

Continuous Monitoring of Conventional Parameters to Assess Receiving Water Quality in Support of Combined Sewer Overflow Abatement Plans

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ABSTRACT: As part of its long-term control plan for combined sewer overflow (CSO) abatement, the city of Buffalo, New York, maintained a network of Hydrolab Datasondes (Hydrolab-Hach Company, Loveland, Colorado) to assess receiving water-quality effects by continuously logging dissolved oxygen, pH, temperature, conductivity, and turbidity. Although the effect of individual CSOs could be visualized, turbidity levels entering the Buffalo River from the upper watershed often were greater than from CSO discharges. Turbidity data showed that the Buffalo River was a net-sediment sink. Low dissolved oxygen levels were observed in the summer during dry weather, baseflow, and watershed-wide storms and CSO events. Some CSOs did not produce dissolved oxygen sags in the receiving waters, but others did. This information, together with the sampling done for organic and inorganic contaminants, can aid the decisionmaking process when prioritizing outfalls for abatement work and provides a baseline against which receiving water-quality improvements can be measured. *Water Environ. Res.*, 77, 543 (2005).

KEYWORDS: receiving water quality, combined sewer overflow abatement, dissolved oxygen, turbidity, Buffalo River.

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Introduction

The potential effect of combined sewer overflows (CSOs) on receiving water quality is a concern in many parts of the world (Michelbach et al., 1994; Moffa, 1990; Ochi, 1994; Schmidt et al., 1997; Schroeter, 1997; Stirrup and Marchant, 2002). In the United States, these concerns resulted in the U.S. Environmental Protection Agency (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 [EPA Administered Permit Programs, 2004]). The intent of this policy was to establish a consistent national approach for controlling CSOs through more effective implementation of the National Pollutant Discharge Elimination System (NPDES) permit program. The major provisions of the policy are as follows:

“CSO permittees should immediately undertake a process to accurately characterize their combined sewer system (CSS) and CSO discharges, demonstrate implementation of minimum technology-based controls identified in the Policy, and develop long-term CSO control plans which evaluate alternatives for attaining compliance with the Clean Water Act, including compliance with water quality standards and protection of designated uses” (Water Environment Federation, 1995).

In developing a long-term control plan (LTCP) for CSO abatement, the policy indicates that the responsible agency should

characterize and monitor receiving water effects. Furthermore, the U.S. EPA (1999 and 2001) recommended that LTCP development should consider watershed-wide issues.

“EPA recognizes that urban water quality may be affected by a combination of CSOs, storm water discharges, other point sources and nonpoint source runoff. These sources may be most effectively addressed on a watershed basis or through [total maximum daily load] TMDL analyses. The CSO Policy encourages permitting authorities to evaluate water pollution control needs on a watershed management basis and coordinate CSO control efforts with other point and nonpoint control activities” (U.S. EPA, 2001).

The city of Buffalo, New York, has a total of 68 CSO points that potentially discharge to several waterbodies, including the Buffalo River, Cazenovia Creek, Buffalo Harbor, Black Rock Canal, Scajaquada Creek, and Niagara River (Figure 1). The city initiated its LTCP in 2000 and, as part of an extensive effort to characterize and monitor receiving water effects, a network of 10 Hydrolab Datasonde 4a's (Hydrolab-Hach Company, Loveland, Colorado) were maintained for a period of 30 weeks to continuously monitor pH, temperature, conductivity, dissolved oxygen, and turbidity. Sampling also was done in the sewer system and receiving water for various contaminants, including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), pesticides, metals, nutrients, and fecal coliform, but it is beyond the scope of this paper to report these results.

The objective of this paper is to summarize the results of the Hydrolab monitoring and illustrate how continuous monitoring of conventional parameters can enhance understanding of watershed response to storm events and the effects of CSOs on receiving water quality. This information can improve decisionmaking in prioritizing CSOs for abatement, aid decisions regarding abatement options at a particular outfall, and provide a baseline against which receiving water-quality improvements can be measured.

Study Approach

Study Area. The city of Buffalo, New York, is located at the eastern end of Lake Erie (Figure 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, with February being the driest month (5.9 cm of precipitation) and August being the wettest month (10.6 cm of

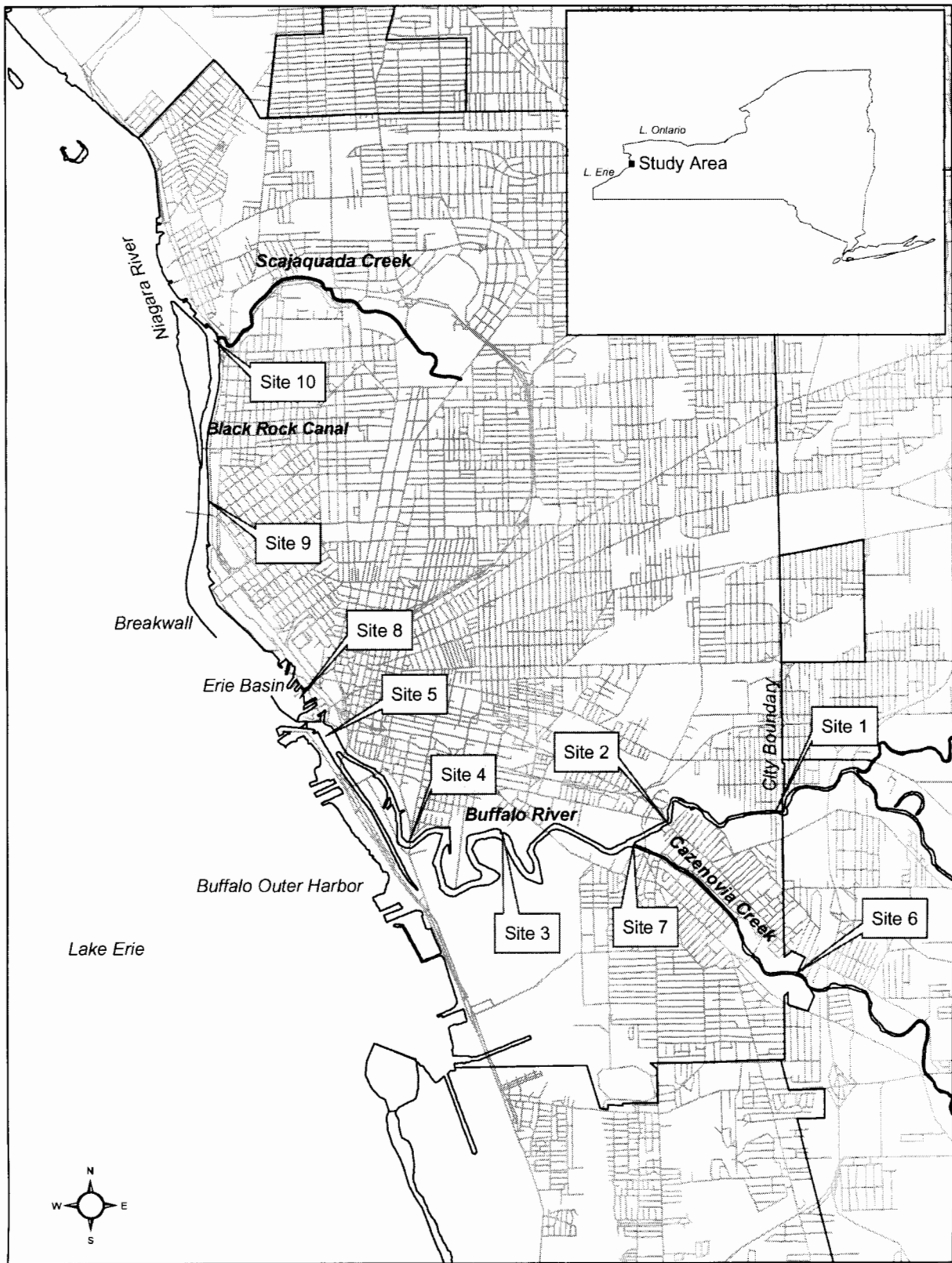


Figure 1—Study area and location of Hydrolabs.

Table 1—Average (and standard deviation) of 30 weeks of mean Hydrolab parameters, from April 17 to November 18, 2000.

	Site 1		Site 2		Site 3		Site 4		Site 5		Site 6		Site 7		Site 8		Site 9		Site 10	
	\bar{x}	s.d.	\bar{x}	s.d.	\bar{x}	s.d.	\bar{x}	s.d.	\bar{x}	s.d.	\bar{x}	s.d.	\bar{x}	s.d.	\bar{x}	s.d.	\bar{x}	s.d.	\bar{x}	s.d.
Temperature (°C)	17.0	5.06	17.2	4.92	17.7	4.86	17.4	4.84	17.6	4.65	16.9	5.26	16.9	5.11	17.3	4.86	16.6	5.12	17.7	4.93
Conductivity (mS/cm)	0.481	0.079	0.493	0.066	0.421	0.061	0.414	0.06	0.354	0.058	0.421	0.056	0.417	0.055	0.286	0.014	0.311	0.035	0.387	0.081
Dissolved oxygen (mg/L)	7.78	1.62	9.36	2.08	6.62	1.78	6.21	1.73	7.09	1.62	8.14	1.78	7.44	2.0	8.97	1.14	6.61	1.65	6.58	1.60
Turbidity (NTU)	67.7	113	48.5	46.7	55.0	55.1	50.8	51.1	23.3	32.9	75.3	58.0	46.8	50.6	3.56	3.82	44.7	85.4	18.0	17.9
pH	8.14	0.315	8.3	0.326	7.85	0.672	7.72	0.374	8.39	0.371	8.24	0.232	8.38	0.305	8.67	0.155	8.17	0.241	8.02	0.305

precipitation). 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 Buffalo Sewer Authority is the agency responsible for overseeing the operation and maintenance of the city's wastewater treatment plant (WWTP) and sewer system. The WWTP is the second largest plant in the state of New York and the 20th largest in the United States, with an average daily design capacity for secondary treatment of 7.88 m³/s (180 MGD). Flows in excess of 15.8 m³/s (360 MGD) bypass secondary treatment, but receive primary treatment. The peak hydraulic capacity of the plant is 24.5 m³/s (560 MGD) (Malcolm Pirnie Inc., 2001). In addition to serving the city of Buffalo, the WWTP also treats waste from several local communities within the metropolitan statistical area. There are more than 1355 km of sewer lines in the city, the majority of which (1274 km) represent a combined system. This system is aging, with approximately 60% of the lines being constructed prior to 1910 and only 8% being constructed since 1941 (Malcolm Pirnie, Inc., 2001).

Installation and Maintenance of Water-Quality Instrumentation. Hydrolab Datasonde 4a's were installed at 10 locations along the Buffalo River, Cazenovia Creek, Buffalo Harbor, and Black Rock Canal (Figure 1) to monitor the following parameters: dissolved oxygen, turbidity, pH, conductivity, and temperature. In general, the sites were selected to provide a good spatial coverage of these receiving water bodies, but some additional criteria also were considered in the selection of sites. Sites 1 and 6 were located near the city boundary to characterize water quality coming into the study area from the 1155-km² Buffalo River watershed (i.e., upstream of the city boundary). Site 7 was located downstream of the 16 combined sewer outfalls found along the channelized section of Cazenovia Creek, and a comparison of data from sites 6 and 7 may identify possible cumulative CSO effects. Sites 3 and 9 were located at the mouth of major combined sewer outfalls, Smith St., and Albany St., respectively. It was expected that the Hydrolabs at these sites would be useful in evaluating specific CSO effects on receiving water quality, as previously had been done for the Babcock St. outfall (Irvine, 2002). The Babcock St. outfall is located upstream of site 3 and downstream of site 2. Site 4 was located at the Ohio St. Bridge because, of any site along the river, this is probably the richest in historical data (e.g., Atkinson et al., 1994; Irvine and Pettibone, 1996; NYSDEC, 1989). Site 5 was used to evaluate the export of material from the Buffalo River system going to either the Black Rock Canal or the Niagara River (Figure

1). Site 8 was located to evaluate water quality associated with the Erie Basin Marina, and, in particular, to assess whether two CSOs discharging to the basin had an effect on water quality. Site 10 was located above the locks on the Black Rock Canal and downstream of the confluence with Scajaquada Creek. It was expected that the site 10 Hydrolab would detect effects on canal water quality because of input from Scajaquada Creek.

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 that occurred because of floating storm debris, and the locked caps provided a level of security from tampering. At all sites except 5 and 10, the PVC tube was fixed to a stationary object (e.g., bridge abutment or sewer grate) so that the sensors would be approximately 1.0 m below the March low water datum. As such, the water depth above the sensors was greater than 1.0 m during storm events. Sites 5 and 10 were attached to buoys so that the depth of measurement always was 1.0 m below the surface.

Complete monitoring began on April 17, 2000 and concluded on November 18, 2000, for a total of 30 weeks. The Hydrolabs were programmed to record data at 15-minute time steps, and, unless very poor weather conditions were experienced, the data were uploaded to a laptop on a weekly basis. All sensors on the Hydrolabs were cleaned weekly, and the dissolved oxygen sensors were calibrated at this time using the 100% (air) saturation method, as described by the manufacturer. The dissolved-oxygen membranes and electrolyte were changed three times during the course of the sampling program. The pH sensors also were calibrated three times during the course of the sampling program. All data were reviewed on a weekly basis, suspicious data were flagged, and discussions were held with the field crew to help identify and resolve the source of the problem.

Results and Discussion

Mean Conditions. As a first step to summarizing the Hydrolab data, mean values were calculated for each week of sampling. The average (and standard deviation) of these weekly mean values are shown in Table 1. The standard deviations of the data in Table 1 reflect variability related to storm events and seasonal effects. For example, water temperature increased through the spring and summer of 2000 and then declined rapidly from September through November. Dissolved oxygen levels, particularly at sites 1 through

Table 2—Average storm event to dry-weather ratios.

Site	Temperature	Conductivity	pH	Turbidity	Dissolved oxygen
1	1.02	0.83	0.97	5.51	0.94
2	1.02	0.83	0.98	5.53	0.94
4	0.97	0.98	0.99	3.40	1.02
5	0.98	1.03	0.99	7.39	0.95
6	1.03	0.79	0.99	3.07	0.94
7	1.01	0.80	0.99	10.69	1.06
8	1.01	1.01	0.99	2.93	0.95
10	1.04	1.08	0.98	11.79	0.96

7 (which are less affected by Lake Erie), declined from spring through summer in response to lower flowrates and warmer temperatures. The dissolved-oxygen levels increased through the fall, as flowrates increased and temperatures declined. Variability in the turbidity data was less related to season and more related to large storms. For example, at site 3, weekly mean turbidity for dry weather periods ranged between 10 and 30 NTU, while, for weeks that experienced large storm events, the weekly mean turbidity exceeded 200 NTU.

Basinwide Runoff and Combined Sewer Overflow Event Mean Concentrations Compared to Dry-Weather Conditions. It is useful to develop an understanding of water-quality characteristics in the receiving waters for storm events as compared to dry-weather conditions. These types of comparisons help to form the baseline against which the effects of various abatement scenarios can be evaluated. The U.S. Geological Survey maintains gauge stations on each of the three major tributaries to the Buffalo River. Daily mean flow at each gauge was adjusted to account for the watershed area downstream of the gauge, and the adjusted values for the three gauges were added to provide an estimate of inflow to the top of the Buffalo River. These flow data, with rainfall data collected at the Buffalo State Field Station (located on the Black Rock Canal, just upstream from site 9), were used to separate storm events from dry-weather flow on a daily basis. The start of an event was defined when the daily hydrograph exhibited an increase from baseflow of the previous 72 hours, while the end of the event was identified when the slope of the daily hydrograph was near zero. A total of 19 storm events were identified. Because of the seasonality in the temperature and dissolved-oxygen data, it was decided to evaluate dry-weather water quality on the basis of a 72-hour period, immediately prior to each of the 19 storm events. As such, a comparison can be made between the averaged 72-hour antecedent dry-weather, water-quality data and the averaged water-quality data for the subsequent storm event (i.e., an event mean concentration).

The mean ratios of storm event to dry-weather concentrations for all events at sites 1, 2, 4, 5, 6, 7, 8, and 10 are shown in Table 2. As noted previously, the Hydrolabs at sites 3 and 9 were installed at the mouth of the Smith St. and Albany St. CSOs, respectively. Therefore, during some of the "watershed-wide" storm events, CSOs also occurred at these sites. The timings of the CSOs were identified using Sigma 920 or 950 area-velocity meter (Sigma, Loveland, Colorado) data from 51 locations throughout south and central Buffalo (including meters located near the outfalls of sites 3 and 9). The sewer-flow data were collected at 15-minute intervals. For sites 3 and 9, parameter values associated with the CSO periods also were separated from the "watershed-wide" or "rest of storm" event data to directly assess CSO effects, and these ratios are shown in Table 3.

Tables 2 and 3 show that, on average, there was not much difference in water temperature or pH between storm-event and dry-weather periods at any of the sites, as the ratios are near unity. Not unexpectedly, event mean turbidity was greater, on average, than dry-weather turbidity. Peak-event turbidity values always were greater than dry weather, and this phenomenon is discussed in more detail in the next section. The CSO-to-dry-weather ratio for turbidity at site 9 was greater than the "rest of storm" to dry weather ratio (Table 3). This indicates that the CSO at Albany St. had an effect on water quality in the Black Rock Canal that is quantifiable and clearly greater than the "rest of storm". The same cannot be concluded for site 3. The turbidity ratio for the Smith St. CSO to dry weather was lower than the "rest of storm"-to-dry-weather ratio. Runoff from the upper watershed appears to have a greater contribution to turbidity at this site than does the CSO.

Conductivity, on average, was lower for events than dry-weather periods at the upper sample sites (1, 2, 6, 7, 3, and 4). It appears that this lower conductivity was related to a dilution effect. Constituents from chemical weathering of soils and bedrock may predominantly enter rivers in temperate, humid climates via groundwater inputs (Marsh, 1987; Morisawa, 1968). As such, conductivity and dissolved-solids concentration would be greater during baseflow conditions, when the principal hydrologic input is groundwater and may become diluted with stormwater runoff (Walling and Webb, 1980). Tomlinson and De Carlo (2003) also observed a dilution effect for conductivity during storms in their monitoring of streams in Hawaii, as did Irvine (2003) in a study of the Allegheny River in Pennsylvania. Conductivity was similar between event and dry-weather periods at the lower sites (4, 5, 8, 9, and 10), as the dilution effect appeared to be reduced. This trend may be because of local inputs or, in the case of sites 5, 8, 9, and 10, may be because of a greater influence from Lake Erie.

The dissolved-oxygen levels, on average, were lower for storm events than dry-weather periods at sites 1, 2, 5, 6, 8, and 10, and were greater for storm events than dry-weather periods at sites

Table 3—Average storm-event-to-dry-weather ratios and combined-sewer-overflow-event-to-dry-weather ratios.

Site	Storm-event*-to-dry-weather ratios					Combined-sewer-overflow-to-dry-weather				
	Temperature	Conductivity	pH	Turbidity	Dissolved oxygen	Temperature	Conductivity	pH	Turbidity	Dissolved oxygen
3	0.98	0.93	1.0	4.15	1.15	0.98	0.92	1.0	2.73	1.14
9	1.01	1.01	0.98	8.12	1.02	0.99	0.81	0.95	35.8	1.15

* Does not include data for the CSO period.

3, 4, 7, and 9. Furthermore, dissolved-oxygen levels, on average, were greater during the CSO periods at sites 3 and 9 than during dry-weather periods. However, care must be taken in interpreting these "average" results for dissolved oxygen, particularly at the CSO sites (3 and 9). For example, the CSO-event-to-dry-weather period ratio was less than unity for 8 of 15 data pairs at site 9, but the ratio was less than unity for only 4 of 15 data pairs at site 3. The complexity of the dissolved-oxygen relationships at the CSOs also is reflected by the standard deviations of the CSO-to-dry-weather ratios. Although the mean-CSO-to-dry-weather ratios were similar for both sites (1.14 to 1.15), the standard deviation was larger for site 9 (0.67) than for site 3 (0.34). These trends, therefore, emphasize the need to examine the water-quality data on an event-by-event basis.

Storm-Event Time Series. Averaging the Hydrolab data provides information on general trends, but the averaging masks some of the important system responses to specific storm characteristics. A visual review of the weekly data, plotted at the 15-minute time steps, revealed some interesting trends, particularly for turbidity and dissolved oxygen.

Numerous studies have examined the relationship between turbidity and total suspended solids (TSS), in an effort to improve our ability to evaluate watershed-scale erosion and sediment transport dynamics (e.g., Davies-Colley and Smith, 2001; Irvine et al., 2003; Lewis, 1996; Sun et al., 2001). There can be several advantages to using automated turbidity measurements as a surrogate for TSS sampling in the examination of sediment erosion and transport. These advantages include the capability of providing fine-time-resolution measurements for extended periods, without having to rely on sampling teams to catch transient storm events with minimal notice (i.e., keeping teams "on call" to chase storms), and reduction of laboratory costs for the analysis of TSS. Ultimately, the success of using turbidity measurements in place of TSS sampling relies on the accuracy of the TSS-turbidity rating curve. Irvine et al. (2003) developed rating curves for four sites (2, 4, 6, and 7) on the Buffalo River and Cazenovia Creek, using data for the 2000 field season, and their relationships were significant, with the r^2 values ranging between 67 and 74%. Pfannkuche and Schmidt (2003) reported an r^2 of 60% between suspended sediment and turbidity, while others (e.g., Davies-Colley and Smith, 2001; Lewis, 1996; Tomlinson and De Carlo, 2003) have produced rating curves with higher r^2 values. Variability in the relationship may be related to a variety of factors, including changes in particle size, shape and composition, and the presence of humic acids.

Figures 2 and 3 show the turbidity for the weeks of May 17 to 24 and June 7 to 14, 2000. The results for the storm events in Figures 2 and 3 were typical of events observed during the study period. Turbidity decreased as the storm wave moved from the upper reaches (sites 1, 2, 6, and 7) through the Buffalo River (sites 3 and 4) to its mouth (site 5). The decrease in turbidity corresponded to a decrease in TSS concentration (data reported by Malcolm Pirnie, Inc., 2001), which suggests that the Buffalo River acted as a net-sediment sink. These results are consistent with past sediment-transport-modeling efforts for the river (e.g., DePinto et al., 1995; Meredith and Rumer, 1987; Raggio et al., 1988; U.S. Army Corps of Engineers, 1988; Wen et al., 1994).

The Buffalo River immediately downstream of sites 2 and 7 is a federally-designated navigable channel that is dredged to a minimum depth of 6.7 m (22 ft) to accommodate lake-going ships. Although local scour areas may occur within the Buffalo River, in general, the sediment deposition is related to the change in

hydraulic characteristics of the navigable channel. The depth of the river increases from approximately 2.4 m (8 ft) immediately upstream of the navigable channel to 6.7 m (22 ft) over the distance of a few hundred meters. River depth is greater than 7.6 m (25 ft) at the mouth. Channel width also increases by 145 m (475 ft) near the mouth of the river. Flow velocity slows with the increased depth and width, resulting in sediment deposition. The lag time in peak turbidity, as the event wave travels downstream through the Buffalo River system, also is visible for many events, although the peak at site 5 can be difficult to identify for some storms because of attenuation (and possibly lake effects).

In general, turbidity levels in the upper part of the Black Rock Canal were not high during watershed-wide storm events (e.g., Figures 2 and 3), although turbidity spikes occurred at site 9 in response to CSOs. Water-column profiling also done in 2000 (Napieralski, 2002) indicated that much of the sediment leaving the Buffalo River, particularly during moderate-sized events, tended to travel down the Niagara River, hugging the breakwall and western shore of Bird Island. Although the Buffalo River plume tended to bypass the canal during storm events, Figure 3 indicates that site 10 could exhibit extended periods of high turbidity in response to a storm (particularly as compared to site 9). This result suggests that Scajaquada Creek can have a measurable effect on water quality in the Black Rock Canal and is consistent with the water-column profiling reported by Napieralski (2002).

Hydrolabs were installed at the mouths of CSOs at two locations: site 3 (Smith St. CSO) and site 9 (Albany St. CSO) to specifically evaluate potential CSO effects. The turbidity and dissolved-oxygen data for a typical overflow event at site 3 are shown in Figures 4 and 5. The turbidity and dissolved-oxygen data for sites immediately upstream and downstream of site 3 also are included for comparison purposes. Increases in turbidity were detected in the river during the CSO events (see Table 3). However, Figure 4 shows that the turbidity increase because of a watershed-wide storm event was greater than the CSO contribution, a situation not unusual for this system. It is difficult to detect any effect on dissolved-oxygen levels from the CSO at site 3 (e.g., Figure 5). In some cases, there seemed to be a slight dissolved-oxygen sag near the beginning of the CSO event, but dissolved-oxygen levels in the river often increased towards the end of the CSO event. It is possible that high levels of turbulence associated with the overflow, which combined with a relatively large contribution from oxygenated surface runoff, produced a CSO with higher-than-expected dissolved-oxygen levels. This type of situation also was observed for the Babcock St. CSO in the summer of 1999 (Irvine, 2002) and does not follow the classically defined dissolved-oxygen sag in a receiving water body resulting from a CSO (Freedman and Marr, 1990).

Turbidity and dissolved-oxygen data for a representative range of overflow volumes and durations at site 9 are shown in Figure 6. Unlike the Smith St. (site 3) and Babcock St. CSOs, dissolved oxygen frequently sagged in the Black Rock Canal in response to a CSO. The difference in response, in part, may be associated with the hydraulic characteristics of the canal. The relative strength of the sanitary flow contribution at this site also might be greater, and the combined wastewater would have a greater travel time than for the Smith St. (site 3) and Babcock St. CSOs, increasing the time for oxygen consumption to occur. The turbidity peaks associated with CSOs were more pronounced above background at site 9, as compared to site 3.

Dissolved-Oxygen Guidelines. New York state guidelines for dissolved oxygen in class C, nontrout waters, such as the Buffalo

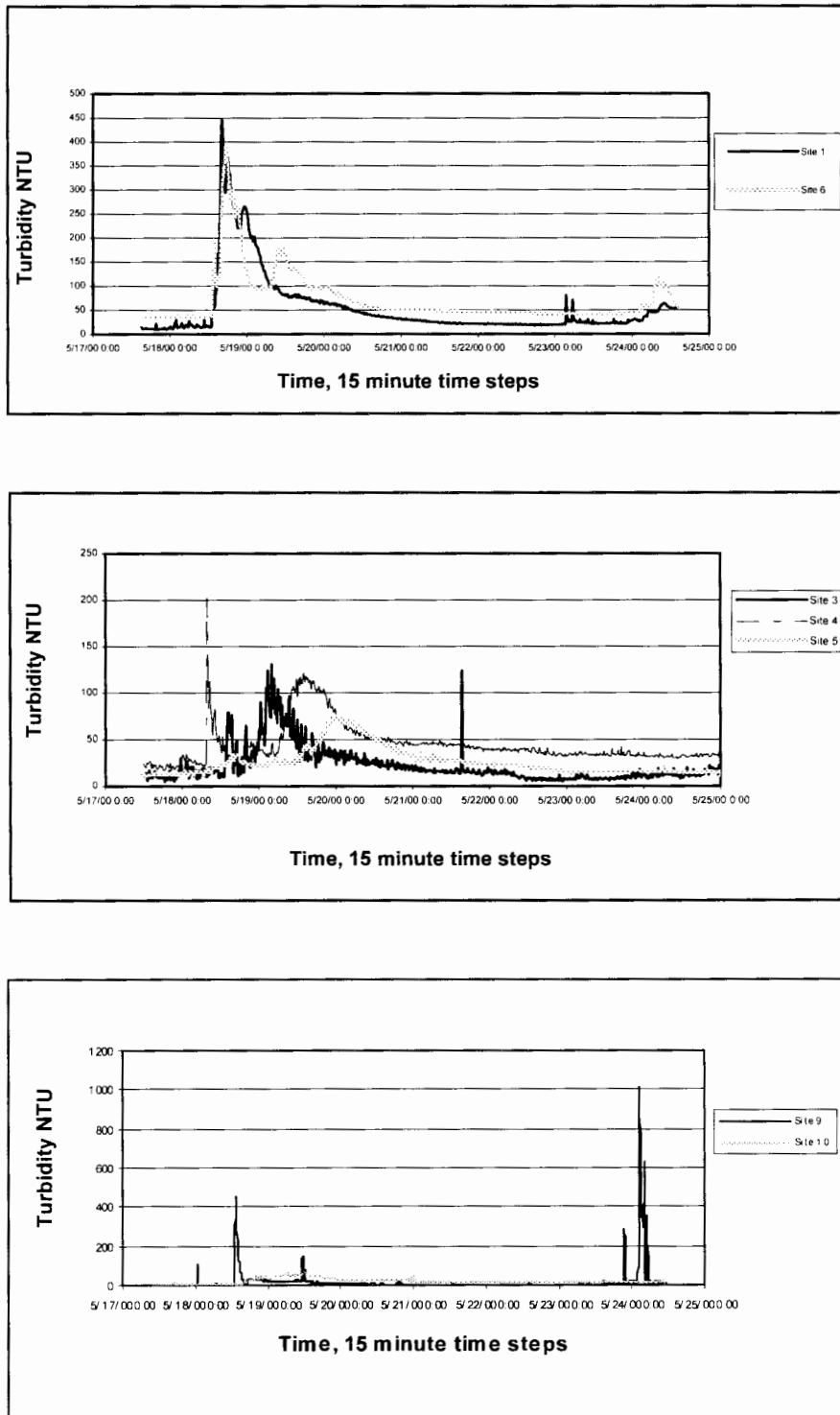


Figure 2—Turbidity results for the Buffalo River (sites 1, 6, 3, 4, 5) and Black Rock Canal (sites 9 and 10), May 17–25, 2000. For clarity, data are not shown for sites 2 and 7, but were similar to sites 1 and 6, respectively.

River, state that "... the minimum daily average shall not be less than 5.0 mg/L, and at no time shall the dissolved oxygen concentration be less than 4.0 mg/L." Daily mean dissolved-oxygen levels were calculated, and the total number of days on which the mean level was less than 5.0 mg/L is summarized in

Table 4. The proportion of days when dissolved oxygen was less than 5.0 mg/L and associated with either storm events or dry-weather periods also is shown in Table 4. Table 4 indicates that days for which dissolved oxygen was less than 5.0 mg/L occurred during both storm events and dry-weather periods. However, the majority

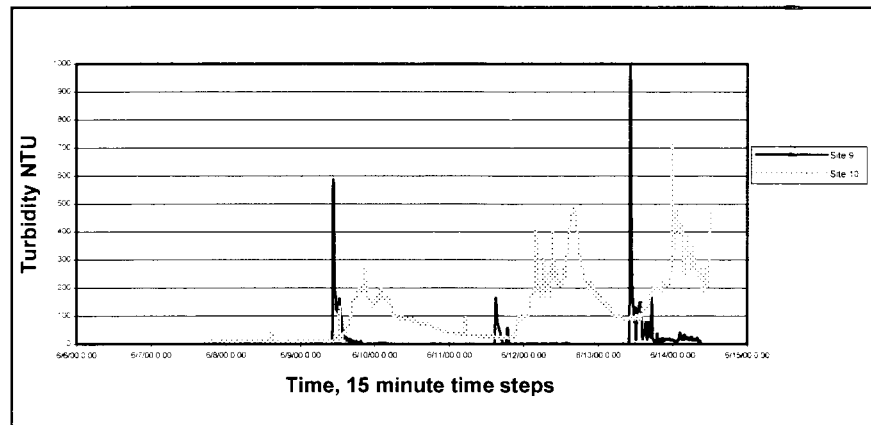
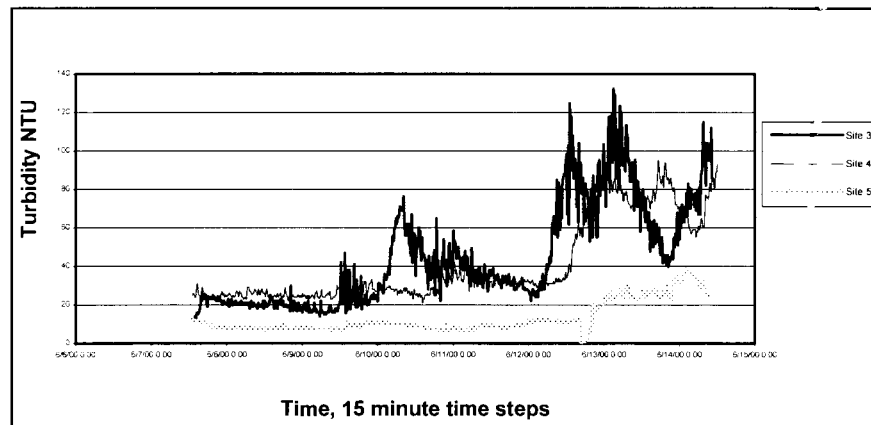
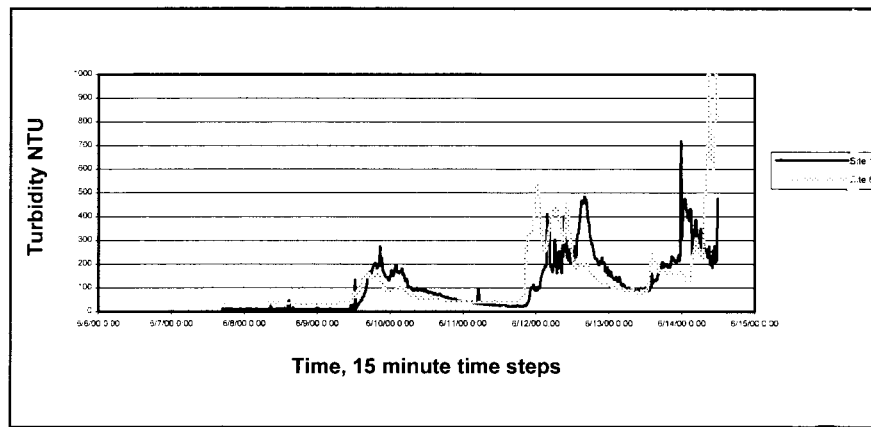


Figure 3—Turbidity results for the Buffalo River (sites 1, 6, 3, 4, 5) and Black Rock Canal (sites 9 and 10), June 7–15, 2000. For clarity, data are not shown for sites 2 and 7, but were similar to sites 1 and 6, respectively.

Table 4—Number of days when daily mean dissolved oxygen was <5.0 mg/L during the study (April 17 to November 18, 2000), with percentage of days associated with storm and dry-weather periods.

Site	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Number of days <5.0 mg/L	5	0	59	66	31	9	30	0	45	48
Percentage of days <5.0 mg/L, storm events	100	0	37	47	61	22	30	0	76	56
Percentage of days <5.0 mg/L, dry weather	0	0	63	53	39	78	70	0	24	44

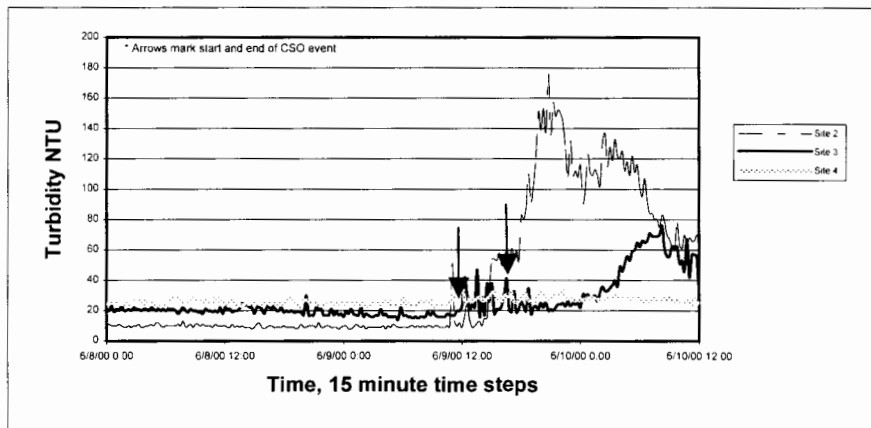


Figure 4—Turbidity results for the Buffalo River. Site 3 is in the river at the mouth of the Smith St. CSO.

of days for sites 3 and 4 occurred during warm, dry-weather periods, in association with low-flow conditions in the Buffalo River. Between sites 6 and 7, there was an increase in the proportion of days less than 5.0 mg/L associated with storms. It is possible that this increase was related to the cumulative effect of the CSOs along the channelized section of Cazenovia Creek, although it is important to note that the creek also becomes wider and deeper in the channelized section between sites 6 and 7. The site-7 data were reviewed in more detail for six weeks in which multiple CSO events were recorded. Typically, it was not possible to visually identify a dissolved-oxygen sag associated with an individual CSO event. In two cases, a small decrease in dissolved oxygen occurred at site 7, after the third CSO event within the week. It is possible that the dissolved-oxygen dynamics between sites 6 and 7 were influenced by the change in channel characteristics (wider and deeper channel with lower velocity) and infrequently occurring hydrologic conditions (i.e., multiple CSO events in a short period of time). Site 9 exhibited interesting results in that the large majority of low-dissolved-oxygen periods (76%) were related to storm events and, in particular, CSOs at the Albany St. outfall. The proportion of days less than 5.0 mg/L associated with storms decreased to 56% at site 10, indicating that the effect of the Albany St. CSO (and other

CSOs discharging to the Black Rock Canal) diminished in the downstream direction.

The times during which the dissolved-oxygen levels were less than 4.0 mg/L at each site also were identified, and these are compared (as a percentage of time) to the total study time (Table 5). The results of Tables 4 and 5 indicate that there is no concern about dissolved-oxygen levels at sites 1, 2, 6, and 8. The increase in frequency of periods less than 4.0 mg/L between sites 6 and 7 may be related to the hydraulics of the channel and possibly the cumulative effect of CSOs along the channelized section of Cazenovia Creek, as also suggested by the results in Table 4. Consistent with the results in Table 4, the Buffalo River (Table 5) exhibited the greatest frequency of time less than 4.0 mg/L, but the influence of Lake Erie water mixing with the river was evident at site 5.

Several dissolved-oxygen-modeling studies were completed through the 1990s for the Buffalo River (Blair, 1992; Hall, 1997; Wight, 1995). These studies concluded that low dissolved oxygen, particularly in the upper portion of the Buffalo River (between sites 2 and 3) was related to a combination of stratification in the river at low flows that can reduce aeration, high sediment-oxygen demand, with long residence times because of system hydraulics, and background biochemical-oxygen demand. The modeling efforts concluded that

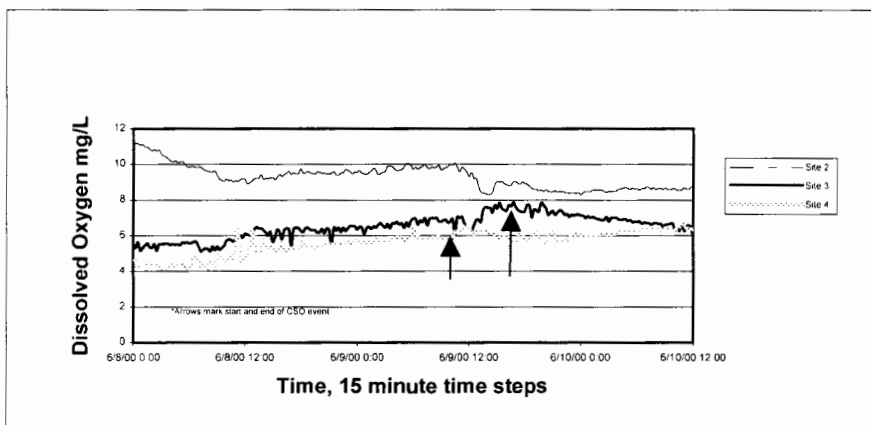


Figure 5—Dissolved oxygen results for the Buffalo River. Site 3 is in the river at the mouth of the Smith St. CSO.

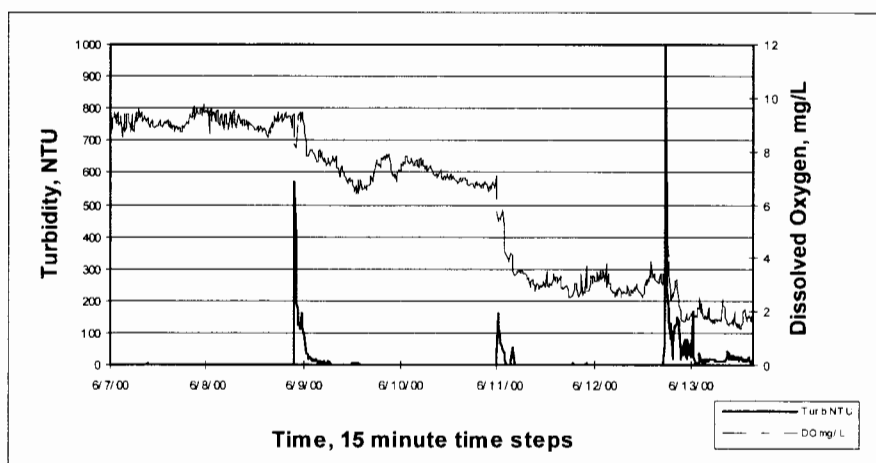


Figure 6—Turbidity and dissolved oxygen results for site 9 in the Black Rock Canal at the mouth of the Albany St. CSO. Spikes in turbidity are associated with CSO events and corresponding reductions in dissolved oxygen levels are apparent.

CSOs discharging to the river had a minimal effect on dissolved oxygen, a finding consistent with the results of this study.

Conclusion

Continuous monitoring of conventional water-quality parameters provided a good understanding of the way in which the Buffalo River, Harbor, and Black Rock Canal responded to watershed-wide runoff events and CSOs. Many of the water-quality trends observed in 2000 reinforced the findings of past studies (e.g., Atkinson et al., 1994; DePinto et al., 1995; Meredith and Rumer, 1987; Raggio et al., 1988; U.S. Army Corps of Engineers, 1988; Wen et al., 1994; Wight, 1995). For example, the importance of sediment sources upstream of the city boundary influencing sediment load within the Buffalo River was underscored. This finding suggests that greater attention needs to be paid to best-management-practice application in the upper watershed to control erosion and sediment transport to the Buffalo River. In general, the Buffalo River appears to be a sink for suspended sediment (i.e., it is aggrading). Turbidity associated with the CSOs at the Albany St. outfall was greater than the “rest of storm” events or the dry weather. It can be concluded that this CSO had a measurable effect on the Black Rock Canal.

The sample sites near the city boundary did not have a problem with dissolved-oxygen levels, while sites in the Buffalo River and Black Rock Canal had the greatest frequency of low dissolved-oxygen levels. Low dissolved-oxygen levels generally were observed during the warmer part of the summer and could occur during dry-weather periods when these water bodies had minimal water movement or during watershed-wide storms and CSO events. Interestingly, CSO events at the Smith St. outfall and the Babcock St. outfall (Irvine, 2002) did not produce a dissolved-oxygen sag within the Buffalo River, while CSO events at the Albany St. outfall

negatively affected dissolved-oxygen levels within the immediate area of the Black Rock Canal. This type of information, together with the sampling done for organic and inorganic contaminants, can aid the decisionmaking process when prioritizing outfalls for abatement work, identifying abatement options at a particular outfall, and providing a baseline against which receiving water-quality improvements can be measured.

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Table 5—Dissolved-oxygen periods <4 mg/L during the study (April 17 to November 18, 2000).

Site	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Hours <4 mg/L	17	0	589	760	298	0	131	0	570	366
Percentage of time <4 mg/L	0.62	0	21.5	27.8	10.8	0	4.7	0	20.8	13.4

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