sediments to the amphipod *Hyalella azteca* (14- and 28-day exposures), and the midges *Chironomus riparius* (14-day exposure) and *C. tentans* (10-day exposure). While these bioassays employed test species that were different from those used by Aqua Tech (1989b), it may be concluded that the reduced survivals (except for *C. tentans*) were indicative of an overall moderate degree of sediment toxicity.

We are not aware of any bioassay data for the period prior to the downscaling of industrial activity on the river. Nevertheless, the structure of benthic communities in terms of species richness and diversity can be used as a tool to gauge the health of an ecosystem. Passino-Reader et al. (1995) summarized results of benthic surveys dating back to the early 1960s. At the time of the earliest surveys, no benthic invertebrates were observed in the dredged section of the river, but by the late 1970s, oligochaetes and chironomids commonly were found.

It should be noted that this ecosystem recovery may be a slow process. Diggins and Stewart (1993) described the benthic community in the Buffalo River AOC as being dominated by at least 90% of pollution-tolerant oligochaetes, with the remainder being comprised mainly of Chironomids classified within the eutrophic indicator groups according to Saether (1979). Canfield et al. (1996) documented a similar community composition, but found that the Buffalo River AOC showed the largest number of benthic taxa (33) when compared to the two other AOC study sites at Saginaw River (20) and Indiana Harbor (14). It should be noted, however, that most of the genera identified at these three AOCs are considered to be tolerant to organic contamination and enrichment. Nevertheless, the midge *Tanytarsus* spp., which reportedly resides in less organically enriched environments (Krieger, 1984), was identified at both Buffalo River and Saginaw River sites.

Diggins and Stewart (1993) contend that the benthic community structure in the AOC in the early 1990s was symptomatic of a combination of industrial contamination and nutrient enrichment. The role of other abiotic and biotic factors in the reflection of benthic community composition, such as habitat conditions and season, also should not be overlooked. This may be particularly true in AOCs such as the Buffalo River because much of the benthic habitat is degraded due to its physical location in the navigation channel, and the fact that it is subjected to frequent disturbances such as vessel prop wash and bottom-dragging, and routine maintenance dredging. Canfield et al. (1996) provided evidence to support this view by using quadrant analyses to demonstrate that benthic community composition indices were less sensitive than sediment laboratory toxicity tests in screening sediment contamination. They concluded that a better understanding of non-contaminant factors is needed in order to more accurately interpret the influence of sediment contamination on benthic communities. In the case of Buffalo River, we contend that low to moderate surface sediment contamination and inhibited habitat conditions are the major variables that determine the overall structure of the existing benthic community.

Biological parameters other than benthic community structure may provide a more relevant indicator of sediment quality. A number of studies have shown an association between increased sediment contamination and the occurrence of deformities in midge (e.g. Hamilton and Saether, 1971; Wiederholm, 1984). Diggins and Stewart (1993) examined the morphological deformities of aquatic larval midges (Chironomidea: Diptera) collected from sediments in the Buffalo River AOC from 1990-1991. They found that abnormal menta (mouth parts) occurred in 29% of all specimens within the genus *Chironomus*, with a notable prevalence of abnormalities at downstream sites. This is compared to a normal abnormality frequency of 0-3% found at non-industrial sites. However, Canfield et al. (1996) found that the Buffalo River AOC consistently showed the lowest mean percentage of Chironomid deformities (7%) in comparison to the Saginaw River (17%) and Indiana Harbor (100%). Based on a criterion that the frequency of deformities in the range of 5 to 25% or greater is indicative of moderate to severe sediment contamination (Wiederholm, 1984; Warwick et al., 1987), this mean frequency of deformities suggests moderately contaminated sediments in the Buffalo River AOC.

USEPA/USACE protocols for the testing and evaluation of sediments dredged in the Great Lakes

To evaluate the quality of sediments in the navigation channels of the Great Lakes harbors and determine appropriate disposal alternatives, the USACE follows guidance contained in the *Testing Manual - Evaluation of Dredged Material Proposed for Discharge in Waters of the U.S.* (U.S.EPA and USACE, 1998a) and *Great Lakes Dredged Material Testing and Evaluation Manual* (U.S.EPA and USACE, 1998b). These manuals were prepared pursuant to the requirements of Section 404(b)(1) of the Clean Water Act, Public Law 92-500. The guidance contained therein is designed to evaluate the compliance of proposed discharges of dredged or fill material into Waters of the U.S. with the Section 404(b)(1) Guidelines (Guidelines) at 40 Code of Federal Regulation (CFR) 230.10. The protocols in these manuals essentially require that a Tier I Analysis be completed whereby the concentrations of pollutants in the navigation channel sediments be compared to those in sediments from a suitable open-water area that is used as a reference to reflect the background levels of sediment contamination. Any pollutants in the navigation channel sediments that significantly exceed those from the background area are termed "contaminants of concern" (COCs). If COCs are identified, the sediments are determined to be unsuitable for open-water disposal, or must be subjected to a Tier II Analysis and/or a Tier III Analysis. The Tier II Analysis generally focuses on the organic COCs (if present) in the sediments and applies the theoretical bioaccumulation potential (TBP) equilibrium partitioning theory-based algorithm (McFarland, 1984) as a screening tool to estimate if the bioavailability of an organic chemical in navigation channel sediments is significantly elevated when compared to the same contaminant in background sediments. The Tier III Analysis involves a suite of biological testing procedures to determine the suitability of the navigation channel sediments for disposal at a designated open-water site. Regarding Great Lakes harbors sediments, the solid phase tests in Tier III include 10-day acute toxicity tests for survival and growth of the midge *C. tentans,* survival of the amphipod *Hyalella azteca*, and a 28-day bioaccumulation test using the oligochaete *Lumbriculus variegatus* (U.S.EPA and USACE, 1998b). *C. tentans* is most sensitive to metals, *H. azteca* is most sensitive to pesticides, and the bioaccumulation test is normally run for organic COCs. In order for the sediments to be considered suitable for open-lake disposal in the Great Lakes, specific criteria must be met under the Guidelines which emphasize the comparison of the biological test results on the navigation channel sediments relative to the background sediments.

Currently, sediments dredged from the Buffalo River navigation channel officially do not meet the Guidelines and are unsuitable for open-lake disposal

(USACE, 1993). However, a Tier I Analysis on the sediments using data from Engineering and Environment (1996a) suggests that sediments dredged from the navigation channel are at a level of contamination that warrants the application of Tier III testing procedures to verify that the navigation channel sediments do not meet the Guidelines. This additional testing on the sediments is scheduled for 2002. We anticipate that the results of these tests may indicate that these sediments, or at least sediments within certain reaches of the navigation channel, will meet the Guidelines and thence be proposed suitable for open-lake disposal. This prediction is not only based on the relative levels of contaminants in the sediments, but also on the limited or negligible bioavailability of metals indicated in the 1996 bioaccumulation study (McFarland, 1997).

Recent changes in the suspended sediment load reaching the Buffalo River

It appears evident that bed sediment quality within the Buffalo River AOC has improved over the past 25 years. This improvement may be related to various factors, including a decrease in industrial activity, more stringent discharge regulations, and the operation of the BRIC (which provided a level of dilution and reduced residence time). The goal of the RAP process is to identify and implement remediation strategies to restore beneficial uses of the waterway and various bed sediment remediation strategies have been explored for the Buffalo River, from artificial armoring to environmental dredging (e.g. Averett et al., 1990; Torok, 1993). However, Irvine et al. (1997; 1999) emphasize that before remediation strategies are implemented, it is essential to understand the dynamics of the impairment sources to ensure success of the strategy. Sediment remediation is expensive and it is important that a contamination problem does not recur some years after remediation because of a lack of source control. An evaluation of the suspended sediment load entering the Buffalo River AOC therefore seems useful as a means of determining the potential success of remediation options (including the no action option of allowing cleaner sediment to naturally cap more contaminated sediment). Furthermore, while it is well-documented that many organic and inorgranic contaminants are preferentially adsorbed and transported by fine sediment (e.g. Allen, 1986; Walling, 1988), high sediment concentrations also can have negative impacts on fish species (e.g. Waters, 1995).

In this section, suspended sediment concentrations determined for the major tributaries of the Buffalo River during a sampling program conducted between 1953 and 1961 are compared with concentration data collected more recently (1989 through 1993). Rating curves are used to summarize changes in suspended sediment regime. The changes in suspended sediment regime are discussed in relation to changes in land use and implementation of soil conservation and bank stabilization programs during the period 1960 through 1993.

Sources of suspended sediment data

Sampling for suspended sediment was done at four locations (Figure 1) between July, 1992 and May, 1993 on a weekly to bimonthly basis. Samples were collected separately in Cayuga and Little Buffalo creeks because the two creeks join several meters downstream of the bridge from which samples were collected, but upstream of the USGS gauging station on Cayuga Creek. To avoid bias from incomplete mixing, samples were collected from both creeks, but rating curves were developed using the Cayuga Creek gauge station for both sites. A total of 43 samples were collected at each site, representing both storm event and inter-event conditions.

Samples of suspended sediment concentration also were collected by the NYSDEC between 1989 and 1992 at 10 different sites representing areas near the mouth of each tributary and the Buffalo River itself. These data are discussed in detail by Atkinson et al. (1994) and a summary of data availability is provided in Table 6. Sampling and analytical methods were similar for the NYSDEC program and our effort in 1992-93.

Finally, suspended sediment samples were collected by Parsons et al. (1963) during storm events at the USGS gauge stations on each of the three tributaries between 1951 and 1963. This data set facilitates the historical comparison with more recent sampling efforts, although some care must be taken in this comparison since Parsons et al. (1963) tended to focus sampling more on storm events.

Suspended sediment rating curves

Suspended sediment concentration dynamics often are evaluated using some type of least squares regression analysis because of the computational simplicity of the method. Although multiple least squares and quadratic analysis can help to explain additional variance in the data (e.g. Guy, 1964; Irvine and Drake, 1987; Mossa, 1989), and despite some limitations, simple regression rating curves most often are developed between suspended sediment concentration and discharge (Ferguson, 1986; Koch and Smillie, 1986; Irvine and Drake, 1987; Walling and Webb, 1988). Simple least squares regression was applied to the data collected between 1992 and 1993 from the four sample sites using the Minitab software package (release 8). Initially the regression was conducted on the raw data, but an examination of the form of the equations and a residual analysis indicated that some type of data transformation was necessary. Hydrologic

Table 6. Data availability, NYSDEC sampling efforts (from Atkinson et al., 1994).

Sample Location	*Number of Samples*	*Period of Record*
Cazenovia Cr. at Cazenovia Parkway	42	7/89-4/90
Buffalo River at S. Ogden St.	44	7/89-9/90
Cazenovia Cr. at Highway 62	41	1/90-7/92
Buffalo River at Highway 62	48	1/90-7/92
Cazenovia Cr. at Northrup Rd.	4	3/92-4/92
Cazenovia Cr. at Cazenovia Parkway	4	3/92-4/92
Buffalo River at S. Ogden St.	4	3/92-4/92
Buffalo Cr. at N. Blossom Rd.	4	3/92-4/92
Cayuga Cr. at Lake Ave.	4	3/92-4/92
Buffalo River at Highway 62	6	10/90-12/91
Buffalo River AOC, Sample Site 1	12	10/90-4/92

Table 7. Rating curves using logarthmically transformed data.

Sub-basin	*Regression Equation*	*Power Form of Equation*	r^2	P, b_o	P, b_1
Cazenovia Cr.	$\log SS = -1.23 + 1.01(\log Q)$	$SS = 0.059Q^{1.01}$	55	<0.001	<0.001
Buffalo Cr.	$\log SS = -1.72 + 1.19(\log Q)$	$SS = 0.019Q^{1.19}$	59	<0.001	<0.001
Little Buffalo Cr.	$\log SS = -0.788 + 0.859(\log Q)$	$SS = 0.163Q^{0.859}$	56	<0.001	<0.001
Cayuga Cr.	$\log SS = -1.65 + 1.13(\log Q)$	$SS = 0.022Q^{1.13}$	73	<0.001	<0.001

Note: Suspended sediment (SS) in this case is in mg l^{-1} and discharge (Q) is in cfs.

systems often are non-linear and in order to use simple least squares estimation techniques for the model parameters, a logarithmic transformation of the data may be employed to linearize the equations (Guy, 1964; Jansson, 1985; Koch and Smillie, 1986; Ferguson, 1987). Following exploratory evaluations with various transformations, rating curves were developed using a logarithmic (base 10) transformation of discharge and suspended sediment concentration. The general form of the regression equation using log-transformed data is:

[1] $\log_{10}SS = \log b_o + b_1 \log_{10} Q$

in which SS is estimated suspended sediment concentration (mg l^{-1}) and Q is discharge (in this case in cfs; conversion is 1 $m^3 s^{-1}$ = 35.315 cfs). The form of equation [1] often is expressed as a power function:

[2] $SS = b_o Q^{b1}$

The results of the regression analyses using the logarithmically transformed data are presented in Table 7. The level of explained variance (r^2) was less for the regressions using the transformed data than for the regressions using the raw data. Similar reductions in r^2 were reported by Irvine and Drake (1987) for the Ausable River in Southern Ontario. However, the data transformation resulted in regression analyses that more fully conformed to the assumptions made under the least squares approach.

None of the available data summarized by Atkinson et al. (1994) were collected at sites common to those from Table 7 and therefore these data were divided into two groups: Cazenovia Creek above the Buffalo River confluence and the Buffalo River and its tributaries above the confluence with Cazenovia Creek. Scattergrams of the data are shown in Figures 7 and 8 and the difference between the suspended sediment and discharge relationship for low and high flows is apparent. For each site, high flow data (above various selected low flow threshold values) were entered into a least squares regression, assuming a power function relationship as described by equation [2]. The best fit equation was determined as that with a threshold value producing the highest correlation. The arithmetic mean of the log-transformed suspended sediment data was then computed for those values below the threshold value of discharge. The point at which the high flow equation equaled the low flow mean suspended sediment value was then set as the threshold value between high and low flows (*i.e.* represented the point of intersection for the two lines). The results of these

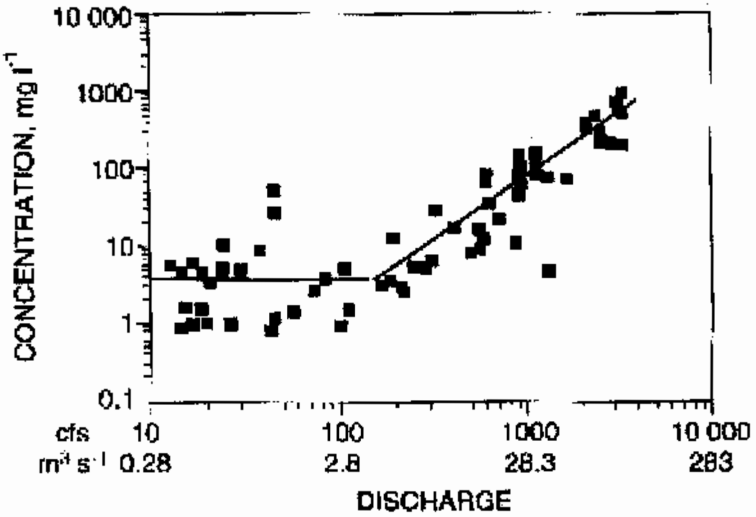

Fig. 7. Regression results for Cazenovia Creek above the Buffalo River confluence using data summarized by Atkinson et al. (1994). For $Q < 154$ cfs (4.4 $m^3 s^{-1}$), predicted sediment concentration is 4 mg l^{-1}. For $Q > 154$ cfs (4.4 $m^3 s^{-1}$), sediment concentration = $0.00120(Q)^{1.610784}$ (Q is in cfs).

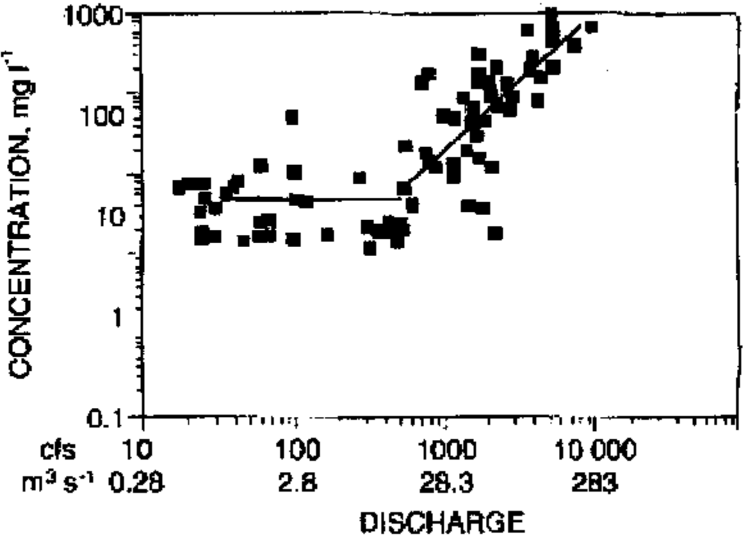

Fig. 8. Regression results for the Buffalo River and tributaries above the confluence with Cazenovia Creek using data summarized by Atkinson et al. (1994). For $Q < 403$ cfs ($11.4\ m^3\ s^{-1}$), predicted sediment concentration is12.8 mg l^{-1}. For $Q>403$ cfs ($11.4\ m^3\ s^{-1}$), sediment concentration = $0.00247(Q)^{1.425741}$ (Q is in cfs).

analyses are shown in Figures 7 and 8. It should be noted that a correction factor (after Havlicek and Crain, 1988; Newman, 1993) to account for bias due to backtransformation was applied to the results in Figures 7 and 8. Singh and Durgunoglu (1989) also observed an apparent difference in the sediment-discharge relationship for low and high flow data from Rapid Creek, Iowa and fit two regression lines (one for the lower range sediment-discharge data and one for the higher range) that intersected at the data inflection point.

Comparison of historical and recent rating curves

Parsons et al. (1963) sampled at each of the USGS gauges on the three major tributaries to the Buffalo River and developed a relationship between discharge and suspended sediment concentration having the general form:

[3] $SS = K \times Q^{0.85}$

where SS is suspended sediment concentration (mg l^{-1}), Q is discharge (cfs), and K is considered an empirical constant reflecting the relative erodibility and exposure of the soil to an eroding agent. Values of K were calculated as:

[4] $K = SS/Q^{0.85}$

Table 8. Seasonal variation in Parson's watershed erodibility factor (K).

Month	*Buffalo Cr. (K)*	*Cayuga Cr. (K)*	*Cazenovia Cr. (K)*
January	1.5	0.8	1.0
February	1.4	1.1	1.2
March	2.0	1.6	1.7
April	1.8	1.6	2.0
May	1.9	1.7	2.1
June	2.7	2.2	2.6
July	2.8	2.4	2.9
August	3.1	2.4	2.9
September	2.7	2.3	2.5
October	2.2	2.1	1.8
November	1.8	1.7	1.6
December	1.4	0.9	1.0

and these values are summarized in Table 8. There is a clear seasonal trend for K, with August values being nearly three times larger than those for January. Seasonality of erosion rates and suspended sediment concentrations also has been observed for other rivers (e.g. Guy, 1964; Irvine and Drake, 1987; Mossa, 1989; Singh and Durgunoglu, 1989) and has been related to factors including hydrometeorologic controls, agriculture, and natural plant growth. Seasonal trends were not apparent in the more recent data, possibly because of the limited number of samples collected throughout the year.

The rating curves developed by Parsons et al. (1963) for Buffalo Creek and Cazenovia Creek are plotted in Figures 9 and 10 with the rating curves developed from the more recent data represented in this study (see Table 7). As noted, recent sampling was done separately for Little Buffalo and Cayuga creeks and therefore comparisons are not made between the recent and historical (Parsons et al., 1963) studies for Cayuga Creek. The Parsons et al. (1963) study focused on storm event sampling, whereas the recent data represent a range of flows and the sampling strategy may have some influence on the final form of the rating curves. Figures 9 and 10 represent two separate rating curves from the Parsons et al. (1963) study. These curves were plotted using the maximum and minimum monthly value of K observed in the year (Table 8) to represent maximum and minimum concentration expected, given a particular discharge.

Recognizing the limitations of each data set, it nonetheless appears that the rating curves developed by Parsons et al. (1963) overestimate more recent suspended sediment concentrations. Finally, it is worth noting that Irvine (1995)

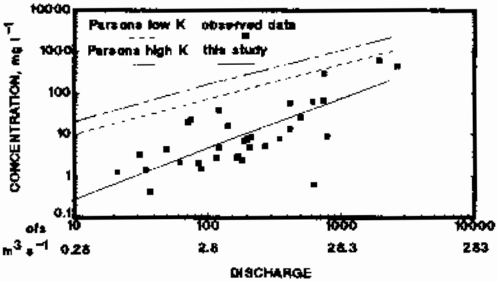

Fig. 9. Suspended sediment rating curves for Buffalo Creek. The dashed lines represent the rating curves from Parsons et al. (1963) for the same site. The lower dashed line was calculated with the minimum K value, while the higher dashed line was calculated with the maximum K value (Table 8).

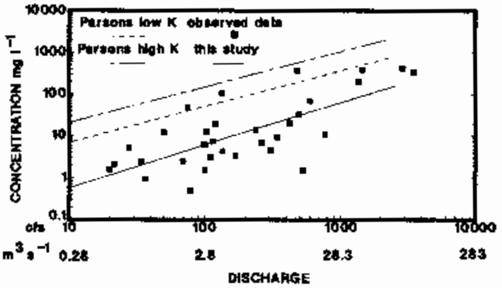

Fig. 10. Suspended sediment rating curves for Cazenovia Creek. The dashed lines represent the rating curves from Parsons et al. (1963) for the same site. The lower dashed line was calculated with the minimum K value, while the higher dashed line was calculated with the maximum K value (Table 8).

examined historical dredging records for the lower Buffalo River. The annual volume of dredged material, on average, declined from 261,393 yd^3 (199,861 m^3) between 1944 and 1955 to 97,319 yd^3 (74,410 m^3) between 1970 and 1992. Care must be exercised in this type of assessment because some of the decreased dredging activity may be related to declining ship traffic and reduced industrial discharges within the AOC. However, the general trend towards reduced dredging is in agreement with the lower suspended sediment loads that have been observed more recently.

Sources of change to suspended sediment regime

It appears that much of the suspended sediment load in the upper watershed now is derived from overland erosion rather than bed and bank entrainment. Buffalo Creek and Cazenovia Creek were part of a U.S. Department of

Agriculture Natural Resources Conservation Service (NRCS, formerly the Soil Conservation Service) bank stabilization program which began in 1953. Bank stabilization (e.g. sloping banks faced with stone) was installed on 19 miles (30.6 km) of the 21 mile (33.8 km) Buffalo Creek and 9 miles (14.5 km) of the 30 mile (48.3 km) Cazenovia Creek. Based on their sampling program, Parsons et al. (1963) concluded that the bank stabilization program had reduced suspended sediment loads in Buffalo Creek and Cazenovia Creek by 40% and 10%, respectively. Sampling of the bed material in each of the three major tributaries to the Buffalo River indicates that over 60% of stream bottoms consist of resistant bedrock (Pettibone and Irvine, 1994; Sargent, 1975).

With relatively less input of suspended sediment from bed and bank erosion the reduction of suspended sediment load in Cazenovia Creek and Buffalo Creek since the early 1960s appears related to two factors: increasing implementation of BMPs; and decline in cultivated acreage. In an analysis of 477 farm tracts that had a field edge within 1,000 ft (305 m) of a Buffalo River tributary, Monahan et al. (1994) found that 89% of the tracts had a grass buffer of 20-100 ft (6-30 m) to filter sediment before reaching the water. Furthermore, 105 of the 477 tracts were considered Highly Erodible Land under the NRCS soil loss definition and some type of conservation practice was listed as being in place on all of these tracts.

Although data are not specifically available for the Buffalo River watershed, Monahan et al. (1995) showed that the farm acreage under production in Erie County declined monotonically from 289,889 acres (117,318 ha) in 1959 to 145,679 acres (58,956 ha) in 1992. The Buffalo River watershed covers about one-third of Erie County and it is expected that the trends for the entire county would be similar at the watershed level. Erie County experienced extensive suburban expansion since the 1950s at the expense of farmland conversion (Erie County DEP, 1991). In general, soil loss from cultivated land is greater than from idle (or abandoned) farmland or suburban surfaces. The reduction in cultivated acreage since 1959 therefore also may account partially for the lower suspended sediment concentrations (cf. Walling, 1988; Marsh, 1991; Kuhnle et al., 1996).

Conclusions

The city of Buffalo, like many other cities around the Great Lakes, has experienced a rise and subsequent decline in the importance of heavy industry within its economic structure. This trend, together with increasingly stringent discharge regulations and BMPs, is reflected in the bed sediment record of the Buffalo River Area of Concern. In general, habitat, sediment, and water quality have improved within the Area of Concern over the past 25 years. Although bed sediment quality has improved, the concentrations of some contaminants still pose a level of risk to aquatic organisms.

The question then remains, how best to manage this risk to aquatic organisms? It appears that sediment loads from the upper watershed have become smaller in recent years, but we are aware of only one study that analyzed the quality of suspended sediment directly and this was done for PAHs, PCBs, and pesticides (Atkinson et al., 1994). Therefore, it is difficult to document any changes in suspended sediment quality or to absolutely define the quality of sediment entering the AOC. Irvine (1997) noted levels of some contaminants, such as Pb, in whole water samples appear to have declined over the past 30 years and certainly surficial sediment within the AOC is cleaner than historical deposits. It would be useful, however, to more rigorously sample suspended sediment quality entering the AOC to support the selection of appropriate sediment management scenarios.

High levels of contamination below the cleaner surficial layer may extend to a depth of 2 m (approximately 6 ft) in some areas of the river (SAIC, 1996) and the cost of remediating such a large volume of sediment likely is prohibitive. The best course of action *may be* a combination of "hotspot" remediation (either in situ or environmental dredging) and "no action". With the latter option, the more recent, cleaner sediment depositing in the Area of Concern would provide a natural armored layer, separating the more contaminated sediment below, from aquatic organisms and the water column. This scenario would require a more detailed study prior to implementation. It also is unclear whether trends towards improved water quality would continue given changes in land use within the watershed. However, the NYSDEC and other agencies appear to be committed to implementing programs such as TMDL analysis to maintain the higher order (A or B) best uses in the upper watershed.

References

Adams, E.D., 1927. *Niagara Power,* Volume I, Bartlett Orr Press, New York, NY, 455p.

Allen, R.J., 1986. The Role of Particulate Matter in the Fate of Contaminants in Aquatic Ecosystems. Scientific Series No. 142, Inland Waters Directorate, Burlington, ON, 128p.

Aqua Tech., 1989a. The Analysis of Sediments from Buffalo River and Harbor, Buffalo, New York (Sediment Chemistry). Technical report prepared under contract to USACE. 86 p.

Aqua Tech., 1989b. The Analysis of Sediments from Buffalo Harbor (Bioassay). Technical report prepared under contract to USACE. 14 p.

Atkinson, J.F., Bajak, T., Morgante, M., Marshall, S., DePinto, J.V., 1994. Model Data Requirements and Mass Loading Estimates for the Buffalo River Mass Balance Study. U.S. EPA Report EPA 905-R94-005.

Averett, D.E., Perry, B.D., Torrey, E.J., Miller, J.A., 1990. Review of Removal, Containment and Treatment Technologies for Remediation of Contaminated Sediment in the Great Lakes.

Miscellaneous Paper EL-90-25. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Baumann, P.C., Harshbarger, J.C., 1995. Decline in liver neoplasms in wild brown bullhead catfish after coking plant closes and environmental PAHs plummet. Environmental Health Perspectives 103, 168-170.

Black, J., 1983. Field and laboratory studies of environmental carcinogenesis in Niagara River fish. J. Great Lakes Res. 9(2), 326-334.

Black, J.J., Holmes, M., Dymerski, P.P., Zapisek, W.F., 1980. Fish tumor pathology and aromatic hydrocarbon pollution in a Great Lakes estuary. In: B.K. Afghan, D. Mackay (Eds.), *Hydrocarbons and Halogenated Hydrocarbons in the Aquatic Environment,* pp. 559-565. Plenum Press, New York.

Bokuniewicz, H.J., Gebert, J., Gordon, R.B. and others, 1977. Field study of the effects of storms on the stability and fate of dredged material in subaqueous disposal area. In: *Subaqueous Capping of Contaminated Sediments: Annotated Bibliography,* published abstract.

Canfield, T.J., Dwyer, J., Fairchild, J.F., Haverland, P.S., Ingersoll, C.G., Kemble, N.E., Mount, D.R., La Point, T.W., Burton G.A., Swift, M.C., 1996. Assessing contamination in Great Lakes sediments using benthic invertebrate communities and the sediment quality triad approach. J. Great Lakes Res. 22(3), 565-583.

Crane, J.L., 1993. Baseline Human Health Risk Assessment: Buffalo River, New York, Area of Concern. U.S. EPA Report EPA 905-R93-008.

DePinto, J.V., Morgante, M., Zaraszczak, J., Bajak, T., Atkinson, J.F., 1995. Application of Mass Balance Modeling to Assess Remediation Options for the Buffalo River. U.S. EPA Report EPA 905-R-95-007.

Diggins, T.P., Stewart, K.M., 1993. Deformities of aquatic larval midges (Chirononidea: Diptera) in the sediments of the Buffalo River, New York. J. Great Lakes Res. 19(4), 648-659.

Engineering and Environment, 1996a. Sediment Sampling for Chemical and Particle Size Analysis, Buffalo River, New York. Report prepared under contract for USACE, Buffalo District.

Engineering and Environment, 1996b. Buffalo River Bioaccumulation Study. Report prepared under contract for USACE, Buffalo District.

Erie County DEP (Erie County Department of Environment and Planning), 1991. Residential Development Trends Study, Erie County, New York, 69p.

Ferguson, R.I., 1986. River loads underestimated by rating curves. Water Resources Research, 22(1), 74-76.

Ferguson, R.I., 1987. Accuracy and precision of methods for estimating river loads. Earth Surface Processes and Landforms, 12,95-104.

Gabler, R.E., Sager, R.J., Wise, D.L., 1997. *Essentials of Physical Geography,* 5th edition, Saunders College Publishing, New York, 587p.

Goldman, M., 1983. *High Hopes – The Rise and Decline of Buffalo, New York,* State University of New York Press, Albany, NY, 324p.

Guy, H.P., 1964. An Analysis of Some Storm-period Variables Affecting Stream Sediment Transport. U.S. Geological Survey Professional Paper 462-E, 40p.

Hall, G.R., 1955. Buffalo Creek Watershed Sediment Problems and Channel Geometry. Report for the Erie County Soil and Water Conservation Service, East Aurora, NY, 11p.

Hamilton, A.L., Saether, O.A., 1971. The occurrence of characteristic deformities in the chironomid larvae in several Canadian lakes. Can. Int. 103, 363-368.

Havlicek, L.L., Crain, C.R., 1988. *Practical Statistics for the Physical Sciences,* American Chemical Society, Washington, D.C.

Hill, H.W., 1923. *Municipality of Buffalo, New York – A History 1720-1923,* Volume II, Lewis Historical Publishing Co., New York and Chicago.

(IJC) International Joint Commission, 1987. Revised Great Lakes Water Quality Agreement of 1978. International Joint Commission, Windsor, ON.

Inza, B., Ribeyre, F., Maury-Brachet, R., Boudou, A., 1997. Tissue distribution of inorganic mercury, methylmercury and cadmium in the Asiatic clam (*Corbicula fluminea*) in relation to the contaminantion levels of the water column and sediment. Chemosphere 35(12), 2817-2836.

Irvine, K.N., 1995. Part I: Evaluation of suspended sediment dynamics and siltation rates. Fish and Wildlife Habitat Assessment of the Buffalo River Area of Concern and Watershed. Report to the U.S. EPA, Great Lakes National Program Office, 53p.

Irvine, K.N., 1997. Cazenovia Creek Watershed Management Program: Baseline Water Quality Analysis, 1996. Report to the Erie County Department of Environment and Planning, 61p.

Irvine, K.N., Drake,, J.J. 1987. Process-oriented estimation of suspended sediment concentration. Water Resources Bulletin, 23(6), 1017-1025.

Irvine, K.N., Pettibone, G.W., 1996. Planning level evaluation of indicator bacteria densities and sources in a mixed land use watershed. Environmental Technology, 17,1-12.

Irvine, K.N., Droppo, I.G., Murphy, T.P., Lawson, A., 1997. Sediment resuspension and dissolved oxygen levels associated with ship traffic: Implications for habitat restoration. Water Quality Research Journal of Canada, 32(2), 421-437.

Irvine, K.N., Droppo, I.G., Murphy, T.P., 1999. Contaminant levels and loading estimates: The first step in identifying restoration options for a Great Lakes Area of Concern. In: T.P. Murphy, M. Munawar, (Eds.) *Aquatic Restoration in Canada,* pp. 51-68. Backhuys Publishers, The Netherlands.

Jansson, M., 1985. A comparison of detransformed logarithmic regressions and power function regressions. Geografiska Annaler, 67A(1-2), 61-70.

Kessel, W.N., 1923. Chemical and Related Industries of Buffalo and the Niagara Frontier, Buffalo Chamber of Commerce Industrial Bureau.

Koch, R.W., Smillie, G.M., 1986. Bias in hydrologic prediction using log-transformed regression models. Water Resources Bulletin, 22(5), 717-723.

Krieger, K.A., 1984. Benthic macroinvertebrates as indicators of environmental degradation in the southern nearshore zone of the Central Basin of Lake Erie. J. Great Lakes Res. 10, 197-209.

Kuhnle, R.A., Bingner, R.L., Foster, G.R., Grissinger, E.H., 1996. Effect of land use changes on sediment transport in Goodwin Creek. Water Resources Research, 32(10), 3189-3196.

MacRae's State Industrial Directory, 1991. MacRae's Blue Book, Inc., New York, NY, 986p.

Marsh, W.M., 1991. *Landscape Planning Environmental Applications*, Second Edition, pp. 461-467. John Wiley and Sons, New York, ch. 12.

McFarland, V.A., 1984. Activity-based evaluation of potential bioaccumulation from sediments. In: R.L. Montgomery, J.W. Leach. (Eds.) *Dredging '84*, Vol. 1, American Society of Civil Engineers, New York, New York.

McFarland, V.A., 1997. Relative Bioaccumulation of Contaminants from Resuspended Buffalo River/ Ship Canal Dredged Sediment vs. Sediments Resuspended by Ambient Conditions. Technical Report prepared for USACE, Buffalo District.

McFarland, V.A., Clarke, J.U., Gibson, A.B. 1985., Bioaccumulation of polychlorinated biphenyls (PCBs) from Sheboygan Harbor sediments in laboratory exposures. Report prepared for U.S. Army Engineer Division, North Central, Detroit, Michigan.

McFarland, V.A., Clarke, J.U., Lutz, C.H., Jarvis, A.S., Mulhearn, B., Reilly, F.J., 1994. Bioaccumulation potential of contaminants from bedded and suspended Oakland Harbor Deepening Project sediments in San Francisco Bay flatfish and bivalve mollusks. Miscellaneous Paper EL 94-7. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

McIntyre, W., 1952. Niagara Falls power development. Economic Geography, 28(3), 261-273.

Meredith, D.D., Rumer, R.R., 1987. Sediment Dynamics in the Buffalo River, Report, Department of Civil Engineering, SUNY at Buffalo, 171p.

Monahan, K.M., Fischer, S., Irvine, K.N., 1994. Spatial analysis of suspended sediment concentrations, Buffalo River Watershed, NY. Middle States Geographer, 27, 1-9.

Monahan, K.M., Miller, K., Irvine, K.N., Whitney, J., 1995. Analysis of the 1993 farmland protection survey for Erie County, NY. Middle States Geographer, 28, 28-36.

Mossa, J., 1989. Hysteresis and nonlinearity of discharge-sediment relationships in the Atchafalaya and lower Mississippi rivers. Sediment and the Environment, IAHS Publication No. 184, pp. 105-112.

Nelson, M.K. and six co-authors. 1993. Whole sediment toxicity tests. In: C.G. Ingersoll, D.R. Buckler, E.A. Crecelius, and T.W. La Point. (Eds.) *Biological Assessment of Contaminated Great Lakes Sediment,* U.S. EPA Report EPA-905-R93-006.

Newman, M.C., 1993. Regression analyses of log-transformed data: Statistical bias and its correction. Environmental Toxicology and Chemistry, 12(6), 1129-1133.

NYSDEC (New York State Department of Environmental Conservation), 1989. Buffalo River Remedial Action Plan, Stage I Report.

NYSDEC, 1996. The 1996 Priority Waterbodies List for the Niagara River-Lake Erie Basin. Division of Water.

Parsons, D.A., Apman, R.P., Decker, G.H., 1963. The determination of sediment yields from flood water sampling. Land Erosion, Precipitation, Hydrometry, Soil Moisture, IASH Publication No. 65, pp. 7-15.

Passino-Reader, D.R., Hudson, P.L., Hickey, J.P., 1995. Baseline Risk Assessment for Aquatic Life for the Buffalo River, New York Area of Concern. U.S. EPA Report EPA 905-R95-001.

Paterson, J.H., 1994. *North America: A Geography of Canada and the United States*, Oxford University Press, New York, NY, 497p.

Perrier, R., Quibler, J., 1974. Thickness changes in sedimentary layers during compaction history: Methods for quantitative evaluation. American Association of Petroleum Geologists, 58(3), 507-520.

Pettibone, G.W., Irvine, K.N., 1994. Levels and Sources of Indicator Bacteria Associated with the Buffalo River Area of Concern. Report to the U.S. EPA, Great Lakes National Program Office, 118p.

Prater, B.L., Anderson, M., 1977a. A 96-hour sediment bioassay of Otter Creek, Ohio. J. Water Poll. Cont. Fed. 49(10), 2099-2106.

Prater, B.L., Anderson, M., 1977b. A 96-hour sediment bioassay of Duluth and Superior Harbor basins using *Hexagenia limbata, Asellus communis, Daphnia magna* and *Pimephales promelas* as test organisms. Bull. Environ. Contam. Toxicol. 18(2), 159-169.

Pratt, E.J., Irvine, K.N., Marshall, S., Loganathan, B.G., Kumar, S., Sikka, H.C., 1995. Planning level estimates of heavy metals (Pb and Cu), total PCBs and HCB loadings to the Buffalo River, NY, from combined sewer overflows. In: W. James, (Ed.), *Modern Methods for Modeling the Management of Stormwater Impacts*, Ann Arbor Science, Ann Arbor, MI, ch. 9.

Raggio, G., Jirka, G., Pacenka, S., 1988. Modeling and Field Studies of Sediment Transport in the Buffalo River, Erie County, NY. Report, New York State Water Resources Institute, Cornell University, 77p.

Ristow, W.W., 1970. U.S. Fire Insurance Maps. Surveying and Mapping 1852-1968, 30, 19-29.

Rossi, M.C., 1995. The history of sewage treatment in the city of Buffalo, NY. Middle States Geographer, 28, 9-19.

Rossi, M.C., 1998. An Historical Evaluation of Industrial Growth and its Environmental Impacts on the Buffalo River, New York. Unpubl. M.S. Thesis, Buffalo State College, 169p.

Saether, O.A., 1979. Nearctic chironomids as indicators of lake typology. Verh. Internat. Verein. Limnol. 19, 1955-1963.

Sargent, D.H., 1975. Water Pollution Investigation: Buffalo River. U.S. EPA Report EPA-905/9-74-010.

Sauder, R.A., 1980. The use of Sanborn Maps in reconstructing "geographies of the past": Boston's waterfront from 1867-1972. Journal of Geography, November, 204-213.

Sauer, D.E., 1979. An Environmental History of the Buffalo River. Buffalo Color Corporation, 88p.

SAIC (Science Applications International Corporation), 1996. Assessment of Sediment in the Buffalo River Area of Concern. U.S. EPA Report EPA 905-R96-011.

Singer, J.K., Irvine, K.N., Snyder, R., Shero, B., Manley, P., McLaren, P., 1995. Fish and Wildlife Habitat Assessment of the Buffalo River Area of Concern and Watershed. Report to the U.S. EPA, Great Lakes National Program Office.

Singh, K.P., Durgunoglu, A., 1989. Developing accurate and reliable stream sediment yields. Sediment and the Environment, IAHS Publication No. 184, pp. 193-199.

Stokoe, P.K., 1993. Development Potential and Other Benefits from Restoration, Enhancement, and Protection of Great Lakes Basin Watersheds. Hickling Corporation, Toronto, ON, 191p.

Strohmeyer, J. 1986. *Crisis in Bethlehem*, Adler and Adler, Inc., Bethesda, MD, 242p.

Sweeney, R.A., 1970. Survey of Benthic Macroinvertebrates and Analysis of Water and Sediment from the Buffalo River, 1969. Great Lakes Laboratory, Special Report #2, 23p.

Symons, G.E., 1940. Report on Buffalo River Stream Pollution Studies 1936-1939. Report to the Buffalo Sewer Authority, 24p.

Symons, G.E., 1946. Final Report on Buffal River Stream Pollution Studies in 1946. Report to the Buffalo Sewer Authority, 17p.

Thompson, J.H., (Ed.). 1986. *Geography of New York State*, Syracuse University Press, Syracuse, NY 543p.

Torok, D., 1993. Artificial Armoring of Buffalo River Sediments and Contaminated Sediment Remediation. Unpubl. M.A. Thesis, Buffalo State College, 133 p.

Ullman, J.E., 1988. *Anatomy of Industrial Decline*, Quorem Books, New York, NY, 201p.

USACE (U.S. Army Corps of Engineers), 1988. Buffalo River Sedimentation Study. Buffalo District, Report, 37p.

USACE, 1993. Environmental Assessment and Section 404(b)(1) Evaluation, Operation and Maintenance, Buffalo Harbor, Black Rock Channel and Tonawanda Harbor.

U.S. Department of Agriculture, 1986. Soil Survey of Erie County.

U.S. EPA (U.S. Environmental Protection Agency), 1983. Buffalo, New York, Area Sediment Survey (BASS). Report prepared for U.S. EPA Great Lakes National Program Office.

U.S. EPA, 1994. Assessment and Remediation of Contaminated Sediments (ARCS) Program, Final Summary Report. EPA 905-S-94-001. U.S. EPA.

U.S. EPA and USACE, 1998a. Evaluation of Dredged Material Proposed for Discharge in Waters of the U.S. – Testing Manual.

U.S. EPA and USACE, 1998b. Great Lakes Dredged Material Testing and Evaluation Manual.

Vink, J.P.M., Winkels, H.J., 1994. In-situ consolidation of lake deposits: An empirical model to reconstruct pollution history. Water Resources Bulletin, 30, 631-638.

Walling, D.E., 1988. Erosion and sediment yield research – some recent perspectives. Journal of Hydrology, 100, 113-141.

Walling, D.E., Webb, B.W., 1988. The reliability of rating curve estimates of suspended sediment yield: Some further comments. Sediment Budgets, IAHS Publication No. 174, pp. 337-350.

Warwick, W.F., Fitchko, J., McKee, P.M., Hart, D.R., Burt, A.J., 1987. The incidence of deformities in *Chironomus* sp. from Port Hope Harbour, Lake Ontario. J. Great Lakes Res. 13, 88-92.

Waters, T.F., 1995. *Sediment in Streams Sources, Biological Effects and Control*, American Fisheries Society, Monograph 7, Bethesda, MD 251p.

Wiederholm, T., 1984. Incidence of deformed chironomid larvae (Diptera: Chironomidae) in Swedish Lakes. Hydrobiologica 109, 243-249.