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Sampling and Modeling Approaches to Assess Water Quality Impacts of Combined Sewer Overflows—The Importance of a Watershed Perspective

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ABSTRACT. *As part of the planning effort for combined sewer overflow (CSO) abatement, a combination of sampling and mathematical modeling was used to characterize both CSO and receiving water quality in the city of Buffalo, NY. Samples collected during storm events showed that while CSOs within the city boundary are a source of fecal coliform to the Buffalo River, higher concentrations enter the river from the upper watershed, upstream of the city. Loading estimates of Pb, Zn, Cu, and Hg were made for design storms and on an annual basis using a combined model and sampling approach. While the metals loads were quantifiable from the CSOs, the loads associated with the upper watershed discharge were greater, for example, by a factor of 3 to 18 times for the design storms. Continuous, automated sampling of conventional parameters at 15 minute time steps indicated that the river experienced non-compliant periods for dissolved oxygen. In some cases, low dissolved oxygen levels may be associated with CSO inputs, but the hydraulics of the river system also had an important negative impact on dissolved oxygen. In developing CSO abatement options for the Buffalo River, it is essential to recognize that there are other significant contaminant sources in the upper watershed that will continue to negatively impact water quality.*

INDEX WORDS: *Combined sewer overflow, watershed planning, receiving waters, fecal coliform, metals, dissolved oxygen.*

INTRODUCTION

The U.S. Environmental Protection Agency (U.S. EPA) reported more than 750 communities and 40 million people throughout the continental U.S. are serviced by combined sewer systems, with the majority of these systems located in the northeastern and Great Lakes states (http://cfpub.epa.gov/npdes/cso/demo.cfm?program_id=5). More than half of the Remedial Action Plans (RAPs) for Great Lakes Areas of Concern (AOCs) indicate that combined sewer overflows (CSOs) are one potential cause of beneficial use impairment. Concern about the negative impacts of CSOs on receiving water bodies resulted in the U.S. EPA issuing the National Combined Sewer Overflow Control Strategy in 1989. This strategy subsequently was refined through the Combined Sewer Overflow Control Policy of 1994 (40 CFR Part 122). The intent of this policy was to establish a consistent national approach for controlling CSOs through more effective implementation of the NPDES (National Pollutant Discharge Elimination System) permit program.

One of the requirements of the 1994 Control Policy is that the agency responsible for operation of the combined sewer system must develop a Long Term Control Plan (LTCP) for CSO abatement. The U.S. EPA (1999) developed a guidance document as a reference for municipalities that had to undertake an LTCP. While the guidance provided the responsible agency with some latitude in the approach taken to developing an LTCP, there were certain considerations central to the LTCP philosophy. First, the

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quantity and quality of flow in the combined sewer system must be characterized. Second, the responsible agency must characterize and monitor receiving water impacts. Third, the U.S. EPA (1999, 2001a) recognized that urban receiving water quality may be affected by contaminant sources in addition to CSOs and therefore recommended that the LTCP take a watershed approach that considered other point and nonpoint control activities. The U.S. EPA has actively promoted a watershed approach because "*. . . it considers all activities within a landscape that affect watershed health. Ideally, a watershed approach will integrate biology, chemistry, economics, and social considerations into decision-making"* (U.S. EPA 2001b). Finally, mathematical models frequently are employed as one tool to help assess sources, transport, and fate of contaminants in the environment and the U.S. EPA (1999) encouraged the use of models to explore the dynamics of pollutant loads under baseline and competing CSO abatement scenarios.

The city of Buffalo, NY, is serviced by a combined sewer system that potentially discharges to local waterbodies at 58 locations during storm events. There are more than 1,355 km of sewer lines in the city, the majority of which (1,274 km) represent a combined system. This system is aging, with approximately 60 percent of the lines being constructed prior to 1910 and only eight percent being constructed since 1941 (Malcolm Pirnie, Inc. 2001a). The city's sewage treatment plant is the second largest in New York State and the 20th largest in the United States, with an average daily design capacity for secondary treatment of 7.88 m^3/s (180 MGD). The city initiated development of an LTCP in 2000 which included an extensive sampling and modeling program to characterize the levels and loads of contaminants in the CSOs and receiving waters. Sampling was done for a variety of contaminants, including PCBs, PAHs, pesticides, metals, nutrients, fecal coliform, and conventional parameters. This paper focuses on the results of the sampling and modeling for an area in south Buffalo that has 33 CSOs potentially discharging to the Buffalo River AOC and illustrates why it is important to take a watershed approach when identifying and assessing CSO abatement options for a community.

STUDY APPROACH

Study Area

The city of Buffalo, NY, is located at the eastern end of Lake Erie (Fig. 1) and has a climate that 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. The population of the city, according to the 2000 census was 292,648, while the metropolitan statistical area of Buffalo had a population of 1.1 million. The southern part of the city, in the area of the Buffalo River, developed a heavy industry base in the mid-1800s to early 1900s that included chemical and dye production, petroleum refining, and steel production (Rossi 1996, Irvine *et al.* 2003a). For the past 20 years, industrial activity has declined to the point that petroleum refining and steel production no longer occur.

The lower 9 km of the Buffalo River were designated an AOC by the International Joint Commission because of various use impairments that included loss of habitat, degradation of benthos, fish tumors, advisories on fish consumption, and restrictions on disposal of dredged sediment. The New York State Department of Environmental Conservation (NYSDEC) developed a Stage I RAP that indicated the potential contaminant sources to the AOC included inactive hazardous waste sites, direct industrial discharge of non-contact cooling water, historically contaminated bed sediment, combined sewer overflows, and unidentified point and nonpoint sources from the upper watershed (NYSDEC 1989). Early work to address remediation options for the river indicated that point and nonpoint contaminant sources from the upper watershed could be as important as the sources within the AOC (Atkinson *et al.* 1994, DePinto *et al.* 1995, Irvine and Pettibone 1996). Much of the AOC is a federally-designated navigable channel and as such is maintained at a minimum depth of 6.7 m through dredging operations overseen by the U.S. Army Corps of Engineers. The dredging operations have increased the hydraulic radius of the channel, thereby reducing flow velocity and promoting sediment deposition.

The Buffalo River watershed is 1,155 km^2 in area and the Buffalo River has three major tributaries (Cazenovia Creek, Cayuga Creek, Buffalo Creek), each of which has a U.S. Geological Survey (USGS) gauge station that continuously measures flow (Fig. 2). Land use within the watershed varies. Much of the upper watershed is characterized by woods and farmland, but prior to joining the Buffalo River the creeks pass through several small communities and receive industrial, commercial, residential, and municipal discharges (Irvine and Pettibone 1996).

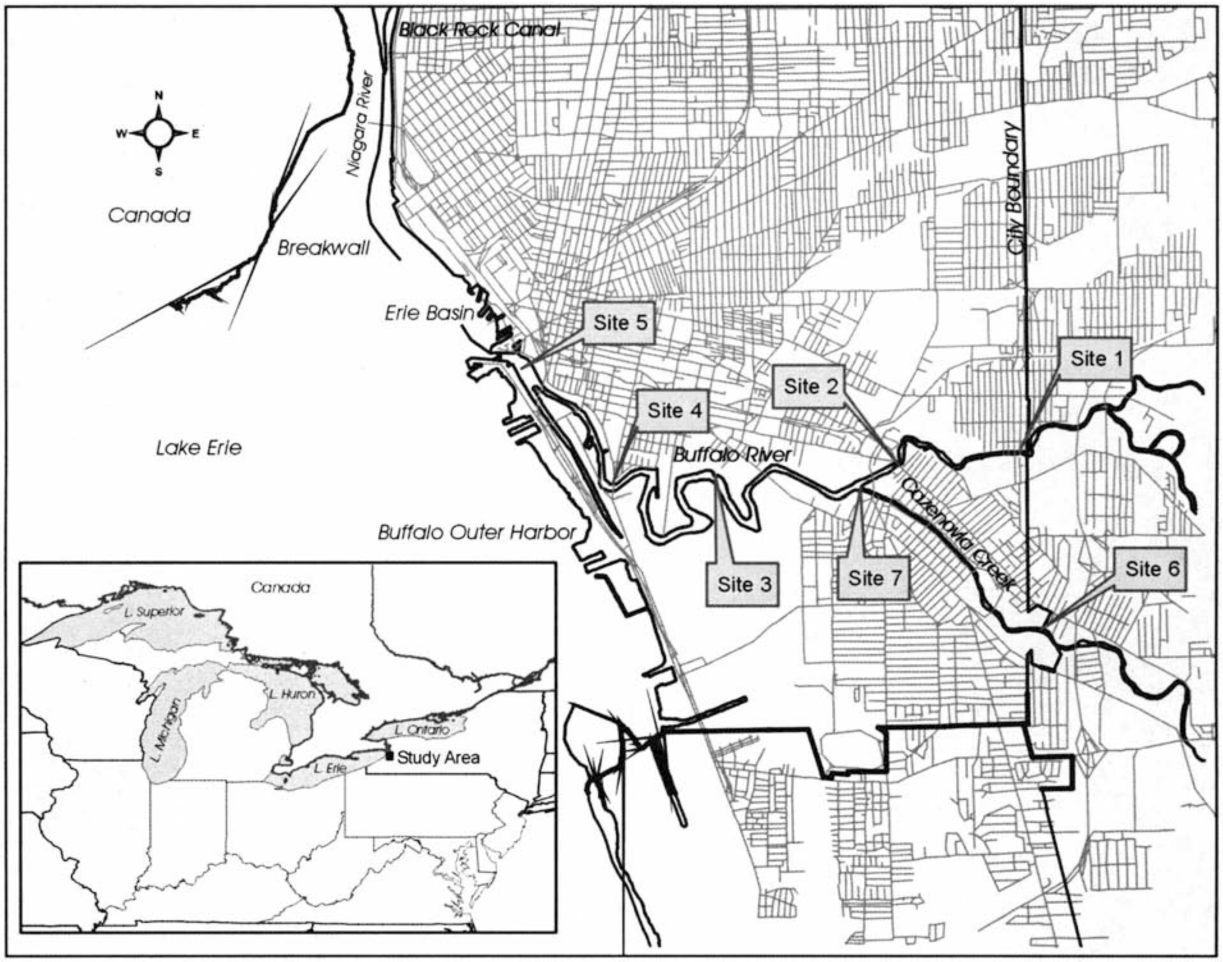

FIG. 1. ***Study area (inset) and water quality sampling locations in the Buffalo River.***

Sampling and Analytical Methods

Water quality samples were collected at seven sites in the Buffalo River (Fig. 1) and 11 sites within the south Buffalo sewer system during two overflow events (9–11 July 2000; 23–25 August 2000) and two dry weather periods (4 May 2000; 7 September 2000). Samples also were collected at several of the sewer sites during the CSO event of 7 August 2000, but because of the short event duration samples were not collected in the receiving waters. Malcolm Pirnie, Inc. (2001a) provided a detailed account of sampling methodology, but briefly, storm samples in the sewer system were collected manually at 15-minute intervals for a maximum of 5 hours, or until the CSO ceased, whichever was the shorter time. At "non-intensive" sewer sample locations, two time-based composite samples were collected, one for first flush (FF) and one for rest of storm (ROS). The FF samples were collected every 15 minutes for the first 45 minutes of the overflow and analyzed separately, while the ROS samples subsequently were collected every 15 minutes and composited into one container. At "intensive" sites samples were collected at 15-minute intervals and analyzed separately. Samples for dry weather dates were single grab samples. Manual samples were collected using Teflon bailers and samples were kept on ice in the field.

Receiving water samples at sites 1 and 6 were collected from a bridge at the mid-point of the channel using Teflon bailers, while samples at the other sites were collected from a boat using a Sigma pump sampler equipped with teflon tubing (except for fecal coliform, semivolatile organic compounds, and PCBs which were collected manually). For wet weather events, samples were collected at intervals of 1, 2, 3, 4, 6, 12, 18, 24, 36, and 48 hours after the first CSOs were reported. For

TABLE 1. List of parameters analyzed in the study.

Parameter List		
Fecal Coliform	Fe, total and dissolved	PCBs/pesticides
BOD	Pb, total and dissolved	Total Cyanide
Total Suspended Solids	Hg, total and dissolved	Total Phenols
Total Settleable Solids	Ni, total and dissolved	Total Phosphorus
Cd, total and dissolved	Zn, total and dissolved	Nitrate/Nitrite
Cr, total and dissolved	EPA 625 Scan (e.g. PAHs, benzenes, phenols)	Kjeldhal Nitrogen
Cu, total and dissolved	EPA 625 Scan (with anilines)	Ammonia Nitrogen

"intensive" sites (1, 3, 5, 6) all samples were analyzed separately. For "non-intensive" sites (2, 4, 7) samples were composited and analyzed as follows (except for fecal coliform which were analyzed as individual samples): first four samples (hours 1, 2, 3, and 4) composited together; next four samples (hours 6, 12, 18, and 24) were composited together; last two samples (hours 36 and 48) were composited together. Samples for dry weather dates were single grab samples. All samples were kept on ice in the field.

The list of analytes for this project is shown in Table 1. All analyses were done by New York State Health Department certified laboratories, following U.S. EPA-approved methods. All analytical and QA/QC data were reviewed by a subcommittee of the project that consisted of environmental engineers, chemists, and environmental scientists. Details of the analytical methodologies were provided in Malcolm Pirnie, Inc. (2001a) and in consideration of space are not discussed here.

Hydrolab Datasonde 4a's were installed at all receiving water sampling locations to monitor pH, conductivity, turbidity, temperature, and dissolved oxygen. All Hydrolabs were installed so that they were contained within a capped PVC tube. The lower section of the PVC tube had holes drilled through it to allow the water to move freely past the Hydrolab sensors. The PVC tubes protected the Hydrolabs from damage due to floating storm debris and the locked caps provided a level of security from tampering. At all sites except site 5, the PVC tube was fixed to a stationary object (e.g., bridge abutment, sewer grate) so that the sensors would be approximately 1.0 m below the March low water datum. The Hydrolab at site 5 was attached to a buoy so that the depth of measurement always was 1.0 m below the surface. Complete monitoring began on 17 April 2000 and concluded on 18 November 2000, a total of 30 weeks. The Hydrolabs were programmed to record data at 15-minute time steps and routine maintenance and data downloading was done on a weekly basis.

Model Application

Two different models were applied in this study; XP-SWMM (Stormwater Management Model) was used to generate flow rates and volumes associated with the CSOs, while the BASINS (Better Assessment Science Integrating point and Nonpoint Sources) version of HSP-F, release 2, was used to estimate flow rates and volumes associated with runoff from the upper watershed entering the Buffalo River AOC. The XP-SWMM model was calibrated using sewer flow data collected by Sigma 920 or 950 area-velocity meters at 51 locations throughout south and central Buffalo. The sewer flow data were collected at 15-minute intervals between 1 May 2000 and 17 November 2000. The BASINS model was calibrated using the daily mean flow from the USGS gauge stations on the three tributaries (Fig. 2) for the periods 1 May through 31 October 1990, 1992, and 1995. These years were chosen because they represented average hydrologic conditions (1990), wet hydrologic conditions (1992), and dry hydrologic conditions (1995) (Lee 2000).

Contaminant Load Calculations

Contaminant mass loads associated with both the CSOs and the upper watershed were calculated on an hourly basis for design storms and on a daily basis for the year 1986, using a simple volumetric approach that considered flow volume and a representative contaminant concentration (e.g., Marsalek and Ng 1989; Marsalek 1990; Irvine *et al.* 1993, 1998; Pratt *et al.* 1995):

$$L_i = C_i Q_i \tag{1}$$

where L_i is the mass load (mg or kg) for the period of interest, C_i is the representative concentration

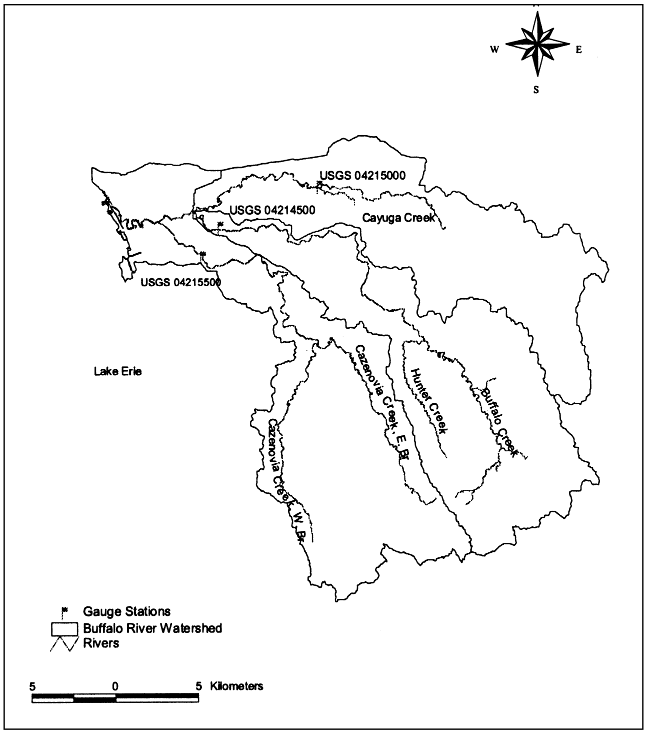

FIG. 2. Buffalo River watershed and USGS gauge stations.

(mg/L), and Q_i is the flow volume (L) for the period of interest. In the case of the design storm CSOs, the value of C_i was determined from the sample data, in which the FF concentration was used in the calculation for the first hour of overflow, while the ROS concentration was used for the remaining hours. The volume of design storm overflow was determined using XP-SWMM on an hourly basis for 72 hours. The representative concentrations from the upper watershed were determined as the average of the mean values of the two sampled storm events in 2000 at sites 1 and 6 (i.e., sample locations at the city boundary). For the annual loading calculations it also was necessary to identify representative dry weather concentrations. The representative concentrations for dry weather periods were calculated as the average of the two dry weather dates from both sites 1 and 6. The volume of flow entering the Buffalo River from the upper watershed was determined using BASINS HSP-F on an hourly basis in the case of design storms and a daily basis for the year 1986.

RESULTS

The laboratory analyses showed that PCBs and pesticides were below detection limit in all of the receiving water body samples collected during wet weather or dry weather sampling. A few PAHs were detected in the second wet weather event, particularly at site 6, which represents the city boundary and reflects concentrations coming into the AOC from the upper watershed. In a preliminary review of the data, Malcolm Pirnie Inc. (2001a) concluded that the analytes of greatest concern were fecal coliform, the metals Pb, Cu, Zn, and Hg, and dissolved oxygen levels. These metals were identified as being of greatest concern based on their higher levels in CSO samples and the potential to generate state water quality standard exceedances.

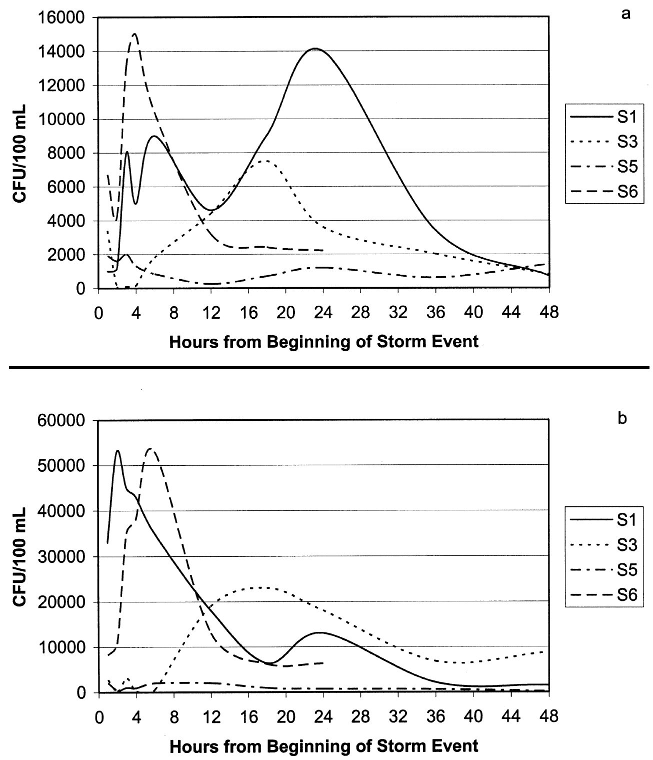

FIG. 3. Fecal coliform levels (cfu/100 mL) in the Buffalo River for (a) storm event 1, 9–11 June 2000; and (b) storm event 2, 23–25 August 2000.

Figure 3 shows the fecal coliform levels associated with the two storm events. Dry weather fecal coliform levels for the sample sites ranged between 20 and 312 cfu/100 mL for the first dry weather sample date and between 5 and 450 cfu/100 mL for the second dry weather date. The representative metals concentrations used for the CSO and upper watershed loading calculations (equation 1) are summarized in Tables 2 and 3. The range of values for the CSOs (Table 2) represents the average FF

TABLE 2. Representative CSO concentrations (total metals) for design storm loading calculations.

Pb, mg/L		Cu, mg/L		Zn, mg/L		Hg, µg/L	
FF	ROS	FF	ROS	FF	ROS	FF	ROS
0.0833–0.22	0.0351–0.192	0.0655–0.138	0.0249–0.0795	0.3033–0.595	0.1285–0.305	0.09–0.37	0.025–0.2462

TABLE 3. Representative concentrations (total metals) for upper watershed loading calculations.

Site	Pb, mg/L	Cu, mg/L	Zn, mg/L	Hg, µg/L
Buffalo River, wet weather	0.00675	0.01345	0.0697	0.0295
Buffalo River, dry weather	0.0074	0.0064	0.043	0.025

and ROS concentrations for up to three overflow events at each of the 11 sample sites. As noted previously, the representative concentrations for the upper watershed and Buffalo River were determined from the site 1 and 6 sample results (Table 3). New York State guidelines for dissolved oxygen in class C, non-trout waters (like the Buffalo River) require a minimum daily average of not less than 5 mg/L, and an instantaneous minimum dissolved oxygen level of not less than 4 mg/L. Daily mean dissolved oxygen levels were calculated for each site and the times for which the mean level was less than 5 mg/L are summarized in Table 4. The proportion of wet and dry weather days when the average dissolved oxygen was less than 5 mg/L also is shown in Table 4. The times during which the instantaneous dissolved oxygen levels were less than 4 mg/L at each site also were identified and these are compared (as a percentage of time) to the total study time in Table 5.

Calibration of the XP-SWMM model was discussed in detail by Malcolm Pirnie, Inc. (2001b) and URS Corporation and State University College at Buffalo (2002) while calibration of the BASINS HSP-F watershed model was discussed in detail by Perrelli *et al.* (in press). Based on professional experience and a review of the literature (e.g., Laroche *et al.* 1996, Srinivasan *et al.* 1998, Carrubba 2000) the study team determined that the models were satisfactorily calibrated.

The loadings of Pb, Cu, Zn, and Hg for the CSOs discharging to the Buffalo River and lower Cazenovia Creek were calculated for the 1, 2, 3, 6, and 12-month design storms, as described by equation 1. The design storms were identified from an analysis of National Weather Service precipitation data at

TABLE 4. Dissolved oxygen non-compliance periods during 30 week monitoring time (daily mean < 5.0 mg/L).

	S1	S2	S3	S4	S5	S6	S7
Number of Non-Compliant Days	5	0	59	66	31	9	30
% of Non-Compliant Days, Storm Events	100	0	37	47	61	22	30
% of Non-Compliant Days, Dry Weather	0	0	63	53	39	78	70

TABLE 5. Dissolved oxygen non-compliance periods during 30-week monitoring time (< 4.0 mg/L).

	S1	S2	S3	S4	S5	S6	S7
Hrs <4 mg/L	17	0	589	760	298	0	131
% Time <4 mg/L	0.62	0	21.5	27.8	10.8	0	4.7

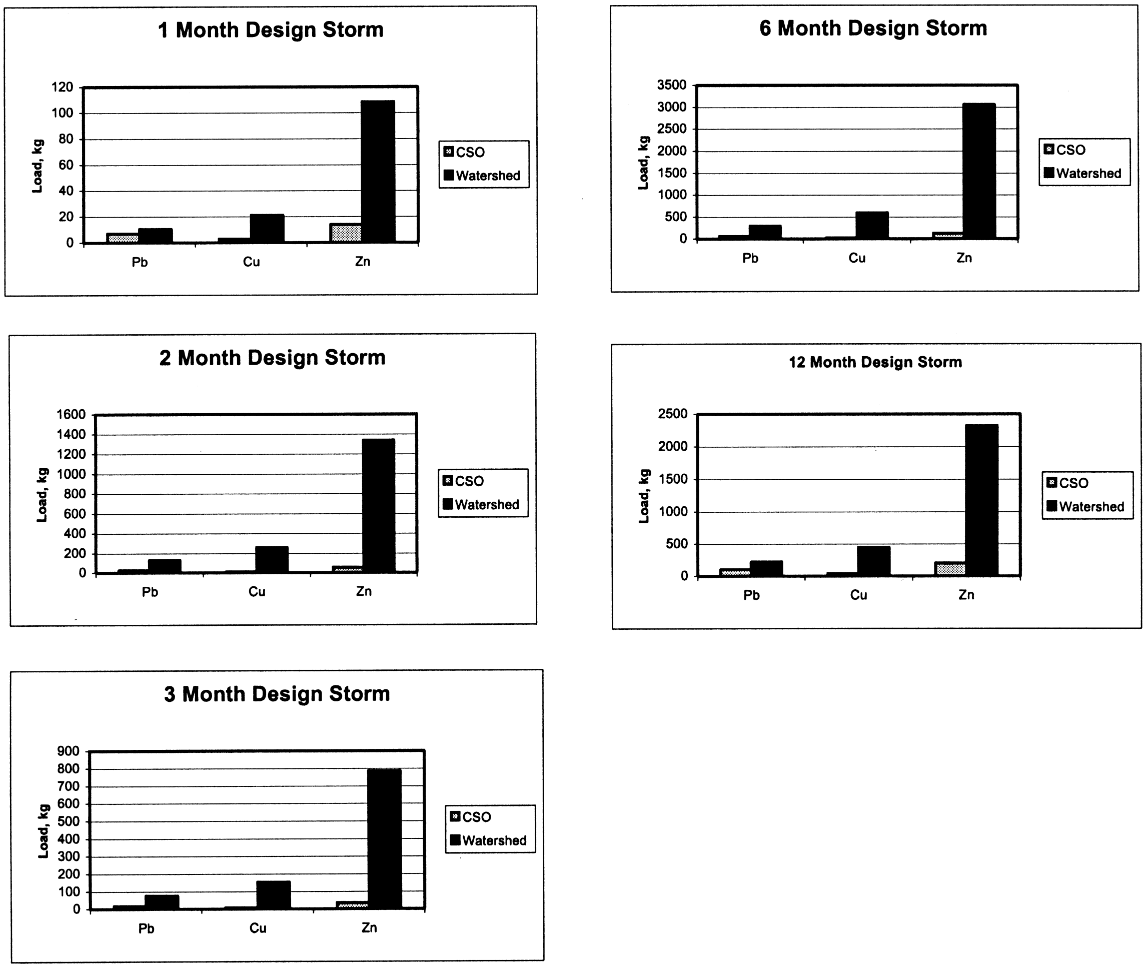

FIG. 4. Design storm loading estimates of Pb, Cu, and Zn for all modeled CSOs (combined) discharging to the Buffalo River and input from the upper watershed.

the Buffalo Airport (Malcolm Pirnie, Inc. 2001a). The metals loadings from the upper watershed that would enter the Buffalo River also were calculated for these design storms. The same 72-hour period was used for the watershed loading calculation and the CSO calculation under each of the design storm scenarios. Because the BASINS HSP-F model was sensitive to "start up conditions," model runs were conducted for the entire year (1-hour time steps) and the design storm was extracted from these results for use in the loading calculations. The CSO and watershed loadings for the different design storms are shown in Figures 4 and 5. It should be noted that due to model limitations only 23 of the 33 CSOs that discharge to the Buffalo River were including in the CSO loading estimates. Those CSOs that were not modeled primarily were small lines discharging to lower Cazenovia Creek and it is not expected that this had a major effect on the total loading estimate. For those CSO sites at which samples were not collected, the representative FF and ROS concentration was taken as a mean of all sample sites combined. The metals loadings from the CSOs and watershed also were calculated for the year 1986 (a "typical" hydrologic year, as determined by Malcolm Pirnie, Inc. 2001a). For the CSO loadings, the representative concentration for each CSO was calculated as a time-weighted mean of the FF and ROS values (as shown in Table 2), so on an annual basis, the first flush phenomenon was not explicitly considered. For the watershed contributions, daily mean flow was modeled for the period 1 March through 30 November 1986. To avoid the complexities of modeling snowmelt the area-adjusted observed flow from the USGS gauges on the three major tributaries was used to calculate flow

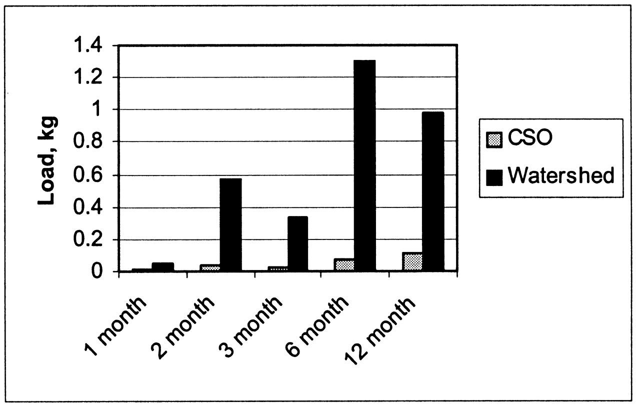

FIG. 5. Design storm loading estimates of Hg for all modeled CSOs (combined) discharging to the Buffalo River and input from the upper watershed.

TABLE 6. Metals loadings for the year 1986.

	Pb Loading, kg	Cu Loading, kg	Zn Loading, kg	Hg Loading, kg
Watershed	3,695	6,739	35,688	15.6
CSOs[1]	498	246	1,114	0.68

[1]represents the sum of all modeled CSOs discharging to the Buffalo River.

for the period 1 January through 28 February 1986 and 1 December through 31 December 1986. The representative concentrations for wet and dry weather flow days were identified in Table 2 and the results of the annual loading calculations are shown in Table 6.

DISCUSSION

Results of the fecal coliform sampling indicate that while the CSOs certainly are a source within the Buffalo River AOC, the overwhelming load comes from the upper watershed outside of the city boundary (see sites 1 and 6, Fig. 3). These results are consistent with previous studies for the watershed (e.g., Irvine and Pettibone 1996, Irvine 1997) and the Erie County Water Quality Committee has begun to focus on evaluation and abatement of upstream sources, including failing septic systems and suburban stormwater runoff (e.g., Irvine *et al.* 2003b). Fecal coliform levels within the AOC decrease in the downstream direction as the result of at least two factors. First, particularly at site 5, water from Lake Erie mixes with the Buffalo River flow and dilutes the concentration. Second, Irvine *et al.* (1995, 2002) showed that at sample sites throughout the watershed, fecal coliform levels were significantly correlated with total suspended solids concentrations. Irvine *et al.* (2002; in press) also noted that the Hydrolab data showed turbidity levels decreased along the Buffalo River in association with sediment deposition. It appears that the decrease in fecal coliform levels may result from sediment (and associated bacteria) deposition.

The estimated watershed loads of metals were greater than the CSO loads for all design storms by a factor that averaged between 3 (for Pb) and 18 (for Zn). This range of ratios is consistent with work done for the Buffalo River in the early 1990's (Atkinson *et al.* 1994). This earlier work expressed loads on an annual basis for Pb and Cu. Although the time scale was different (i.e., annual vs. design storm), Atkinson *et al.* (1994) calculated the watershed to CSO load ratio as 2.5 for Pb and 8.6 for Cu.

Apparent trends in Figures 4 and 5 require additional comment. First, the metals loadings from both the CSOs and the watershed were greater for the 2-month design storm than the 3-month design storm. This pattern was the result of the definition of the design storms (Malcolm Pirnie, Inc. 2001a). The designated 2-month storm had a total rainfall depth of 30.5 mm over a period of 4 consecutive hours, with a peak rainfall intensity of 13.7 mm/hr. The 3-month design storm had a greater total rainfall depth (37.8 mm), but this depth was distributed over a period of 25 hours. The peak rainfall intensity for the 3-month storm was 5.6 mm/hr. Although the 3-month storm had a greater total depth, the lower intensity, longer duration rainfall event produced a smaller volume of CSO (the sewer system was able to retain more water) and less direct runoff from the watershed (more water infiltrated and was stored as a soil moisture component). As a result, the lower flow volumes during the 72-hour calculation period produced smaller loadings for the 3-month storm as compared to the 2-month storm.

The CSO loadings for the 12-month storm were greater than those of the 6-month storm, but the watershed loadings for the 12-month storm were less than those of the 6-month storm. The 6-month design storm rainfall occurred on 26 September 1977, while the 12-month design storm rainfall occurred on 20 August 1980. A review of the modeled flow for the Buffalo River showed that the months of

August and September, 1977, were particularly wet, with numerous high flow events. As such, antecedent conditions for the 6-month rainfall included high soil moisture storage zone content and high flows in the tributaries and lower Buffalo River. On the other hand, antecedent conditions for the 12-month rainfall in 1980 were relatively dry, which produced a smaller storm runoff volume as compared to the 6-month storm.

The loadings of Cu, Zn, and Hg from all CSOs combined represented only 3-4% of the watershed load to the lower Buffalo River on an annual basis. The loading of Pb from all CSOs combined represented 13% of the watershed load to the lower Buffalo River on an annual basis. This higher loading percentage for Pb from the CSOs reflects the relatively higher concentrations of Pb in the combined sewage. The loading estimates presented in Table 6 are higher, but consistent with the CSO and watershed estimates made by Atkinson *et al.* (1994). The earlier study used a synthetic "average" year to represent flow volume from the watershed and CSO volumes were based on PCSWMM4 model results for the year 1990 (Irvine *et al.* 1994). These differences in the study approach partially explain the differences in annual loading estimates for the two studies.

Irvine *et al.* (in press) provided a thorough summary of Hydrolab data collected for this study to evaluate CSO impacts on the Buffalo River and Black Rock Canal. Briefly, however, it seems that dissolved oxygen levels at the city boundary (sites 1 and 6) are quite good. The duration of time that dissolved oxygen levels dropped below state guidelines increased between sites 6 and 7 (particularly for storm periods). This may reflect the cumulative impact of the 16 CSOs located on lower Cazenovia Creek, between the two sites, but Irvine *et al.* (in press) indicated that it was difficult to identify dissolved oxygen sags at site 7 after most CSO events. Cazenovia Creek becomes channelized and is wider and deeper between sites 6 and 7. It is possible the changes in dissolved oxygen characteristics between sites 6 and 7 result from a combination of channel hydraulics and CSOs.

The dissolved oxygen data from the Hydrolab located at a specific CSO (site 3) did not provide a clear indication of dissolved oxygen sag associated with overflow events. Irvine (2002) and URS Corporation and Buffalo State (2003) also did not observe dissolved oxygen sags in the river near two other CSO sites. Several dissolved oxygen modeling studies conducted for the river (Blair 1992, Wight 1995, Hall 1997) concluded: i) stratification in the river at low flows reduced aeration (from mixing); ii) high sediment oxygen demand, together with long residence times due to system hydraulics and background BOD, can produce low dissolved oxygen; and iii) CSOs to the river had minimal impact on dissolved oxygen. The Hydrolab data from this study are consistent with this latter conclusion.

CONCLUSION

Sample and model results showed that while CSOs are a source of some contaminants, the upper watershed may be a more important source to the Buffalo River AOC. In particular, given the levels of fecal coliform entering the Buffalo River AOC as measured at the city line, it can be concluded that even if all CSOs were eliminated, there still would be high bacteria levels in the river. On an annual basis, the loadings of Cu, Zn, and Hg from all CSOs combined represented only 3–4% of the watershed load to the lower Buffalo River, while the loading of Pb from all CSOs combined represented 13% of the watershed load. These results suggest that a coordinated, watershed-wide management plan will need to be developed to address some water quality issues in the Buffalo River. Conversely, the low dissolved oxygen levels seem less related to CSOs or upper watershed inputs than the hydraulics of the river that reduce flow and increase the importance of sediment oxygen demand. It is important to take a watershed approach to water quality and CSO studies to help identify appropriate, cost-effective abatement plans. In particular, the community needs to know how much various abatement scenarios will cost as well as the relative benefit to the environment.

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REFERENCES

Atkinson, J.F., Bajak, T., Morgante, M., Marshall, S., and DePinto, J.V. 1994. Model *Data requirements* *and mass loading estimates for the Buffalo River Mass Balance Study*. U.S. EPA, EPA 905-R94-005.

Blair, S.M. 1992. Dissolved oxygen model for the Buffalo River. Masters thesis, University at Buffalo, Buffalo, NY, USA.

Carrubba, L. 2000. Hydrologic modeling at the watershed scale using NPSM. *J. Am. Wat. Res. Assoc.* 36(6):1237–1246.

DePinto, J.V., Morgante, M., Zaraszczak, J., Bajak, T., and Atkinson, J.F. 1995. *Application of mass balance modeling to assess remediation options for the Buffalo River*. U.S. EPA, EPA 905-R-95-007.

Gabler, R.E., Sager, R.J. and Wise, D.L. 1997. *Essentials of Physical Geography, 5th ed.* New York: Saunders College Publishing.

Hall, J.S. 1997. Examination of a numerical model for dissolved oxygen in the Buffalo River. Master of Engineering Project. University at Buffalo, Buffalo, NY, USA.

Irvine, K.N. 1997. *Cazenovia Creek Watershed Management Program: Baseline water quality analysis, 1996*. Erie County Department of Environment and Planning.

_____. 2002. Buffalo River floatables control and continuous water quality monitoring demonstration project. In *Best modeling practices for urban water systems – Monograph 10*, ed. W. James, ch. 10. Guelph: Computational Hydraulics International.

_____, and Pettibone, G.W. 1996. Planning level evaluation of densities and sources of indicator bacteria in a mixed land use watershed. *Environ. Technol*. 17:1–12.

_____, Loganathan, B.G., Pratt, E.J., and Sikka, H.C. 1993. Calibration of PCSWMM to estimate metals, PCBs and HCB loadings in combined sewer overflows from an industrialized catchment, Buffalo, NY. In *New techniques for modelling the management of stormwater quality impacts*, ed. W. James, Ch. 10. Boca Raton: Lewis Publishers, Inc.

_____, Pratt, E.J., and Marshall, S. 1994. Estimate of combined sewer overflow discharges to the Buffalo River Area of Concern. U.S. EPA, Great Lakes National Program Office.

_____, Pettibone, G.W., and Droppo, I.G. 1995. Indicator bacteria-sediment relationships: Implications for water quality modeling and monitoring. In *Modern methods for modeling the management of stormwater impacts*, ed. W. James, ch. 14. Ann Arbor: Ann Arbor Science.

_____, Droppo, I.G., Murphy, T.P., and Stirrup, D.M. 1998. Annual loading estimates of selected metals and PAHs in CSOs, Hamilton, Ontario, using a continuous PCSWMM approach. In *Advances in modeling the management of stormwater impacts—Volume 6*, ed. W. James, ch. 20. Guelph: Computational Hydraulics International.

_____, Somogye, E.L., and Pettibone, G.W. 2002. Turbidity, suspended solids, and bacteria relationships in the Buffalo River Watershed. *Middle States Geographer* 35:43–52.

_____, Frothingham, K.M., Rossi, M.C., Pickard, S., Atkinson, J., and Bajak, T. 2003a. Contaminated sediment in the Buffalo River area of concern—historical trends and current conditions. In *Sediment quality assessment and management: Insight and progress*, ed. M. Munawar, pp. 81–112. Burlington: Ecovision World Monograph Series.

_____, Perrelli, M., Brown, N., and Rossi, M.C. 2003b. *Septic system pollution prevention BMPs: Development of public outreach approaches, assessment and decision-making tools for local government*. New York State Water Resources Institute.

_____, McCorkhill, G., and Caruso, J. in press. Continuous monitoring of conventional parameters to assess receiving water quality in support of CSO abatement plans. *Water Environment Research.*

Laroche, A-M., Gallichand, J., Lagace, R., and Pesant, A. 1996. Simulating atrazine transport with HSPF in an agricultural watershed. *J. Environ. Engineering* 122(7):622–630.

Lee, T. 2000. Application of a GIS-based watershed model to estimate runoff and bacteria loads in Cazenovia Creek, New York. Masters thesis. University at Buffalo, Buffalo, NY, USA.

Malcolm Pirnie, Inc. 2001a. *Long-term control plan for CSO abatement, water quality assessment report, Volume 1.* Buffalo Sewer Authority, Buffalo, NY.

_____. 2001b. *Model calibration report.* Buffalo Sewer Authority, Buffalo, NY.

Marsalek, J. 1990. Evaluation of pollutant loads from urban nonpoint sources. *Water Science and Technology* 22(10/11):23–30.

_____, and Ng, H.Y.F. 1989. Evaluation of pollution loadings from urban nonpoint sources: Methodology and applications. *J. Great Lakes Res*. 15:444–451.

NYSDEC. 1989. *Buffalo River Remedial Action Plan*. International Joint Commission.

Perrelli, M.F., Irvine, K.N., and Lee, T.S. in press. Calibration of BASINS HSP-F in support of a watershed approach to CSO Long Term Control Planning. In *Effective Modeling of Urban Water Systems, Monograph 13,* ed. W. James. Guelph: Computational Hydraulics International.

Pratt, E.J., Irvine, K.N., Marshall, S., Loganathan, B.G., Kumar, S., and 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 *Modern Methods for Modeling the Management of Stormwater Impacts*, ed. W. James, ch. 9. Ann Arbor: Ann Arbor Science.

Rossi, M.C. 1996. An historical sketch of industry along the Buffalo River, New York, with a focus on chemical manufacturers. *Middle States Geographer* 29:86–94.

Srinivasan, M.S., Hamlett, J.M., Day, R.L., Sams, I., and Petersen, G.W. 1998. Hydrologic modeling of two glaciated watersheds in northeast Pennsylvania. *J. Am. Wat. Res. Assoc*. 34(4):963–978.

U.S. EPA. 1999. *Combined sewer overflows guidance for monitoring and modeling*. EPA 832-B-99-002.

_____. 2001a. *Guidance: Coordinating CSO long-term planning with water quality standards reviews*. EPA-833-R-01-002.

_____. 2001b. *Protecting and restoring America's watersheds, status, trends, and initiatives in watershed management*. EPA-840-R-00-001.

URS Corporation and State University College at Buffalo. 2002. *Combined sewer overflow study draft long term control plan south central district*. Buffalo Sewer Authority, Buffalo, NY.

URS Corporation and Buffalo State, State University of New York. 2003. *Hamburg Drain CSO and Buffalo Inner Harbor water and sediment quality—A preliminary assessment*. Empire State Development Corporation, Buffalo, NY.

Wight, M. 1995. A numerical model to examine dissolved oxygen in the Buffalo River. Master of Engineering Project. University at Buffalo, Buffalo, NY, USA.

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