

## Levels and Sources of Indicator Bacteria Associated with the Buffalo River “Area of Concern,” Buffalo, New York

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**ABSTRACT.** Elevated levels of indicator bacteria within an Area of Concern (AOC) are recognized by the International Joint Commission as a water quality impairment. Combined sewer overflows are assumed to be the major source of bacteria to the Buffalo River AOC and current remediation strategies largely disregard other potential sources, including waters entering the river from the upper watershed. To assess the influence of upstream sources on pollution indicator bacteria levels in the Buffalo River, fecal coliform (FC) and fecal streptococci (FS) densities were determined at 12 sites in the Buffalo River watershed during 1992–1993. FC and FS densities were highly correlated throughout the year ( $r = > 0.83$ ) and the mean levels of both indicator groups increased at sites closer to the Buffalo River. The highest levels of indicator bacteria in the water column coincided with rainfall events but FC levels violated New York State water quality standards at the three sites closest to the Buffalo River in 79% of all samples. Total suspended solids were strongly correlated with FC ( $r = 0.86$ ) in the upper watershed during the summer months when flow velocities were greatest, and solids may play an important role in transporting bacteria into the Buffalo River. The fluctuations and relative magnitude of indicator bacteria levels were similar in the Buffalo River and at the upstream sites in the absence of combined sewer overflow events. The data depict a strong influence of upstream waters on the Buffalo River AOC. Upstream tributaries may make important contributions to the pollutant loading in AOCs and should not be overlooked in remediation planning.

**INDEX WORDS:** Indicator bacteria, fecal coliform, suspended solids, Area of Concern (AOC), Buffalo River.

### INTRODUCTION

The water and sediment quality of the Buffalo River, New York, historically have been impacted by a variety of industrial pollutants including metals, polychlorinated biphenyls, polyaromatic hydrocarbons, and bacteria. Due to past environmental impairments, the International Joint Commission (IJC) has designated the lower 9.2 km of the Buffalo River as one of 43 Areas of Concern (AOC) located within the Great Lakes drainage basin. Consequently, a Level One Remedial Action Plan (RAP) was developed (New York State Department

of Environmental Conservation 1989) for the river and has been submitted to the IJC.

Under the guidelines of the IJC, 14 use impairments may be considered in the listing of a site as an AOC, one of which considers bacterial contamination in the form of beach closings (Hartig *et al.* 1990). The New York State Department of Environmental Conservation (NYSDEC) has not considered the beach closing impairment as applicable to the Buffalo River since there are no public beaches within the AOC. However, the river routinely is used for swimming, water skiing, and boating; therefore, high bacteria levels constitute a potential health risk to these populations. Proposed waterfront development of the river also may result in an increase in recreational use of the river. The Buffalo River is not unique in these respects, and many

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ivers within Great Lakes AOCs are similarly used for recreation and other purposes (Dutka and Marsalek 1993).

The primary focus of testing in the Buffalo River, to date, has been the characterization of levels and sources of toxic compounds, not the levels of enteric bacteria (Atkinson *et al.* 1994, Pratt *et al.* 1995). It has been assumed that 38 combined sewer overflows (CSO) that discharge to the Buffalo River AOC are the primary source of bacterial contamination, and there has been little investigation regarding input of bacteria from other sources (New York State Department of Environmental Conservation 1989, Irvine and Pettibone 1993). Current remediation strategies address the impact of the CSOs on the bacterial quality of the Buffalo River but disregard other potential sources, including those entering the river from upstream.

Recent investigations (Irvine and Pettibone 1993) suggest that although CSOs are contributors to the bacterial contamination of water and sediment in the Buffalo River, high levels of indicator bacteria may reach the AOC from upstream tributaries. Remediation plans developed for AOCs should not ignore the potential contributions from upstream sources since they can serve as receiving bodies for potentially pathogenic bacteria and other pollutants. Because of limited knowledge about the population dynamics of fecal pollution indicator bacteria in the Buffalo River, this study was undertaken to monitor the levels of indicator bacteria within the AOC and evaluate the contribution of bacteria to the AOC from upstream sources. Selected physical parameters commonly used to assess water quality also were examined for their influence on bacterial densities.

## MATERIALS AND METHODS

### Study Sites

The Buffalo River watershed has a total drainage area of 1,155 km<sup>2</sup> and is fed by three major tributaries: Cayuga Creek, Buffalo Creek, and Cazenovia Creek. The Buffalo River itself begins at the confluence of Cayuga and Buffalo creeks, approximately 13 km above the mouth of Lake Erie. Cazenovia Creek enters the Buffalo River below the junction of Cayuga Creek and Buffalo Creek to form the main river. The Buffalo River flows through an area that is serviced by a combined sewer system and there is a total of 38 combined sewer outfalls that discharge to the AOC. Much of

the upper Buffalo River watershed is characterized by woods and farmland and is not as severely impacted by anthropogenic sources as the AOC. Twelve sites were selected within the Buffalo River watershed to represent both non-point source areas and areas upstream and downstream of potential point sources of bacteria (Fig. 1). Sites 10, 11, 5, and 6 also were selected for their proximity to U. S. Geological Survey (USGS) recording gauge stations. Sample sites in the upper watershed generally were characterized by bedrock or sand bottoms and had slopes ranging between 0.001 and 0.007. Site 13 within the Buffalo River is in a designated navigable channel that is maintained by annual dredging at an average depth of approximately 7 m. As a consequence, this area is wider, deeper and has a bed slope that is shallower (average of 0.0002) than in the tributaries. The differences in hydraulic geometry in the Buffalo River result in lower flow velocities than typically observed in the tributaries.

### Field Methods

*Water*—Samples were taken once a week during the summer of 1992, twice per month during the fall of 1992 and spring of 1993, and once per month during the winter of 1992–1993. On each sample day, 500 mL of water was collected in a sterile glass bottle for bacteriological analyses and an additional one to two liters were collected in clear glass bottles for analyses of suspended and dissolved solids. Samples from the upstream sites were collected from mid-channel at approximately 0.6 of the depth of the river. If low flow conditions prevented collection at 0.6 of the depth, the sample bottles were filled by resting the bottle on the river bed. Water samples from sites within the Buffalo River were taken at 1 meter below the surface. All water samples were kept on ice until returned to the laboratory.

Dissolved oxygen (DO) was measured at each of the upstream sites (i.e., upstream of sites 12 and 13) using a YSI Model 50B meter. The meter was calibrated at each site prior to measurement using the 100% air saturation method outlined by the manufacturers. Water temperature was recorded using the YSI 5739 temperature probe attached to the DO meter. Water pH measurements before 26 October 1992 were obtained in the laboratory using a Fisher Accumet 915 pH meter. After 26 October, pH was measured in the field with a field pH meter (Cole-Parmer Digi-Sense Model 5985-80). Both pH meters were calibrated immediately prior to use

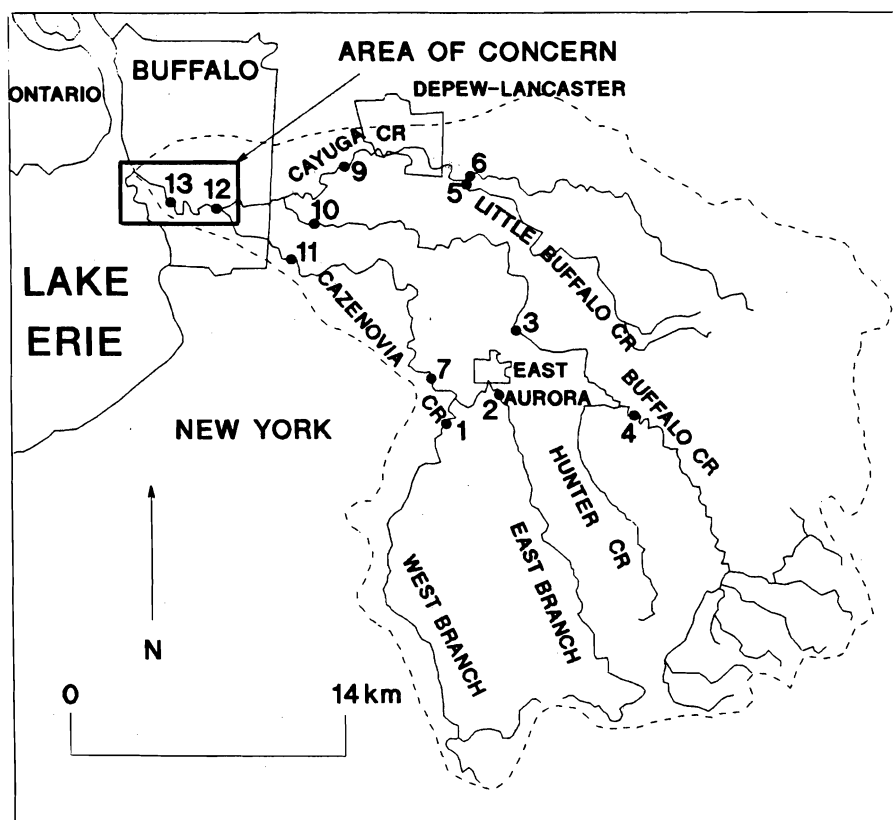


FIG. 1. Location of sample sites in the Buffalo River watershed and the Area of Concern.

against commercially available buffers of 7.00 and 10.01. Water conductivity was measured in the laboratory using a Hanna Instruments HI8633 meter calibrated using commercially available standards.

**Sediment**—Samples of bed sediment were collected at site 13 using a mini-Ponar dredge on the same dates and in the same vertical (to the extent possible) as the water samples. For each sediment sample, five subsamples of approximately 10 g each were aseptically taken from areas not in contact with the dredge and combined in a sterile polyethylene bag for bacterial analyses. Samples were placed on ice until processed, which usually was within four hours.

### Laboratory Methods

#### Enumeration of bacteria

**Water**—Appropriate dilutions of the water samples were filtered through Gelman cellulose acetate

(GN6) filters (pore size 0.45  $\mu\text{m}$ ) and rinsed three times with sterile 0.1% peptone water. Filters, in triplicate, were placed on the surface of either mFC agar containing 1% rosolic acid for enumeration of fecal coliforms or mEnterococcus agar for the enumeration of fecal streptococci. mFC agar plates were wrapped in water-tight plastic bags and incubated for  $24 \pm 2$  h submerged in a circulating water-bath (Blue M, General Signal, IL) held at 44.5°C. After incubation, all blue colonies were counted as fecal coliforms. Selected bacteria were verified as fecal coliforms by gas production in both lauryl tryptose broth and EC broth at 35°C and 44.5°C, respectively. mEnterococcus plates were incubated at 35°C for  $48 \pm 3$  h after which pink to red colonies were counted as fecal streptococci. Typical bacteria were verified as fecal streptococci by a negative catalase test after growing on Brain Heart Infusion (BHI) agar at 35°C and by growth in BHI broth during 24 h incubation at 44.5°C.

Water samples also were analyzed for general levels of bacteria using the heterotrophic plate

count (HPC). Samples were diluted in 0.1% peptone water and 0.1 mL volumes spread-plated onto the surface of triplicate nutrient agar plates. Plates were incubated at room temperature (18–20°C) for  $48 \pm 3$  h after which all colonies were counted and included in the calculation of the HPC. All colony counts for pollution indicator bacteria and HPC were made using magnifications between 10–15 power.

**Sediment**—Ten grams of wet sediment were added to 90 mL of sterile 0.1% peptone water and homogenized for 30 s at high speed in a Waring® blender. This sediment slurry was further diluted and 1 mL volumes of the appropriate dilutions were used to inoculate a 5-tube Most-Probable-Number (MPN) series for fecal coliforms and fecal streptococci. Lauryl Tryptose broth and Azide Dextrose broth served as the presumptive media for fecal coliforms and fecal streptococci, respectively. Confirmation of fecal coliforms was determined by gas production in EC medium after 24 h incubation at 44.5°C. Fecal streptococci were confirmed if black-brown colonies developed on bile esculin agar incubated at 35°C.

#### *Determination of Sediment Concentrations*

Water samples collected for suspended and dissolved sediment analyses were kept at room temperature and processed within 72 h of collection. Appropriate volumes were passed through 0.45  $\mu\text{m}$  Millipore® filters and that material retained by the filter was regarded as suspended solids. Thirty mL of each sample filtrate were evaporated at 180°C and weighed in tared evaporation tins to determine the dissolved solids concentration in the sample. In general, the determination of suspended and dissolved solids followed Standard Method 2540 D and 2540 C, respectively (APHA 1989).

## RESULTS

### Physical Parameters

Water temperatures within the watershed showed characteristic seasonality averaging 18.1°C and 0°C during the summer and winter, respectively. Annual DO and pH values typically fell within expected norms for the region and do not appear limiting for aquatic biota. Total suspended solids (TSS) exhibited a wide range of values over the year ranging between 0.2–453 mg L<sup>-1</sup> in the area above the AOC (sites 1 through 11) and 0.6–674 mg L<sup>-1</sup> within the AOC (sites 12 and 13). A strong positive correla-

tion existed between TSS and stream discharge rate at sites 5 ( $r = 0.904$ ), 6 ( $r = 0.987$ ), 10 ( $r = 0.934$ ), and 11 ( $r = 0.740$ ) which are near USGS gauge stations. Complete data for all of the conventional physical parameters tested in this study (total suspended solids, dissolved solids, dissolved oxygen, pH, and conductivity) can be obtained from the authors upon request.

### Levels of Indicator Bacteria

The geometric mean and range of counts for fecal coliforms, fecal streptococci, the resulting FC:FS ratio, and the heterotrophic plate count during summer and winter are shown in Tables 1 and 2, respectively. Summer samples were taken June through September 1992 and May–June 1993. In general, geometric mean levels of indicator bacteria at the individual sites were relatively constant throughout the year. Mean fecal coliform and fecal streptococci densities decreased during the winter at the four sites in the upper watershed located above municipalities (Sites 1, 2, 3, 4) but only mean counts from Site 4 were significantly different in summer and winter ( $p < 0.05$ ; Students t-test). Geometric mean fecal coliform densities at each of the other study sites during summer were not significantly different than the mean densities during winter ( $p > 0.05$ ).

The dynamics of indicator bacteria at sites above the AOC were similar throughout the year (Fig. 2). Sharp increases in the level of indicator bacteria in the upper watershed were related to storm or snowmelt events. Ten summer event dates and five non-event (interevent) dates were identified using stream velocity data from the USGS gauging stations. Dates were classified as non-event days on the basis of baseline flow levels and a flat hydrograph at the gauge stations for several days prior to sampling. Discriminant analysis (Minitab 1991) revealed that fecal coliform or fecal streptococci levels with either total suspended solids or conductivity correctly classified events or non-events between 69–100% of the time. Geometric mean levels of fecal coliforms from event samples ( $n = 80$ ) collected from the ten sites above the AOC averaged 13.5 mL<sup>-1</sup> and ranged between 1.4–955 mL<sup>-1</sup>. In contrast, mean fecal coliform levels from interevent samples ( $n = 48$ ) averaged one log less (1.3 mL<sup>-1</sup>) and ranged between 0.4–5.8 mL<sup>-1</sup>. The difference between the geometric means for fecal coliforms from event and interevent samples was significant at  $p < 0.001$ .

Fecal coliform levels, and the resulting FC:FS ra-

**TABLE 1.** Mean\* and range of counts for bacteria from 12 sites within the Buffalo River watershed during summer months (22 June through 28 September 1992 and from 5 May and 7 June 1993).

Site	FC mL <sup>-1</sup>		FS mL <sup>-1</sup>		FC:FS		HPC mL <sup>-1+</sup>	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
13	10.7	0.7-180	6.6	0.3-300	2.6	0.3-7.6	9.3	1.0-193
12	34.0	1.3-230	5.9	0.1-330	9.1	0.7-43.9	27.0	1.0-193
11	6.0	1.5-180	3.8	0.3-125	1.9	0.4-5.0	12.9	2.6-131
10	7.8	0.5-140	4.7	0.4-140	2.2	0.2-7.3	12.9	1.2-281
9	10.0	0.7-280	3.4	0.1-310	4.0	0.9-11.7	16.2	4.4-216
7	3.4	0.4-116	1.8	0.2-210	2.3	0.6-5.5	9.8	3.0-159
6	3.5	0.5-120	1.9	0.1-98	0.4	0.4-10.0	12.0	1.3-137
5	5.5	0.8-85	3.8	0.3-100	1.7	0.5-5.2	12.0	3.0-99
4	14.0	1.9-960	6.9	0.6-750	2.6	0.5-8.2	15.1	4.0-217
3	8.9	1.0-770	5.5	0.2-690	2.2	0.6-8.9	15.5	3.0-150
2	4.5	1.0-165	3.7	0.3-155	1.7	0.4-5.2	8.5	3.1-86
1	2.2	0.4-160	2.0	0.3-155	1.3	0.6-3.7	9.3	3.4-78

\*Geometric Mean

+HPC values X 10<sup>3</sup>**TABLE 2.** Mean\* and range of counts for bacteria from 12 sites within the Buffalo River watershed during winter months (19 October 1992 through 12 April 1993).

Site	FC mL <sup>-1</sup>		FS mL <sup>-1</sup>		FC:FS		HPC mL <sup>-1+</sup>	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
13	12.0	2.7-47	5.9	0.8-25	2.4	0.9-5.3	40.7	9.8-227
12	34.0	1.9-970	8.5	0.4-195	4.4	1.4-6.6	24.5	1.6-169
11	7.4	1.7-23	1.7	0.4-17	5.2	1.2-9.9	11.5	1.9-650
10	5.6	0.8-115	2.4	0.2-116	3.0	1.0-8.0	20.9	2.1-199
9	14.0	2.9-70	2.1	0.3-99	19.5	0.7-114	13.8	2.1-156
7	4.3	0.8-51	1.3	0.5-5.7	4.3	1.4-13.1	5.2	1.1-173
6	3.2	0.9-37	1.2	0.2-39	3.6	0.8-9.3	9.5	0.5-155
5	3.1	0.7-34	1.3	0.1-29	3.4	0.9-10.6	11.2	1.8-162
4	2.6	0.3-34	1.3	0.1-29	2.4	1.0-4.2	6.5	0.6-141
3	1.9	0.1-57	1.2	0.1-33	1.8	1.0-4.0	14.8	1.5-101
2	1.5	0.6-3.6	0.7	0.2-4.1	2.5	0.9-5.0	8.3	1.2-99
1	1.6	0.1-7.7	0.7	0.1-6.5	2.8	0.9-6.3	5.4	1.6-206

\*Geometric Mean

+HPC values X 10<sup>3</sup>

tios, in the upper watershed tended to increase at sites closer to the AOC and could indicate increased input from anthropogenic sources. The yearly geometric mean for fecal coliforms at Site 9, which is downstream from Lancaster/Depew, was significantly different ( $p < 0.001$ ) from the means of the two sites above the municipality. Likewise, the geo-

metric mean for fecal coliforms from Site 11 (near the AOC and downstream of East Aurora) was significantly different ( $p < 0.001$ ) from the means of the two sites above East Aurora. Site 10, which does not lie downstream of a major urban center did not show a significant increase in fecal coliform counts compared to the two upstream sites.

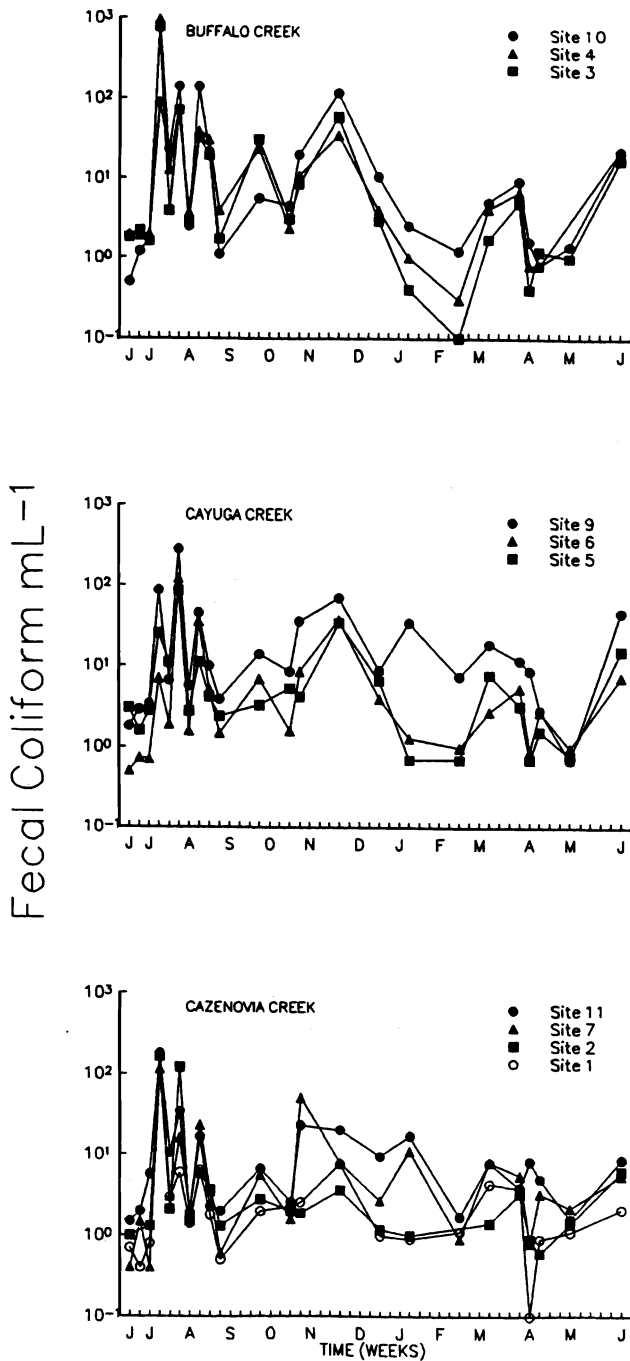


FIG. 2. Population dynamics of fecal coliform from 22 June 1992 through 7 June 1993 at 10 sites in the Buffalo River watershed above the Buffalo River Area of Concern.

Correlations

Correlation matrices for bacteria and selected physical parameters from summer and winter samples are shown in Tables 3 and 4, respectively.

TABLE 3. Correlation coefficients\* (r) for parameters<sup>+</sup> tested during summer months (22 June through 28 September 1992 and from 5 May and 7 June 1993) at 10 sites above the Buffalo River AOC.

	FC	FS	TSS	HPC	DS
FS	0.92				
TSS	0.86	0.79			
HPC	0.82	0.74	0.73		
DS	-0.23	-0.23	-0.22	-0.30	
COND	-0.19	-0.20	-0.19	-0.24	0.37

\*Correlation coefficients are calculated using geometric means; N for the parameters range between 128 (FC and FS) and 117 (HPC).

<sup>+</sup>FC, fecal coliform; FS, fecal streptococci; TSS, total suspended solids; HPC, heterotrophic plate count; DS, dissolved solids; COND, conductivity

TABLE 4. Correlation coefficients\* (r) for parameters<sup>+</sup> tested during winter months (19 October 1992 through 12 April 1993) at 10 sites above the Buffalo River AOC.

	FC	FS	TSS	HPC	DS
FS	0.83				
TSS	0.41	0.48			
HPC	0.62	0.72	0.53		
DS	-0.13	-0.23	-0.53	-0.42	
COND	-0.07	-0.19	-0.34	-0.14	0.51

\*Correlation coefficients are calculated using geometric means; N for the parameters range between 104 (FC and FS) and 88 (HPC)

<sup>+</sup>FC, fecal coliform; FS, fecal streptococci; TSS, total suspended solids; HPC, heterotrophic plate count; DS, dissolved solids; COND, conductivity

Fecal coliforms and fecal streptococci were the two parameters most closely correlated throughout the study (r = 0.94). Both FC and FS showed strong positive correlations with TSS during the summer months (Table 3) but these weakened during the winter (Table 4). The heterotrophic plate count data obtained in this study represent only a fraction of the bacteria present in the water samples since no medium is capable of growing all of the types of bacteria present (Atlas and Bartha 1993). However, the HPC was used to indicate the relative bacterial load in the water column and showed a strong posi-

tive correlation with FC, FS, and TSS during the summer, but became weaker during the winter. In general, correlations among most of the parameters became less strong during the winter months.

### Buffalo River AOC

The number of indicator bacteria in the water column at the sites within the Buffalo River AOC tended to reflect upstream levels, particularly in the absence of overflows from CSOs. In general, fluctuations and relative magnitudes of FC levels were similar throughout the year at sites within the Buffalo River and at upstream sites, with some exceptions. A combined sewer overflow event occurred within the AOC on 19 July 1992, the day prior to the 20 July sample date. The effect of the CSO event was to increase coliform counts at site 13 by almost one log unit compared to upstream sites which showed a decrease in levels from the previous week.

The rapid changes in the levels of indicator bacteria observed in the water column were not seen in the sediment samples from site 13. The densities of FC and FS in Buffalo River sediment at this site ranged between 1 to 5 logs higher than in the overlying water column (Fig. 3). Fecal coliform densities remained relatively constant during the summer at between  $10^4$ – $10^5$   $g^{-1}$ . Fecal streptococci exhibited similar survival patterns but counts showed greater variability than FC counts. The densities of both indicator groups in sediment declined by two to three logs during the winter months but FC were still present at concentrations two to three logs higher than in the water column.

### DISCUSSION

Survival of FC and FS in freshwater is related to a complex of factors and reports of both die-off (Sjogren and Gibson 1981) and growth (Dutka 1973) of indicator bacteria exist in the literature. In our study, indicator bacteria in upper tributaries to the Buffalo River were maintained at relatively high levels throughout the year. Comparable densities of indicator bacteria in both winter and summer seasons suggest continuous input from various sources year round. Approximately 500 farms are in close proximity of the tributaries in the upper Buffalo River watershed above municipalities that could contribute enteric bacteria to the waterways (Irvine and Pettibone 1996). The levels of indicator bacteria at the four sites above municipalities de-

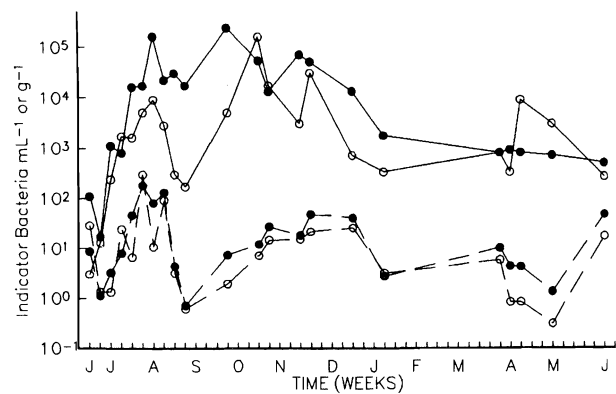


FIG. 3. Fecal coliform (●) and fecal streptococci (○) densities in water (- - -) and sediment (—) at Site 13 in the Buffalo River Area of Concern.

creased during winter when runoff from non-urbanized lands would be reduced.

The influence of the municipalities is evident at sites closer to the Buffalo River. Even during the winter, FC levels increased between one and two logs below the two major towns in the upper watershed (see Fig. 2, site 9 versus sites 5 and 6; sites 11 and 7 versus 1 and 2, 1 November 1992). Irvine and Pettibone (1996) reported that ten sewage treatment facilities, at least 27 CSOs, 117 commercially-permitted septic systems, and an unknown number of residential septic systems potentially discharge to the Buffalo River tributaries and could introduce bacteria to the waterways during the winter season. Kittrell and Furfari (1963) suggested that, even though FC introduced to receiving streams from sewage treatment plants are approximately three times lower in the winter than in the summer, lower water temperatures in winter may allow for longer survival of FC as a result of decreased predation. The level of FC in the tributaries during the winter exceeded state water quality guidelines (200 FC/100 mL) in 66% of all samples (69 of 104). Since input from runoff would be minimal during winter, point source discharges are likely responsible for the majority of these violations.

Although indicator bacteria levels were elevated during the winter, the largest fluctuations and peak densities of indicator bacteria were seen during the summer. Storm events clearly affected counts in the waterways and this is substantiated by the discriminant analysis results. The significant difference in the density of indicator bacteria found from sam-

ples collected during storm events compared to non-event flows concurs with other reports (Culley and Phillips 1982, Niemi and Niemi 1990, Wyer *et al.* 1995) that levels of bacteria in water increase after rainfall. Barbé and Francis (1995) found a relationship between stream discharge and an increase in the number of FC. Although a strong positive correlation between stream discharge and FC at the USGS gauging stations was seen in this study, the association may depend on when the sample was taken in relation to the hydrograph. The correlation between discharge, suspended sediment, and bacterial levels at the study sites could be influenced by previous conditions, storm event hysteresis, variable storm conditions, and hydrologic characteristics of the watershed (Elder 1987, Wilkinson *et al.* 1995).

Runoff processes rather than resuspension of bottom sediments probably are responsible for input of most bacteria into the upper waterways since the streambeds are generally characterized as bedrock or sand. Storm runoff from agricultural and pastureland has been implicated as a significant source of indicator bacteria in waters in rural areas (Niemi and Niemi 1991, Tiedemann *et al.* 1988) and may be especially important near river banks and channels which may act as major sinks for bacteria (McDonald *et al.* 1982). For these reasons, we expected that the influence of agricultural runoff would be greatest in the regions around sites 1, 2, 3, and 4 (Fig. 1).

The ratio of FC to FS has been used to determine whether humans or animals are contributors of fecal pollution to freshwater. Geldreich (1976) suggests that FC:FS ratios above 4.0 indicate human sources of enteric bacteria while ratios below 0.6 typically signify that bacteria are from other warm-blooded animals. Ratios between 0.6 and 4.0 have not been adequately defined and should be considered intermediate in value. Although individual sources of bacteria were not identified in this study, FC:FS ratios were calculated in an attempt to make some comparisons regarding the general origin of pollution at all sites. During the summer, the average FC:FS ratios at sites above the Buffalo River fell between 1 and 3 (Table 2) and as a result are not easily interpreted (Geldreich 1976). Geldreich (1976) notes that the FC:FS ratio can change over time due to differential die-off of certain enteric streptococci and thereby cause changes in the ratio which are unrelated to source. Differences in the ratios between sites in this study should be minimally impacted by die-off since travel time between sites

is less than one day even during low flow conditions. Rather, the observed FC:FS ratios probably reflect input of bacteria from a variety of mixed sources including agricultural, residential and commercial (Irvine and Pettibone 1996).

Although the FC:FS ratios did not definitively indicate that domestic animals or wildlife were acting as a major source of bacteria at the most distant sites, the higher ratios at the sites closer to the Buffalo River AOC suggest a human contribution. The increases in fecal coliforms likely are due to anthropogenic input, since counts from sites below municipalities (sites 9 and 11; Fig. 1) were significantly higher than counts from sites upstream. For all sample dates, the three sites closest to the AOC (sites 9, 10, 11) exceeded State Water Quality guidelines in 79% of the samples. By comparison, state guidelines were exceeded at the remaining seven upstream sites in 61% of the samples.

The high levels of bacteria in the upstream waters were translated to the Buffalo River and determined the dynamics of indicator bacteria in the river during periods not influenced by overflows from CSOs. Comparable results were obtained by Dutka and Marsalek (1993) who found that levels of FC in the St. Marys River were similar to an upstream control site in the absence of CSO discharges. They suggested that urban sources of bacteria had only a minor impact on overall water quality. Our data support their observations. FC levels and FS levels (data not shown) at site 13 and the three sites closest to the AOC (sites 9, 10, and 11) were remarkably similar considering the distance and number of CSOs between the sites. The exception was on 20 July 1992, 1 day after a major CSO event. Although no overflow occurred on the day samples were taken, the effect of the overflow from the previous day was seen as a dramatic increase in the density of indicator bacteria. McCorquodale *et al.* (1993) reported that recirculation zones in the Detroit River kept indicator bacteria at elevated levels for approximately 18 hours after they were introduced.

Total suspended solids was the physical parameter that most strongly correlated with bacterial densities, and this relationship was strongest in summer (compare Table 3 and Table 4) when inputs from runoff or CSOs would be greatest. The correlation between HPC and TSS remained relatively high during the winter (Table 4) which could reflect reduced input of allochthonous bacteria and the recovery of autochthonous populations. Turbidity, which may include a TSS component, has been

shown to be correlated with FC densities in some lotic waters (Tiedemann *et al.* 1988).

The association between indicator bacteria and TSS is important in that solids present in the water column may offer a vehicle by which bacteria are kept in suspension and transported downstream. Auer and Niehaus (1993) showed that greater than 90% of fecal coliform in lake water were associated with small-sized particles (0.45–5  $\mu\text{m}$ ). In addition, suspended particles offer an environment that promotes the growth of enteric bacteria and protects them from grazing (Brettar and Hofle 1992). Such particle associations influence the sedimentation rate of bacteria generally by increasing the rate of loss compared to unattached cells. However, the faster flow velocities observed at the tributary sites in our study would tend to keep particles in suspension. Sedimentation of bacteria-colonized particles could then occur in the Buffalo River where the flow velocity is reduced.

Lick *et al.* (1995) have characterized the Buffalo River as a low energy river that allows fine grained sediment to accumulate. Enteric bacteria that are deposited in Buffalo River sediments potentially could serve as a source of these bacteria to the water column when resuspended by perturbation. There is abundant literature to indicate that sediments protect and concentrate enteric bacteria (Schillinger and Gannon 1985, Lim and Flint 1989) and the levels of fecal coliforms in sediments often are one to four orders of magnitude higher than in overlying water (Van Donsel and Geldreich 1971, Matson *et al.* 1978, Shiaris *et al.* 1987). Likewise, during the summer the sediment at site 13 in the Buffalo River contained levels of fecal coliforms and fecal streptococci up to five logs higher than the water column. These data are consistent with previous observations made in the Buffalo River (Irvine and Pettibone 1993).

Upstream tributaries can serve as a major source of pollutants to AOC waterways. Atkinson *et al.* (1994) found that only about 10% of the PCBs in the Buffalo River could be accounted for from sources within the AOC. Moreover, our study shows that the bacterial loading of the Buffalo River is generally determined by upstream levels. In this regard, the Buffalo River appears similar to other urban rivers located within AOCs of the Great Lakes basin (Dutka and Marsalek 1993). Remediation plans for designated AOCs, therefore, should consider measures that ensure the quality of waters from upstream sources.

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