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# DYNAMICS OF INDICATOR BACTERIA POPULATIONS IN SEDIMENT AND RIVER WATER NEAR A COMBINED SEWER OUTFALL

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## ABSTRACT

Sediments collected throughout the summer of 1991 from a river bed around a combined sewer outfall were found to have geometric mean faecal coliform and faecal streptococci densities ranging between $10^2$-$10^4$ $g^{-1}$ and $10^1$-$10^2$ $g^{-1}$, respectively. During the study period, faecal coliform densities in water samples from the same river reach were several logs lower than in the sediment, but still exceeded state guidelines for primary contact in six of nine sample weeks. Bacteria densities in sediment were weakly correlated with particle size and organic content (as represented by loss-on-ignition) during steady-state baseline flows. Correlations were stronger at the outfall site in the two weeks following an overflow event. Multiple regression analyses indicated that organic content was the dominant factor in explaining variability in bacterial densities in post-overflow sediments. Using a simple combination of sampled physical parameters (flow velocity, river discharge and bed sediment size distribution) and well-established hydrologic relations (Hjulstrom diagram, flow duration curve), it is expected that bacteria-laden sediments around the outfall could be resuspended, on average, thirteen days per year. Resuspension of contaminated sediments, therefore, could adversely impact water quality even in the absence of overflow events.

Keywords: Coliforms, combined sewer overflows, indicator bacteria, sediments, water pollution

## INTRODUCTION

The sanitary quality of water routinely is monitored by testing for faecal coliforms and faecal streptococci. These bacteria may be concentrated in river or lake-bed sediments through the deposition of bacteria-bound particles from the overlying water column (1). Sediments may act as a source of nutrients for allochthonous bacteria and the ability of freshwater sediments to serve as reservoirs for enteric bacteria has been well documented (2). Combined sewer overflows (CSOs) may be an important source of enteric bacteria to the sediments near the outfalls (3). In addition, CSOs may contribute to the physical, chemical and biological matrix of the sediments (4, 5, 6).

Bacteria-colonized sediments may become resuspended by perturbations severe enough to overcome the critical shear velocities of the various-sized bottom sediments. McDonald *et al.* (7) found total coliform and *Escherichia coli* levels in water increased by more than ten fold due to sediment resuspension in a river receiving discharge from a reservoir. Mar (8) found bacterial densities were up to an order of magnitude greater in water above a mechanically disturbed sediment than above an undisturbed sediment. These studies underscore the potential for resuspension of bacteria into the water column from bottom sediments.

The Buffalo River has been designated as an Area of Concern (AOC) by the International Joint Commission (IJC) due to observed environmental impairments, including fish tumours and other deformities; degradation of benthos; and restrictions on disposal of dredged sediment. Various research programs are being conducted to characterize pollutant sources and loadings, to assess human health risks, and to determine appropriate remediation strategies for the river (9, 10, 11). In this paper we report on the temporal variability of indicator bacteria densities both in Buffalo River sediment near a combined sewer outfall and in the overlying water column. Physical characteristics of the fluvial system that affect indicator bacteria densities (e.g. sewer overflows, basin-wide runoff events, sediment properties) also are evaluated. In general, however, much of the study was conducted during summer steady-state baseflow conditions. This sampling timeframe provided insights into the persistence of bacteria in sediment in the absence of numerous event inputs. Summer also is a time of heaviest recreational use, with the greatest potential for health impacts. Finally, a preliminary assessment of the potential for re-entrainment of bacteria-laden bed sediment in the Buffalo River is provided. This assessment was done using a simple combination of sampled physical parameters (flow velocity, river discharge and bed sediment size distribution) and well-established hydrologic relations (Hjulstrom diagram, flow duration curve).

## SAMPLE SITES

The Buffalo River basin drains an area of 1155 km$^2$, although the AOC encompasses only the lower 9.6 km of the river (Figure 1). There is a variety of pollutant sources to the AOC (9), including thirty-nine combined sewer outfalls that drain a mix of industrial, commercial, and residential areas. Most of the AOC is designated a navigable channel and is maintained at a minimum depth of 6.7 m through dredging operations.

Water and sediment samples were collected from the river in the vicinity of a combined sewer outfall (Figure 1). This area was chosen for study for several reasons. An automated overflow quantity and quality sampling station has been installed near the outfall (summer through fall) since 1990 and therefore some flow, metals and organics data were available prior to the initiation of this study (10). The outfall is one of the major overflow points contributing to the Buffalo River (12), having a pipe diameter of 1.83 m and draining an area of approximately 256 ha of industrial and residential land. The outfall is located near the upstream limit of the AOC and interruptions in sampling due to lake-going vessels and pleasure craft were minimal.

Measured discharge data were not available for the Buffalo River. However, the U.S. Geological Survey maintains recording gauges on the three tributaries to the river (Figure 1) and mean daily discharge data were available for the gauges beginning in 1940. Simple summation of the discharges would underestimate flow entering the AOC since the gauges do not represent the entire contributing area. A proportional-area approximation has been used (13) to adjust the flow record for the upper end of the AOC and this approach was used here:

$$Q_t = Q_g \text{ x } (A_t/A_g) \qquad \text{(i)}$$

where $Q_t$ is the daily flow from the tributary into the AOC (m$^3$s$^{-1}$), $Q_g$ is the daily flow at the gauge in the tributary (m$^3$s$^{-1}$), $A_t$ is the total drainage area at the mouth of the tributary (km$^2$), and $A_g$ is the drainage area upstream of the gauge (km$^2$).

## METHODOLOGY

### Sediment Sampling

Sediment samples were taken from the riverbed using a modified polyethylene 60 cc syringe tube attached to the end of a pole. The syringe was inserted gently into the riverbed and the "mini cores" were then retrieved. Approximately the upper 3 cm of each core was extruded from the syringe into a sterile polyethylene bag. The samples immediately were placed on ice until processed in the laboratory. The syringe was washed thoroughly in river water and rinsed with sterile deionized water between each use to avoid cross-contamination.

Sediment samples were taken once per week (with the exception of 1 July and 29 July) from 3 June to 12 August, 1991. On the first three sample weeks, 15 samples were taken at 0.3 m intervals along a transect 1.5 m out from the sewer outfall mouth. After the third sample week (17 June), three fewer samples were taken in front of the outfall and three cores routinely were taken at a location 180 m upstream from the outfall and 5 m from the north bank. Water depth typically was 5 m at both the outfall and upstream sites.

### Water Sampling

Water samples were obtained from 1 m below the surface using a Wheaton manual screw-type sampler and sterile glass bottles. Duplicate 400 ml water samples were taken on

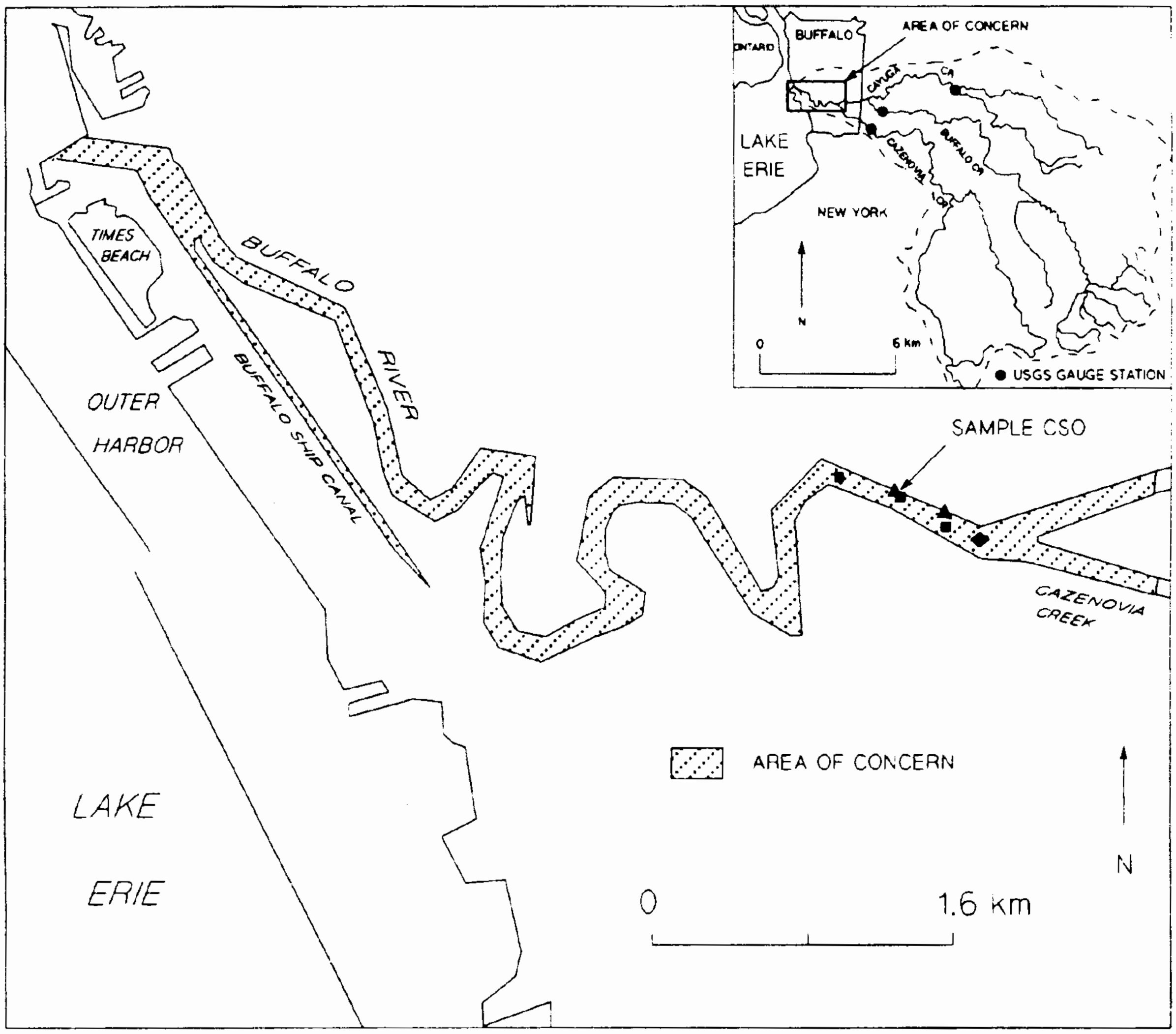

Figure 1. The Buffalo River watershed (inset) and Area of Concern. Symbols are: water sample locations (■); sediment sample locations (▲); and flow velocity measurement location during storm events (♦).

the same days as sediment samples and were obtained from mid-channel at the locations shown in Figure 1. Duplicate samples also were taken 1.5 m out from the centre of the sewer outfall mouth. The water samples immediately were placed on ice until processed in the laboratory.

Flow velocity measurements were taken at the water sampling site in front of the sewer outfall mouth using a Montedoro-Whitney PVM 2-A electronic velocity meter. Measurements were taken within 5 cm of the bed. Water samples also were taken (1 m below the surface) at the upstream, downstream and outfall mouth sites (Figure 1) to determine temperature, pH, conductivity and total suspended solids concentration.

## Sewer Sampling

The automated sampling equipment near the mouth of the combined sewer outfall consisted of a Montedoro-Whitney System Q flow measurement device connected to a Sigma Steamline Model 700 Composite Sampler. Flow measurements were recorded at 5-minute intervals and when an overflow was detected, the System Q signalled the composite sampler to initiate sampling on a flow-proportioned basis. Overflow samples from 1991 were used for organic compound rather than bacteria analysis (10). However, the overflow quantity data collected by the System Q were available for our study.

Although samples of the combined sewer

overflows were not obtained for bacteria analysis, duplicate grab samples of the sanitary flow near the overflow chamber were taken in the morning, at noon and late afternoon on 2 August, 1991. The sanitary samples were placed on ice until processed in the laboratory.

## Laboratory Methods

### *Bacteria:*

Water and sediment samples generally were processed within six hours when enumerating bacteria. Each sediment sample was mixed manually in the collection bag before being weighed to minimize separation of sediment and water phases. Ten grams of mixed sediment from each sample was aseptically weighed, added to 90 ml of sterile 0.1% peptone water and homogenized in a sterile blender at high speed for 20 s. The homogenized sediment was added to a sterile beaker and kept in suspension by a magnetic stirrer. This slurry was used to make further dilutions or to inoculate media. Additionally, triplicate 5 g amounts of each sediment sample were weighed and dried at 105°C for 24 h to determine the sample dry weight. Water samples were shaken vigorously before use, but were not otherwise treated.

All water and sediment samples were analyzed for total coliforms, faecal coliforms, and faecal streptococci. Selected samples also were analyzed for *E. coli*. All groups of bacteria were enumerated using a 5-tube Most Probable Number (MPN) technique (14). Briefly, total coliforms were determined using lauryl tryptose broth (LTB) as the presumptive medium and brilliant green bile broth as the confirmation medium. Faecal coliforms were determined by subsampling gas-positive lauryl tryptose tubes to EC medium tubes which were then incubated at 44.5°C in a circulating water bath. *Escherichia coli* density determinations were made using lauryl tryptose broth containing 4-methylumbelliferyl-β-D-glucuronide (MUG). These LTB-MUG tubes were incubated for 24-48 h and were scored as positive for *E. coli* only if they exhibited a blue-white fluorescence when exposed to long wavelength ultraviolet light. Faecal streptococci densities were estimated using azide dextrose broth as a selective medium. Tubes showing turbidity after 24 or 48 h were streaked onto bile esculin azide agar and were considered positive if the medium developed a black colour. All MPN calculations were made using published charts (14). Incubations were at 35°C, except where noted. All bacteriological media were purchased from Difco Laboratories, Detroit, Michigan.

### *Sediment and conventional parameters:*

A subsample of 7-10 g (dry weight) was taken from each core to determine loss-on-ignition at 440°C. The general methodology to determine loss-on-ignition followed that described in (15). Approximately 0.4 g of each subsample used in the loss-on-ignition analysis was mixed with a 10% sodium hexametaphosphate solution (to disperse flocs) and the sediment/water slurry was stirred mechanically for 5 minutes. The slurry subsequently was passed through filters having pore sizes of 60 μm, 5 μm and 0.45 μm. This filtration technique followed that discussed in (16) and essentially divided the bed sediment into sand (>60 μm), silt (5-60 μm) and clay (<5 μm) fractions. Samples for suspended solids concentration determinations were filtered through 0.45 μm Millipore filters.

The pH and conductivity of the water samples were determined using an Accumet 915 pH meter and an Hanna Instruments HI8633 conductivity meter, respectively. The meters were calibrated weekly with commercially available solutions.

## RESULTS

The period from 1 March to 31 May, 1991 was characterized by intermittent heavy rains that contributed to large fluctuations of discharge in the Buffalo River (Figure 2). During the period of our study (3 June-12 August, 1991), flows typically were steady-state baseflows, although several small, basin-wide runoff events also were observed (Figure 2, inset).

Combined sewer overflow events occurred at the monitored site during the month of April. Short duration, localized, intense storms also produced overflows on 29 May; 4, 7 and 8 July. The overflow volumes for these latter four events ranged between 0.018 and 4060 $m^3$ (average 1172 $m^3$) while peak overflow rates ranged between 0.00005 and 1.11 $m^3s^{-1}$ (average 0.35 $m^3s^{-1}$). The average peak overflow rate and volume for the sample period of record since 1990 were 0.406 $m^3s^{-1}$ and 2941 $m^3$, respectively. Overflow characteristics are discussed in more detail in (10). Although instantaneous river discharge data were not available for this study, the sewer overflow volumes can be compared to the daily mean river discharge. The largest overflow in our study period occurred on 4 July, having a total volume of 4060 $m^3$ and a duration of 2.8 hours. As

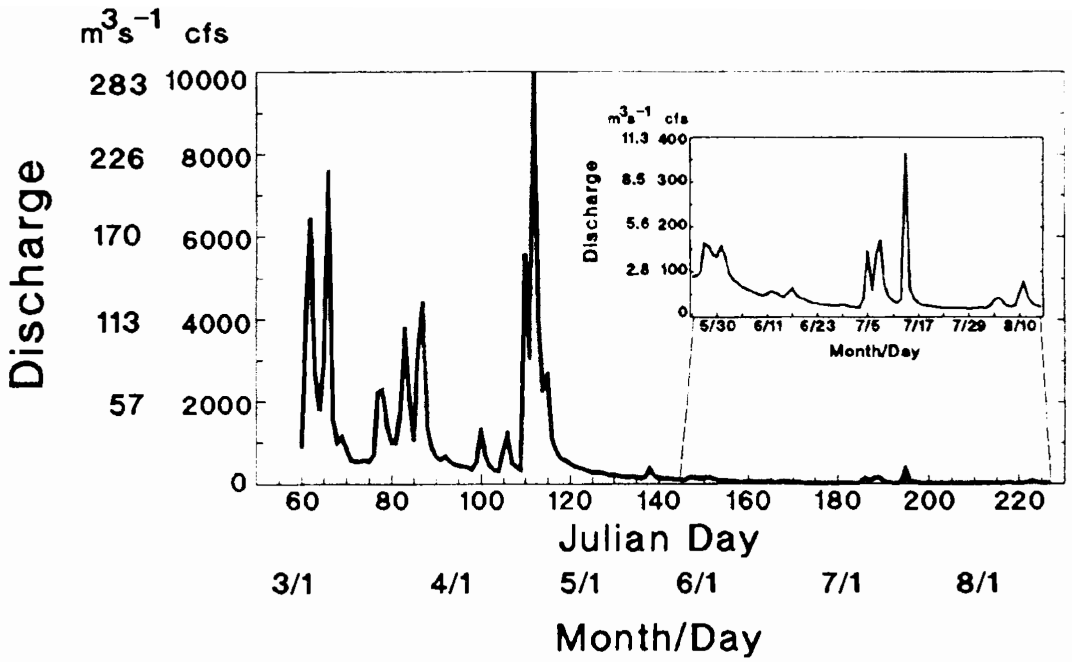

Figure 2 Daily mean discharge into the top of the Area of Concern, 1 March to 15 August; and 24 May to 15 August (inset).

computed using equation (i), river flow volume was 11794 m$^3$ for the same time period. Therefore, this single major combined sewer outfall may have contributed up to 34% of the river discharge during the overflow event. Large CSO contributions of this type occur primarily in the summer when localized, intense storms generate overflows but not large events within the entire watershed.

## Densities of Bacteria in Sediment

Weekly mean densities of all bacterial groups enumerated from the sediment taken along the sample transect are shown in Figure 3. Mean MPN values for total coliforms were between $10^3$-$10^4$ $g^{-1}$ (dry weight) of sediment. Faecal coliform densities ranged between 21-51% of total coliform values. Mean MPN values for *E. coli* typically were between 50-160% of faecal coliform values. *Escherichia coli* densities that were higher than faecal coliforms in some samples possibly may be explained by the presence of anaerogenic *E. coli* in approximately 4% of the EC medium MPN tubes (17). The density of faecal streptococci in sediment was lower than faecal coliform densities by 0.8 to 2.1 logs. All bacterial groups appeared to exhibit similar trends in sediment and all means increased for the sample period following the CSOs of 4, 7 and 8 July.

Densities of indicator bacteria in the sediment upstream of the sample transect were similar to those found near the outfall, except following the CSOs of 4, 7 and 8 July. The mean counts at the upstream site were approximately half of those at the outfall site after the overflow event.

## Densities of Bacteria in Water and Sanitary Flow

The densities of all bacterial groups enumerated from the river water samples are shown in Figure 4. For simplicity, Figure 4 represents the geometric mean of the 6 water samples taken each week (2 duplicates at 3 sites), except for *E. coli*, which was determined for one randomly selected sample. The variability between same-week samples (as represented by the vertical outlier bars) was smaller for the water samples than for the sediment samples. However, the week to week variability of mean densities tended to be greater for water than for sediment (Figures 3 and 4). Bacterial densities were highest in the water following the CSOs (4, 7 and 8 July) and following small, basin-wide runoff events that did not produce CSOs in the South Buffalo area (i.e. 14 July, 5 August, 11 August).

The geometric mean densities of total

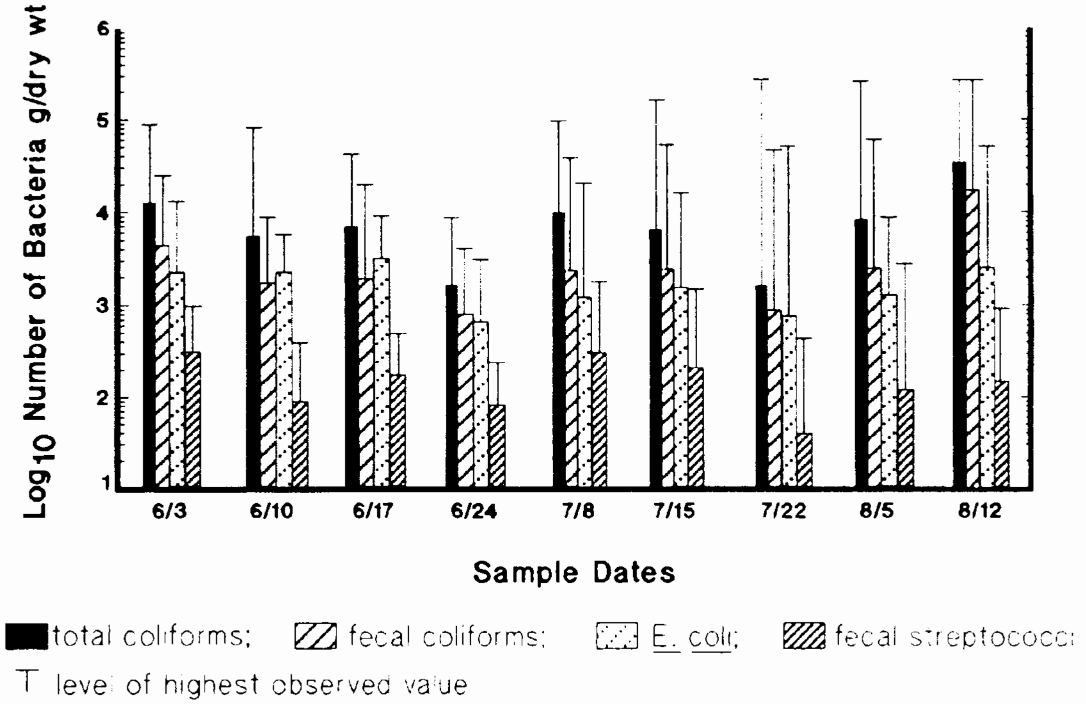

Figure 3. Weekly mean densities of indicator bacteria in sediments along sample transect at the mouth of the combined sewer outfall.

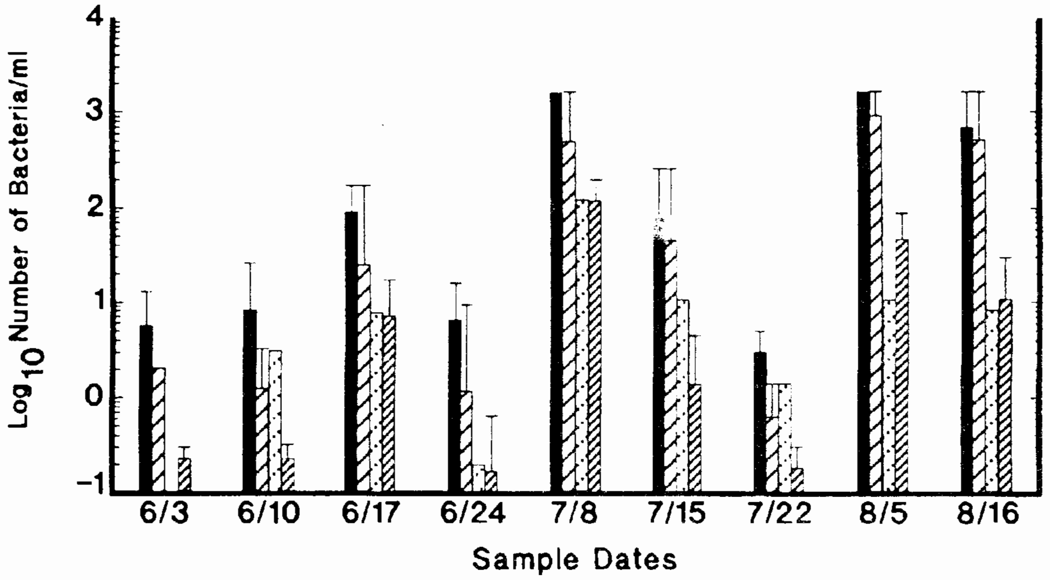

Figure 4. Weekly mean densities of indicator bacteria in river water. Symbols are the same as in Figure 3.

coliforms, faecal coliforms and faecal streptococci for the 6 samples (duplicates at 3 different times) of sanitary flow were 91,000, 42,000, and 5,000 ml$^{-1}$, respectively. *E. coli* was not determined for the sanitary samples. Geometric mean densities of total coliforms, faecal coliforms and faecal streptococci in the sanitary flow were 2.7-4.5; 3.2-4.8; and 2.7-4.5 logs greater, respectively, than in the sampled river water associated with non-storm events. A smaller difference was observed between bacteria densities from the sanitary flow and the river samples taken after small, basin-wide storm events (8 July, 5 and 12 August). The smaller difference results from the higher bacteria densities in the basin-wide storm runoff.

Conventional Parameter Characteristics

The bed sediment size distributions were similar for the samples taken at the mouth of the sewer outfall and at the upstream site (Figure 5). The mean percent sand, silt and clay for the different weeks at the two sites ranged between 39.6-53.7% (sand); 46.4-59.6% (silt); and 0.4-1.5% (clay). A qualitative examination of the data indicated no distinct relationships between sediment size and river flow rate or sewer overflow events for the study sample period.

The weekly mean organic content of sediment near the mouth of the outfall ranged between 4.20 and 4.56% during the sample period (standard deviation range was 0.26 to 0.68%). The weekly mean organic content of sediment at the upstream site ranged between 4.79 and 5.39% (standard deviation range was 0.15 to 1.11%). Although mean organic content did increase in the week after the CSOs of 4, 7, and 8 July, and in the week following a basin-wide runoff event (14 July), the sample standard deviations suggested that the increases were not significant.

The data for the conventional water parameters are summarized in Table 1. The relatively small range of the parametric values reflects the general steady-state condition of the river during the sample period. The small, basin-wide runoff events had minimal impact on the sampled conventional water parameters, although the highest suspended sediment concentrations were observed in association with the 8 July event. The limited conventional parameter response to small events also, in part, may be a function of the time at which the samples were collected. It was beyond the scope of this study to collect multiple samples through an event to assess the relationship between conventional parameters and instantaneous river discharge.

Bacteria levels from the duplicate water samples at each site for each sample date were averaged and correlations were calculated between bacteria levels, total suspended solids concentrations, pH and conductivity. Correlations between faecal coliform levels at all sites (n=21) and total suspended solids concentrations, pH and conductivity were 0.259, -0.700 and 0.024, respectively. It should be noted that the relationship between faecal coliform levels and pH was curvilinear and a log-log

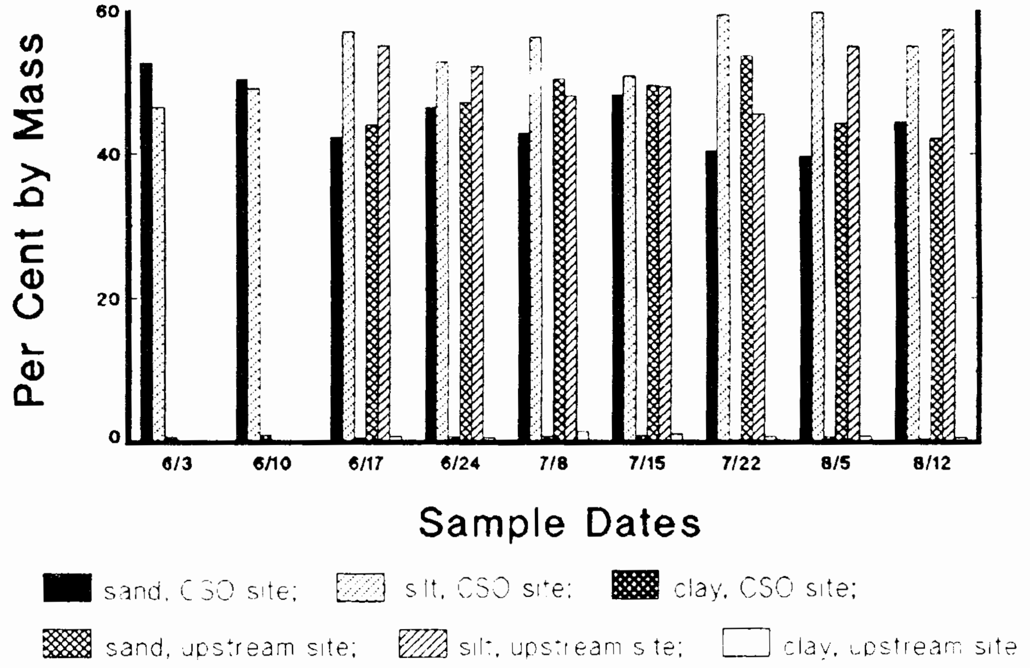

Figure 5. Particle size distribution of bed sediment at the mouth of the combined sewer outfall and upstream site.

Table 1. Conventional water parameters.

| | Total Suspended Solids, mgl$^{-1}$ | pH | Conductivity, µmhos | Flow Velocity, ms$^{-1}$ |
|---|---|---|---|---|
| Mean* | 10 | 7.28 | 437 | 0.03 |
| Range | 8-19 | 6.84-8.09 | 407-475 | -0.09 - +0.01 |

* The mean and range for total solids, pH and conductivity represent all samples taken at the 3 sites while the mean and range for velocity represents measurements taken near the mouth of the outfall (within 5 cm of the river bed). Negative velocities result from flow reversals in the river and mean velocity was calculated from absolute velocity values.

transformation therefore was used in the correlation analysis. Correlations between faecal streptococci levels at all sites (n=21) and total suspended solids concentrations, pH and conductivity were 0.727, -0.671 and -0.039, respectively. A log-log transformation was used in the faecal streptococci-pH correlation. The few data from the small, basin-wide runoff events had a particularly large influence on the correlation results between bacteria levels and total suspended solids concentrations.

### Sediment/Bacteria Relations

Correlations between indicator bacteria and organic matter (represented by loss-on-ignition) are shown in Table 2 for the site at the mouth of the sewer outfall. Table 3 presents correlations between bacteria and only the sand size class, since this size class generally represented the highest r values. Relationships between bacteria, organic matter and particle size for the site at the sewer outfall typically were weak. Stronger correlations were observed in the two weeks (15 July, 22 July) following CSOs (4, 7 and 8 July). Multiple regression was done using organic matter and sand content as independent variables and the results for the two sample weeks after the overflow events are shown in Table 4. The magnitude of the equation co-efficients and a Student's t-Ratio indicate that organic content is the dominant factor in explaining bacteria density variability in the samples after the overflow events.

## DISCUSSION

We found that indicator bacteria were maintained at high levels in sediments characterized by a high sand and silt content (Figure 5) both near the mouth of a major combined sewer outfall and at a site upstream of the outfall (but downstream from other combined sewer outfalls). High indicator bacteria levels were maintained throughout the sample period (Figure 3) although there were only three small

Table 2. Correlation (r) between indicator bacteria levels and organic content, sewer outfall site.

| | Bacteria | | | |
|---|---|---|---|---|
| Sample Date | TC | FC | Ec | FS |
| 6/3 | 0.186 | -0.007 | -0.825 | 0.079 |
| 6/10 | 0.001 | -0.177 | 0.137 | 0.074 |
| 6/17 | 0.319 | -0.017 | 0.947 | -0.026 |
| 6/24 | -0.712 | -0.209 | -0.885 | 0.223 |
| 7/8 | 0.213 | 0.188 | 0.265 | 0.233 |
| 7/15 | 0.643 | 0.702 | 0.936 | 0.565 |
| 7/22 | 0.673 | 0.665 | 0.824 | 0.486 |
| 8/5 | -0.294 | -0.349 | 0.179 | -0.092 |
| 8/12 | 0.122 | 0.233 | 0.178 | 0.048 |

TC - total coliforms; FC - faecal coliforms; Ec - *E. coli*; FS - faecal streptococci

Table 3. Correlation (r) between indicator bacteria levels and per cent sand, sewer outfall site.

| Sample Date | Bacteria | | | |
|---|---|---|---|---|
| | TC | FC | Ec | FS |
| 6/3 | 0.257 | 0.492 | 0.011 | 0.134 |
| 6/10 | -0.234 | -0.314 | 0.132 | -0.193 |
| 6/17 | 0.318 | 0.316 | 0.328 | 0.410 |
| 6/24 | 0.510 | 0.041 | -0.013 | -0.516 |
| 7/8 | -0.389 | -0.431 | -0.103 | -0.232 |
| 7/15 | 0.246 | 0.378 | 0.413 | 0.269 |
| 7/22 | 0.468 | 0.561 | 0.716 | 0.467 |
| 8/5 | 0.604 | 0.559 | -0.100 | 0.281 |
| 8/12 | 0.220 | 0.167 | 0.330 | -0.454 |

TC - total coliforms; FC - faecal coliforms; Ec - *E. coli*; FS - faecal streptococci

Table 4. Post-CSO event regression for bacteria and sediment (at the mouth of the sewer outfall).

| Equation* | Std. Dev. of Coef. | | | t-Ratio | | | $r^2$ |
|---|---|---|---|---|---|---|---|
| | $b_o$ | $b_1$ | $b_2$ | $b_o$ | $b_1$ | $b_2$ | |
| $tc_A$=-219584-1279sa +70051org | 129307 | 2766 | 29207 | -1.70 | -0.46 | 2.40 | 43 |
| $fc_A$=-77360+8sa +19108org | 34014 | 728 | 7683 | -2.27 | 0.01 | 2.49 | 49 |
| $fs_A$=-1705-3.9sa +510org | 1244 | 27 | 281 | -1.37 | -0.15 | 1.81 | 32 |
| $tc_B$=1026740+5675sa +190662org | 336337 | 4818 | 79007 | -3.05 | 1.18 | 2.41 | 53 |
| $fc_B$=-183214+1361sa +31040org | 55426 | 794 | 13020 | -3.31 | 1.71 | 2.38 | 58 |
| $fs_B$=-1136+10.4sa +184org | 593 | 8.5 | 139 | -1.92 | 1.23 | 1.32 | 34 |

* General form of the equation: $y = b_o + b_1x_1 + b_2x_2$. The short forms for the equations: $tc_A$, $fc_A$, $fs_A$ are total coliforms, faecal coliforms and faecal streptococci densities in sediment (counts $g^{-1}$), respectively for the sample week 15 July; $tc_B$, $fc_B$, $fs_B$ are total coliforms, faecal coliforms and faecal streptococci densities in sediment (counts $g^{-1}$), respectively for the sample week 22 July; sa is per cent (by weight) sand content of the sediment; and org is per cent (by weight) organic content of the sediment.

basin-wide runoff events and three closely spaced sewer overflow events. It was not determined whether the indicator bacteria were bound to sediment particles or existed free-living in sediment pore water. In either case, bacteria could be resuspended during periods of increased bed shear velocity.

A more detailed analysis of sediment size distribution using dry sieving and hydrometry was done by (18) for two sites near the sample area. In general, the size distribution determined in our study and by (18) (4% gravel; 32% sand; 55% silt; and 9% clay) are comparable. The more detailed data from (18) therefore can be used in evaluation of resuspension rates.

Resuspension of bacteria-colonized sediments in the Buffalo River may result from higher flow velocities associated with storm events. Flow velocities generally were low during the period of our study. However, velocity measurements were taken during storm events in 1990, 1991 and 1992 at a mid-channel location, approximately 500 m upstream from our outfall site. Daily mean discharges for the sampled events ranged between 28 and 89 $m^3 s^{-1}$ and had corresponding velocities of between 14 and 42 $cm s^{-1}$.

River discharge is related to flow velocity in the general form:

$$Q = w \times d \times \bar{u} \qquad (ii)$$

where Q is discharge ($m^3 s^{-1}$); w is river width (m); d is river depth (m); and $\bar{u}$ is mean flow velocity ($ms^{-1}$). This relationship can be used to provide a preliminary estimate of the frequency of resuspension from storm events and the size of the sediment that would be resuspended. The well-known Hjulstrom diagram relates the size of sediment that can be eroded or transported to mean flow velocity (19). Although the Hjulstrom diagram was developed under idealized flume conditions, it can be useful in providing a preliminary indication of the sediment sizes that may be resuspended in the Buffalo River. The Hjulstrom diagram (not shown) indicates that at the low end of the observed event flow velocities (e.g. 14 $cms^{-1}$), material with diameters of 0.12-0.5 mm (fine to medium sand) could be resuspended. The higher observed mean velocities (e.g. 42 $cms^{-1}$) could resuspend material with diameters of 0.027-2.4 mm (silt to very coarse sand). These resuspension estimates do not consider the influence of bacterial colonization of sediment particles and most models assume that sediment is entrained and transported as discrete particles rather than flocs. Studies of floc dynamics in fluvial systems are limited in number and numerical models for flocculation are still being developed (20, 21).

A flow duration curve for the upper AOC was developed by (13) using the daily mean data (equation i) for the period 1940-1985. A flow duration curve essentially represents the observed cumulative frequency that a given flow is equalled or exceeded. The flow duration curve developed by (13) would be valid for the site at which the event flow velocity measurements were taken. Flows in the 89 $m^3 s^{-1}$ range (corresponding to the higher mean velocities) were equalled or exceeded approximately 3.5% of the time during the period of record. Therefore, on average, resuspension of a range of different sized material (silt to very coarse sand) would occur 13 days per year.

Another potential cause of sediment resuspension in the river is the turbulence resulting from lake-going ship traffic. It has been observed (22) that a range of maximum bottom velocities (33.5-570 $cms^{-1}$) may be produced by the propeller action of large ships in confined channels. These velocities would be capable of resuspending most sediment sizes in the Buffalo River. Large ship traffic currently is infrequent in the upper part of the AOC near our sample site, but a traffic density of 1 to 3 ships per week is not uncommon during spring to fall in the lower part of the river.

Resuspension of bacteria-bound particles can lead to an impairment of water quality (e.g. 2, 7, 23). Our data indicate a viable population of enteric bacteria was maintained throughout the summer in the sediments at our sample sites. Although the relative contribution of bacterial growth *in situ* and input from upstream sources was not evaluated, the influence of CSOs on sediment bacteria populations in the sample transect was seen as an increase in the density of all bacterial groups for two weeks after the CSOs. Bacteria-laden sediment may be resuspended in the Buffalo River by factors including natural storm events, dredging and ship traffic. The re-introduction of enteric bacteria into the water column represents a health risk, particularly since the Buffalo River is used for swimming and recreational boating. The importance of sediment-water interactions recently has been recognized in the United States through proposed amendments to the Clean Water Act. Sediment quality standards have not previously been considered, but the proposed amendments consider toxic, nonconventional and conventional parameter levels (including faecal coliforms). This emphasis on sediment quality suggests a need for continued research on the dynamics of indicator populations in sediment (including the effects of seasonality) and the potential for introduction to the water column from resuspension.

Although bacteria densities in the sediment generally are high, the physical characteristics of the sediment measured in this study account for only a small percentage of the density variability (Tables 2 and 3). The explanatory power of the physical characteristics increases for a period of time immediately after CSOs (Table 4), indicating that the physical characteristics of the sediment in the overflow and bacteria densities are related. Weak (positive) correlations between faecal coliforms and sediment size and total organic carbon also have been reported by (3). It is possible that other factors not measured in this study, such as predation of bacteria by protozoa, may affect faecal coliform and faecal streptococci densities in the sediment (24).

The distance from a combined sewer outfall or sewage treatment plant discharge can be a dominant factor explaining the spatial variability of bacteria densities in sediment (3, 25). The impact of the sample overflow on densities of bacteria in the sediment and the relationship between densities and the physical characteristics of sediment in this study may be obscured because of multiple bacteria sources to the AOC. For example, the densities of indicator bacteria in the sediment at the site upstream of the sewer outfall were similar to those found near the outfall, except following the CSOs of 4, 7 and 8 July, as noted above. Sources of bacteria for the upper AOC may include 27 combined sewer outfalls within the city of Buffalo; discharges from small, upstream package plants; poorly functioning septic drainfields and agricultural activities.

Geometric mean faecal coliform levels in river water were several logs lower than in the sediment, but exceeded the state guidelines for primary contact (200 counts per 100 ml) in six of the nine sample weeks. It appears that although the several small, basin-wide events did not result in local sewer overflows, bacteria were transported to the AOC from upstream tributaries. These results also suggest the importance of contributions from multiple upstream activities.

Although faecal coliform densities would be diluted by stormwater runoff, the high counts in the sanitary flow, combined with a large proportion of volumetric input to the river flow, indicate that the sampled sewer outfall would have a periodic negative impact on river water quality. These impacts would be greatest during summer lowflow periods when dilution by natural river flow is minimal. The summer also is the period of heaviest recreational use and therefore potentially represents a time of greatest health impacts.

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## REFERENCES

1. E.A. Matson, S.G. Horner and J.D. Bock, Pollution indicators and other microorganisms in river sediment. *J. Water Pollut. Control Fed.*, **50**, 13-19 (1978).
2. Goyal S.M., Gerba C.P. and Melnick J.L., Occurrence and distribution of bacterial indicators and pathogens in canal communities along the Texas coast. *Appl. Environ. Microbiol.*, **34**, 139-149 (1977).
3. Shairis M.P., Rex A.C., Pettibone G.W., Keay K., McManus P., Rex M.A., Ebersole J. and Gallagher E., Distribution of indicator bacteria and *Vibro parahaemolyticus* in sewage-polluted intertidal sediments. *Appl. Environ. Microbiol.*, **53**, 1756-1761 (1987).
4. J.B. Ellis, R. Hamilton and A.H. Roberts, Sedimentary characteristics of suspensions in London stormwater. *Sediment. Geol.*, **33**, 147-154 (1982).
5. R.W. Hoffman and R.B. Meighan, The impact of combined sewer overflows from San Francisco on the western shore of central San Francisco Bay. *J. Water Pollut. Control Fed.*, **56**, 1277-1285 (1984).
6. Klemetson S.L., Factors affecting stream transport of combined sewer overflow sediments. *J. Water Pollut. Control Fed.*, **57**, 390-397, (1985).
7. McDonald A., Kay D. and Jenkins A., Generation of fecal and total coliform surges by stream flow manipulation in the absence of normal hydrometeorological stimuli. *Appl. Environ. Microbiol.*, **44**, 292-300 (1982).
8. Mar P., Clean Up Rural Beaches (CURB) Report, Report to the Ontario Ministry of Environment from the Metropolitan Toronto and Region Conservation Authority (1991).
9. New York State Department of Environmental Conservation, Buffalo River Remedial Action Plan, Report the International Joint Commission (1989).
10. Irvine K.N., Loganathan B.G., Pratt E.J. and Sikka H.C., Calibration of PCSWMM to estimate metals, PCBs and HCB loadings in CSOs from an industrialized sewershed, Buffalo, NY. In: *New Techniques for Modelling the Management of Stormwater Quality Impacts*, James W. (ed.), Lewis Publishers, Inc., Boca Raton, FL, Chapter 10 (1993).
11. Wang P-F. and Martin J.L., Temperature and conductivity modeling for the Buffalo River. *J. Great Lakes Res.*, **17**, 495-503 (1991).
12. Calocerinos and Spina, Buffalo Combined Sewer Overflow Phase II Study, State Project C-36-1044-01-3 (1989).
13. Meredith D.D. and Rumer R.R., Sediment Dynamics in the Buffalo River. Report, Department of Civil Engineering, State University of New York at Buffalo (1987).
14. Water Pollution Control Federation, *Standard Methods for the Examination of Water and Wastewater*, 17th ed., Washington, D.C. (1989).

15. U.S. Department of the Interior, Bureau of Reclamation. Publication USBR 5430-89, Denver, CO (1990).
16. Irvine K.N., Drake J.J. and James W., A dynamic, physically-based method for estimating erosion of pervious urban land. *Canadian Water Res. J.*, **15**, 303-318 (1990).
17. Pettibone G.W., The use of lauryl tryptose broth containing 4-methylumbelliferyl-β-D-glucuronide (mug) to enumerate *Escherichia coli* from freshwater sediment. *Letts. Appl. Microbiol.*, **15**, 190-192 (1992).
18. Aqua Tech, Inc. Sediment Analyses Buffalo River, and Harbor, Buffalo NY, Technical Report #G0193-06A, for the U.S. Army Corps of Engineers, Buffalo District (1989).
19. Knighton D., *Fluvial Forms and Processes*. Edward Arnold, Baltimore, MD, 218 pp. (1987).
20. Lick W., Gailani J., Cardenas M. and Pickens K., Sediment and contaminant transport and fate in rivers. In: *Proceedings International Symposium on Environmental Dredging*, Erie County Environmental Education Institute, Buffalo, NY, Chapter 3 (1992).
21. Droppo I.G. and Ongley E.D., The state of suspended sediment in the freshwater fluvial environment: a method of analysis. *Water Res.*, **26**, 65-72 (1992).
22. Liou Y.C. and Herbich J.B., Sediment Movement Induced by Ships in Restricted Waterways. Texas A&M University, for the U.S. Army Corps of Engineers, Report No. 188 (1976).
23. Grimes D.J., Bacteriological water quality effects of hydraulically dredging contaminated upper Mississippi River bottom sediment. *Appl. Environ. Microbiol.*, **39**, 782-789 (1980).
24. Marino R.P. and Gannon J.J., Survival of fecal coliforms and fecal streptococci in storm drain sediment. *Water Res.*, **25**, 1089-1098 (1991).
25. Loutit M.W. and Lewis G., Faecal bacteria from sewage effluent in sediments around an ocean outfall. *New Zealand J. Marine Freshwater Res.*, **19**, 179-185 (1985).