

## Chapter 14

### **Indicator Bacteria-Sediment Relationships: Implications for Water Quality Modeling and Monitoring**

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The sanitary quality of water is routinely monitored by testing for fecal coliforms and fecal streptococci (indicator bacteria). Indicator bacteria may not be pathogenic, but high levels in water suggest a greater probability for the presence of pathogenic bacteria and human health risks (Geldreich, 1990). Many bathing areas throughout the Great Lakes Basin

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commonly are closed due to elevated fecal coliform levels. Concern over beach closings and degraded water quality has resulted in the initiation of various remedial programs such as the Metropolitan Toronto and Region Conservation Authority's (MTRCA) Rural Beaches Project. The long-term goals of the MTRCA project are to improve water quality at identified problem beaches and provide technical assistance towards improving surface water quality in all of the Authority's rural waterways (Mar, 1991).

Indicator bacteria may be concentrated in river or lake-bed sediment through deposition of bacteria-bound particles. These sediments may act as a source of nutrients, provide protection from the destructive action of sunlight and protect against predation by other microorganisms. As a result, the sediment may serve as a reservoir for enteric bacteria. Bacteria-colonized bed sediment may become resuspended by perturbations, including storm events, ship/boat passages and swimmers, thereby negatively affecting water quality.

Bacteria may colonize suspended sediment within various environments, including freshwater and combined sewer systems, and this may serve as one mechanism that generates flocculation (i.e. the joining of several discrete particles that move as a single unit). Flocculation modifies the hydrodynamic properties of the particles and this will affect the transport of particle-bound contaminants.

Data collected for the Buffalo River, NY and tributaries are used to illustrate the interactions between bacteria and sediment and the implications for water quality modeling and monitoring are discussed. Specifically, the levels of indicator bacteria in riverbed sediment are examined on a seasonal and annual basis and the probability of resuspension is evaluated. The relationships between total suspended solids and bacteria levels at several sites within the Buffalo River watershed are examined through simple correlation analysis. Finally, sediment floc characteristics are examined for freshwater and sanitary sewage samples collected within the Buffalo River watershed and the role of bacteria in the flocculation of these samples is discussed.

## **14.1 Previous Research on Bacteria-Sediment Interactions**

Numerous studies have examined the levels of indicator bacteria and pathogens in the sediment of a variety of marine and freshwater

environments (Hendricks, 1971; Van Donsel and Geldreich, 1971; Goyal et al., 1977; Loutit and Lewis, 1985; Marino and Gannon, 1991; Albinger, 1992; Irvine and Pettibone, 1993). The levels of fecal coliforms in sediment often are reported to be from 1 to 4 orders of magnitude greater than the levels in overlying water and it has been suggested that the bacteria may be concentrated in the sediment through deposition of bacteria-bound particles (Van Donsel and Geldreich, 1971; Matson et al., 1978; Irvine and Pettibone, 1993). Once inoculated, river and lake bed sediments may have the ability to maintain high levels of fecal coliforms for a period of at least one week and up to several months (Van Donsel and Geldreich, 1971; Irvine and Pettibone, 1993). Longer survival rates in sediment, as compared to freshwater, are possibly due to a combination of factors, including abundant nutrient sources; and protection from solar radiation, bacteriophage and microbial toxicants and predation by other aquatic microorganisms (Schillinger and Gannon, 1985; Burton et al., 1987). Recent experimental studies using a recirculating river/flume model indicated that fecal coliforms even had some ability to multiply in urban stormwater drain sediments (Marino and Gannon, 1991). The relationships between indicator and various pathogenic bacteria have been examined and it has been found, for example, that the isolation of salmonellae in sediment typically corresponded to areas having fecal coliform levels of at least 2,000 M.O./100 ml in the overlying water (Van Donsel and Geldreich, 1971; Goyal et al., 1977). Van Donsel and Geldreich (1971) indicated that the survival rates of salmonellae and fecal coliforms were similar in various types of sediment. Burton et al. (1987), using a flow-through microcosm, found that there was no statistically significant difference in the survival rate of *Pseudomonas aeruginosa*, *Salmonella newport*, *Escherichia coli*, and *Klebsiella pneumoniae*. However, there was a consistent trend for *P. aeruginosa* and *K. pneumoniae* to survive longer than *E. coli* and *S. newport*.

Attempts have been made to explain the variability of bacteria levels in sediment using correlations with other environmental parameters and this has produced mixed results. Shiaris et al. (1987) found a strong positive correlation between fecal coliform densities and total organic carbon content in intertidal sediments affected by combined sewer discharges. A weak negative correlation was found between fecal coliform densities and median particle diameter. Albinger (1992) found a significant positive correlation between fecal coliform densities in sediment and organic content (measured through loss-on-ignition); and a significant

negative correlation with sediment size. Burton et al. (1987) qualitatively found that pathogenic bacteria tended to survive longer in sediments having at least 25% clay, but did not find that organic content positively influenced survival rate. Irvine and Pettibone (1993) found a strong positive correlation between fecal coliform densities and organic content in river sediment adjacent to a combined sewer outfall for two weeks after a major overflow event. However, a weak positive correlation was also observed between fecal coliform densities and sand content in the sediment samples. Both Shiaris et al. (1987) and Goyal et al. (1977) found that fecal coliform densities in sediment decreased with distance from a combined sewer outfall.

Bacteria-colonized bed sediments may become resuspended by perturbations and this may re-introduce pathogens to the water column. McDonald et al. (1982) produced resuspension events in a river through the release of additional water from an upstream reservoir. The additional discharge increased downstream shear velocities, but this practice also controlled inputs of bacteria from stormwater runoff. Total coliform and *E. coli* levels in the river water increased more than ten-fold after reservoir releases and this was attributed to resuspension of riverbed sediment. Mar (1991) mechanically disturbed near-shore sediment at bathing beaches to simulate the action of swimmers. The geometric mean fecal coliform levels in the water of the disturbed samples were three times higher than the undisturbed samples and bacteria levels in individual disturbed samples were up to an order of magnitude greater than undisturbed samples. Gary and Adams (1985) also mechanically disturbed bottom sediment in the streams of a mountain watershed and sampled for fecal coliforms and fecal streptococci up and downstream of the disturbed area. The mean concentration of fecal coliforms for the downstream (disturbed) samples was 1.7 times greater than the mean for the upstream (undisturbed) samples, but this was not a significant difference ( $\alpha=0.05$ ). It should be noted that the fecal coliform densities in this environment were low, with the highest levels being 31 M.O./100 ml. The mean concentration of fecal streptococci was 2.7 times greater in the downstream (disturbed) samples as compared to the upstream samples and this was a significant difference ( $\alpha=0.01$ ). Grimes (1980) reported an increase in indicator bacteria densities of 4 to 50-fold in waters below a dredging operation on the Mississippi River compared to upstream waters.

Within the water column of a fresh or saltwater system, or within a combined sewer system, bacteria may colonize suspended sediment and promote flocculation. Furthermore, combined sewer discharges may be a

significant source of bacteria to receiving water bodies (Freedman and Marr, 1990) and may serve to further promote flocculation within these waters. Flocculation modifies the hydrodynamic properties of particles and affects transport of particle-bound contaminants. Discrete, fine particles that would not settle individually may settle as a floc. These fine particles may also preferentially adsorb organic and inorganic contaminants. However, flocs of a particular size would have a different settling velocity than a discrete particle of the same size, due to differences in density, porosity and shape. Much work has been reported on floc characteristics and flocculation mechanisms in the marine and sewage treatment literature (e.g. Kranck, 1984; Kranck et al., 1992; Muschenheim et al., 1989; Li and Ganczarczyk, 1991; Namer and Ganczarczyk, 1993; Urbain et al., 1993). Evaluation of freshwater flocs primarily has focused on size (both the effective (flocculated) and absolute (de-flocculated) distributions) and settling velocity (Droppo and Ongley, 1992; Lau and Krishnappan, 1992; Walling and Woodward, 1993; Auer and Niehaus, 1993; Nakamura et al., 1993). The marine and sewage treatment literature can help in our understanding of freshwater flocculation, although the relative importance of the various flocculation mechanisms will be environment-dependent. Factors in addition to bacteria that can affect flocculation include: organic carbon; major ions; suspended sediment concentration; pH; water turbulence and temperature (Kranck, 1984; Tsai et al., 1987; Muschenheim et al., 1989; Lau, 1990; Rao et al., 1991). It is clear that flocculation is common in freshwater fluvial systems and even may be the dominant form of sediment transport (Droppo and Ongley, in press).

Bertrand-Karjewski et al. (1993), in an extensive literature review on urban surface and sewer sediments, discussed research pertaining to organic and mineral fractions, size distributions, specific gravity and sediment cohesion, but did not specifically address flocculation dynamics. Michelbach and Wohle (1992) determined settling velocities for 134 combined sewage and combined sewer overflow samples, 55 dry weather samples and 80 slime/biofilm samples from sewers in Germany. The samples were plotted against percent dry weight, but floc characteristics were not explicitly evaluated. A recent international workshop on sewer sediment categorized three types of sediment: sanitary solids; fine (storm-water) material; and sewer grit (bed material) (Verbanck et al., 1994). It was suggested that the median size of sanitary waste typically ranged between 30 and 40  $\mu\text{m}$ , had median settling velocities of 0.4-0.5  $\text{mm s}^{-1}$

and densities near 1.0. Verbanck et al. (1994) recognized that stormwater solids flocculate, but emphasized that a precise definition of sewer sediment in terms of particulate and other physico-chemical characteristics had not yet been achieved.

Some recent modeling efforts have attempted to consider floc effects, although most open water and sewer models assume that particles behave discretely (Ongley et al., 1992; Bertrand-Krajewski et al., 1993). For example, Coghlan et al. (1993) employed a spreadsheet optimization procedure to account for particle diameter and specific gravity in the application of the Ackers-White model to estimate sewer sediment transport rates. Measurements of these variables were not made explicitly, but model validation runs produced estimated wet weather sediment concentrations that were in the range of 1/4 to 4 times the observed concentration for 91.3% of the samples. Ongley et al. (1992) examined the sensitivity of their modeling approach to the assumption of sediment flocculation. Model results for cross-sectional and longitudinal profiles of an area of the Grand River, Ontario showed differences of up to an order of magnitude in sediment concentration and sediment flux between flocculated and unflocculated runs. Gailani et al. (1991) modeled sediment transport in the Lower Fox River, Wisconsin using a two-dimensional, vertically-integrated, time-dependent hydrodynamic and transport model, coupled with a three-dimensional, time-dependent model of the sediment bed and associated physical properties. It was assumed that the modeled medium-sized sediment was cohesive and would flocculate. The average floc diameter was estimated using a function that considered fluid shear stress, sediment concentration and experimentally-determined constants. Settling velocities for the flocs also were estimated as a function of floc diameter, sediment concentration, fluid shear stress and experimentally-determined constants.

## **14.2 Study Methods**

### **14.2.1. Sample Locations and Methodology**

All sampling was done within the Buffalo River watershed. The lower Buffalo River has been designated an Area of Concern (AOC) by the International Joint Commission (IJC) due to observed environmental impairments. The entire watershed has an area of 1244 km<sup>2</sup>, although the AOC encompasses only the lower 9.2 km (Figure 14.1). There are a variety

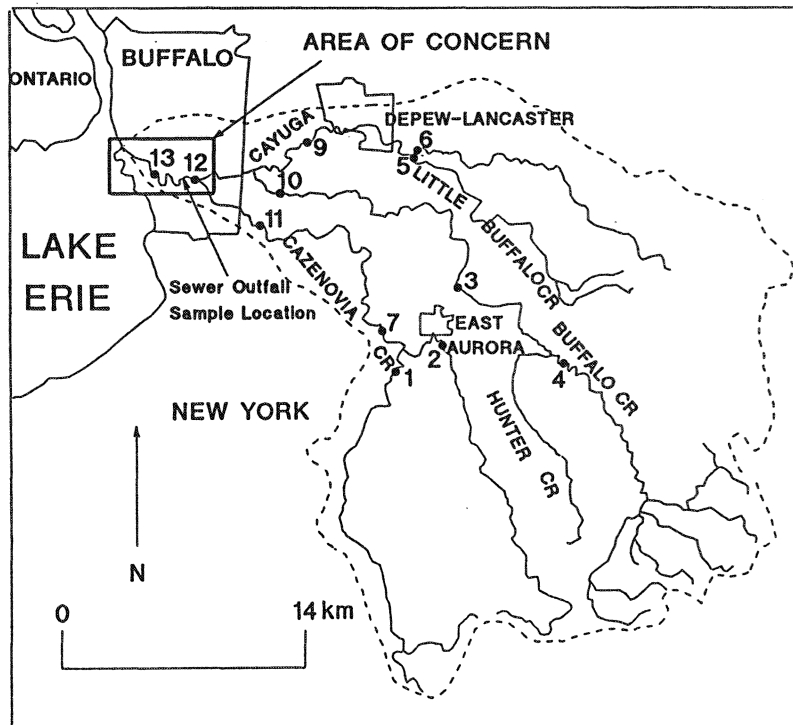
of pollutants (PCBs, pesticides, PAHs, metals, bacteria) and pollutant sources that discharge to the AOC (New York State Department of Environmental Conservation, 1989). Bacteria are input to the AOC from sources including 38 combined sewer outfalls that drain the mixed urban landuses of South Buffalo; general urban and suburban runoff; upstream municipal package plants; failing septic systems and agricultural runoff. Despite high bacterial counts, the river is used for swimming, water skiing and sailing. Most of the AOC is designated a navigable channel and is maintained at a minimum depth of 6.7m through dredging operations. The slope of the riverbed within the AOC averages 0.0002. In contrast, tributaries in the upper part of the watershed tend to be shallow and fast flowing, with slopes ranging between 0.001 and 0.007. Land-use in the upper watershed is a mix of agriculture and forest, with scattered small towns.

Samples of bed sediment within the AOC were collected at one site (site 13, Figure 14.1) using a mini-ponar dredge. Samples were taken weekly 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 1992-93. Ice cover prohibited sampling on two dates. Sub-samples of the sediment within the dredge were scooped into sterile Whirlpack polyethylene bags using sterilized aluminum spatulas. Care was taken to collect the sub-samples from areas that had not touched the dredge sampler. The samples were kept on ice in the field.

Water samples were collected at the same location as the sediment samples, on the same dates. Water samples were collected at one additional sample site within the AOC and at 10 sites within the watershed (Figure 14.1), also on the same dates. Water samples were collected 1m below the surface at the AOC sites (12 and 13) and 0.6 of the total depth below the surface at the sites upstream of the AOC. All sampling for bacteria was done aseptically and samples were kept on ice in the field. Samples at each site also were collected for analysis of pH, conductivity, dissolved oxygen, total suspended solids and dissolved solids.

Samples of suspended sediment in the water column were collected at sites 10, 11 and 13 (Figure 14.1) on 93.11.23 for analysis of bacteria levels and floc characteristics. The general sample methodology for bacteria determinations followed that described above. Sample methodology for floc determination followed that described by Droppo and Ongley (1992). Briefly, suspended solids were collected by placing a plankton settling chamber under the surface of the water and parallel to the direction of flow. The chamber was filled to capacity and capped under

water to minimize turbulence in the chamber. The particulate matter in the samples was settled for 24 hours onto the settling chamber's glass microscope slide prior to preparation for image analysis. Samples of sanitary sewage flow also were collected within a combined sewer overflow chamber on 93.11.23 for analysis of bacteria levels and floc characteristics. This sewer sample site was selected because previous studies have focused on the area, thereby providing some continuity for water quality evaluations (cf. Irvine and Pettibone, 1993; Irvine et al., 1993). All floc samples were transported within the glass microscope slides to the National Water Research Institute (NWRI) for optical analysis.



**Figure 14.1**

**The Buffalo River Area of Concern and watershed.**

(The numbers within the watershed represent sample locations. The sewer outfall sample location refers to samples collected in the Irvine and Pettibone, 1993, study and also sanitary flow collected in this study).

### 14.2.2. Laboratory Methods

Water samples for the enumeration of indicator bacteria were filtered, in triplicate, through Gelman 47 mm cellulose acetate filters (GN 6) with a pore size of 0.45 mm. For fecal coliform enumeration, filters were placed on the surface of mFC agar plates and incubated at 44.5°C in a circulating waterbath for 22 to 26h. For fecal streptococci enumeration, filters were placed on the surface of mEnterococcus agar and incubated at 35°C for 45 to 51h. All colony counts from membrane filters were made using magnification between 10 -15 power.

Indicator bacteria were enumerated from sediment using a 5-tube Most-Probable-Number (MPN) method. Ten grams of wet sediment were homogenized in 90 ml of 0.1% peptone water to provide a slurry. Appropriate dilutions of the sediment slurry were delivered to tubes of lauryl tryptose broth and azide dextrose broth, for enumeration of fecal coliform and fecal streptococci, respectively. Confirmation tests followed Standard Method 9221C for fecal coliform and Standard Method 9230B for fecal streptococci (APHA, 1989).

Approximately 2L of water was passed through 0.45 mm Millipore filters to determine total suspended solids concentration. In general, however, determination of suspended solids concentration followed Standard Method 2540D (APHA, 1989).

Size distributions of the suspended particulate matter collected at the various sites in November, 1993 were determined at the NWRI using an Optimax V automated image analysis system interfaced with an IBM computer and a Zeiss Axiovert 100 inverted microscope. Where possible, 50,000 particles were digitized and sorted into size classes. Distributions are presented as percent by both volume and number, based on equivalent spherical diameter. Both the effective (flocculated) and absolute (de-flocculated) size distributions were determined for each sample. Samples were de-flocculated by sonication in a 10% solution of sodium hexametaphosphate for 2 minutes, followed by a 24-hour resettling period.

## 14.3. Results and Discussion

### 14.3.1. Bacteria Levels in Buffalo River Sediment and Water

Fecal coliform and fecal streptococci densities in sediment and water collected at site 13 (see Figure 14.1) are summarized in Table 14.1.

**Table 14.1**  
**Fecal coliform and fecal streptococci densities in water and sediment (dry weight), site 13.**

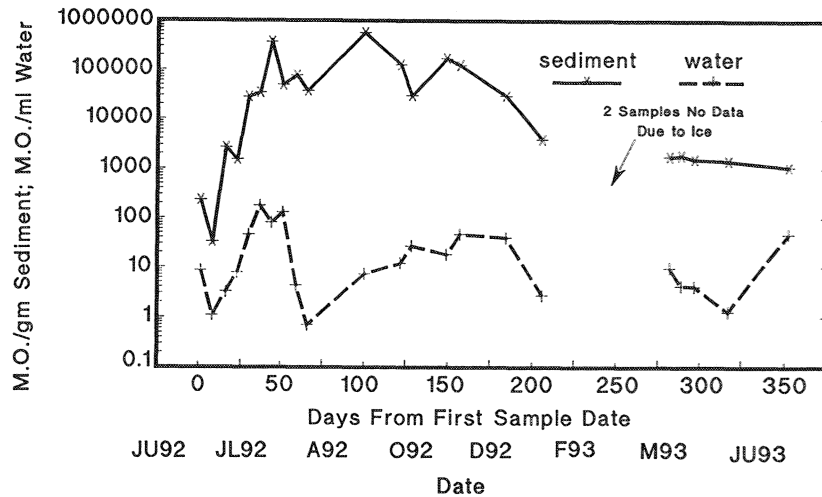
Date	FC/ml	FS/ml	FC/gm	FS/gm
6/22/92	8.60	29.00	235	6
6/29/92	1.10	1.30	33	25
7/6/92	3.20	1.30	2673	583
7/13/92	7.80	24.00	1536	3264
7/20/92	46.00	6.50	28320	2832
7/27/92	180.00	297.00	34680	10200
8/3/92	80.30	10.50	369600	20790
8/10/92	130.00	90.00	50160	6384
8/17/92	4.30	3.10	78000	780
8/24/92	0.70	0.60	37570	376
9/28/92	7.30	1.90	576000	12000
10/19/92	12.00	7.10	127900	379200
10/26/92	27.00	15.00	30290	39160
11/16/92	18.00	15.00	170800	7320
11/23/92	47.00	21.00	127000	76200
12/21/92	40.00	25.30	30420	1638
1/11/93	2.70	3.10	3927	762
2/15/93	No data	No data	No data	No data
3/8/93	No data	No data	No data	No data
3/29/93	9.80	5.60	1768	1768
4/5/93	4.20	0.80	1872	686
4/12/93	4.10	0.80	1576	17730
5/3/93	1.30	0.30	1456	6240
6/7/93	47.30	17.30	1090	589

The geometric mean fecal coliform density of 1,127 M.O./100 ml exceeds the state guidelines of 200 M.O./100 ml for primary contact. On an individual sample basis, 19 of 22 (86%) samples collected at site 13 exceeded state guidelines for primary contact. Fecal coliform levels in the water generally were greater than the levels of fecal streptococci, with an average FC:FS ratio of 2.53. The FC:FS ratio often is used to distinguish relative bacterial inputs from human and animal sources (Freedman and Marr, 1990). A ratio of 4 or greater is indicative of human sources, values of 1 or less are indicative of warm-blooded animal sources, while values between 1 and 4 are considered indeterminate. The FC:FS ratio at site 13 was less than 1 for 5 of 22 samples (23%). The second-highest ratio of 7.08 was recorded for samples collected the day after a storm event that produced combined sewer overflows (sample of 92.07.20). Freedman and Marr (1990) note that the FC:FS ratio should be used with caution because of differences in bacterial survival rates.

Although fecal coliform levels in the water column at site 13 were relatively high throughout the year, levels in the bed sediment typically were 1 to 5 orders of magnitude greater. The levels of fecal coliforms in river water and bed sediment are shown as a time series in Figure 14.2. Several of the peaks observed for the water samples (July, August and December) are associated with rainfall and snowmelt runoff events. A seasonal trend can be observed for the fecal coliforms in the bed sediment. In general, fecal coliform levels increased steadily through the early summer, stayed relatively constant at  $10^4$ - $10^5$   $\text{gm}^{-1}$  from mid-July to November and declined through the winter into early summer. While fecal coliform levels declined through the winter, viable populations still were observed.

Rigorous quantitative information was not collected on resuspension rates of sediment and bacteria. It has been noted (Irvine, pers. obs.) that the passage of lake-going ships results in considerable turbidity due to sediment resuspension. Our monitoring of ship traffic during the summer of 1993 indicated a frequency of 2 to 8 passages per week in the area of site 13. Meredith and Rumer (1987) used the HEC-6 model to evaluate sediment erosion dynamics in the river resulting from storm events. It was found that storm events with discharge magnitudes occurring approximately 1 to 2% of the time generate enough shear stress to resuspend bed material.

Irvine and Pettibone (1993) also sampled Buffalo River bed sediment near the mouth of a combined sewer outfall (Figure 14.1) on a weekly basis throughout the summer of 1991. Sediment samples were



**Figure 14.2**  
Fecal coliform densities in bed sediment and overlying water at site 13, Buffalo River, June 1992 through June 1993.

collected using a modified 60 cc syringe tube attached to the end of a pole and approximately the upper 3 cm of each sediment core was extruded into a sterile polyethylene bag. The geometric mean fecal coliform and fecal streptococci densities ranged between 102 to 104 gm<sup>-1</sup> and 101 to 102 gm<sup>-1</sup> of sediment (dry weight), respectively. Densities of indicator bacteria in sediment at a control site 180 m upstream (but downstream from other sewer outfalls) were similar to those found near the sample outfall, except following combined sewer overflow events of 91.07.04, 91.07.07 and 91.07.08. The mean counts at the upstream site were approximately half of those at the outfall site after the overflow events. During the study period, fecal coliform densities in water samples from the same river reach were several orders of magnitude lower than in the sediment, but still exceeded state guidelines for primary contact in 6 of 9 weeks. In general, the results reported by Irvine and Pettibone (1993) are consistent with the findings of this study. It appears that fecal contamination of sediment in the Buffalo River is widespread. The indicator bacteria survive at high levels throughout the summer months and the populations are maintained

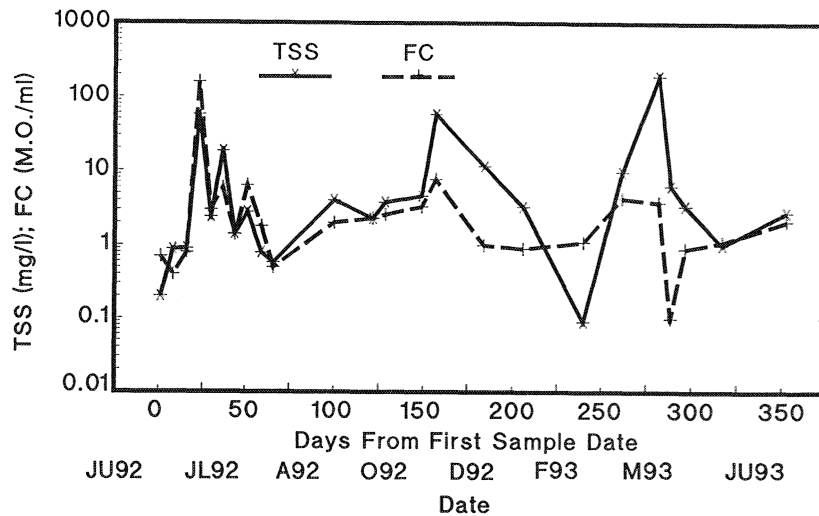
even in the winter, although at lower levels. Fecal coliform levels in the water often have exceeded state guidelines for primary contact over the past two years, yet levels in bed sediment typically are 1 to 5 orders of magnitude higher. It appears that resuspension of contaminated bed sediment can have a negative impact on water quality in the river.

### 14.3.2 Relationship Between Fecal Coliforms and Suspended Sediment

Pearson's Product Moment Correlations ( $r$ ) were calculated between the levels of fecal coliforms and suspended sediment in samples collected at all sites (Figure 14.1) and the results are shown in Table 14.2. There is a strong positive correlation between fecal coliforms and suspended sediment during the summer months (June through September) at all sites. However, the correlations for the two Buffalo River sites (12 and 13) are lower than those observed for the upstream, tributary sites. The

**Table 14.2**  
Correlation between suspended sediment and fecal coliforms.

site	$r_{\text{summer}}$	$r_{\text{year}}$
1	0.96	0.23
2	0.96	0.36
3	0.98	0.37
4	0.98	0.52
5	0.90	0.20
6	0.99	0.08
7	0.96	0.22
9	0.97	0.10
10	0.96	0.17
11	1.00	0.63
12	0.77	0.05
13	0.82	0.12



**Figure 14.3**  
 Relationship between fecal coliform (FC) density and total suspended solids (TSS) concentration at site 1, June 1992 through June 1993.

lower correlations may be related to differences in landuse, sediment/bacteria source areas, channel hydraulics and floc settling properties. The Buffalo River is urbanized and also is deeper and wider than the tributaries. The change in hydraulic geometry typically results in a net deposition of sediment within the AOC and this may produce greater variability in the suspended sediment-bacteria relationships.

A seasonal component also was observed in the suspended sediment-bacteria relationship, as correlations at all sites were lower (0.05 to 0.63) when data for the entire year were analyzed. This seasonality can be detected visually in time series plots of fecal coliforms and suspended sediment (Figure 14.3). During the summer months, the trends in fecal coliform and suspended sediment levels are consistent. The peaks in the suspended sediment and fecal coliform levels during this time are related to rainfall-generated runoff events. The trends in fecal coliform and suspended sediment levels diverge during the period November through March. In particular, high suspended sediment levels are observed in association with snowmelt-generated runoff events, but fecal coliform levels do not respond at the same rate. The divergence of the suspended

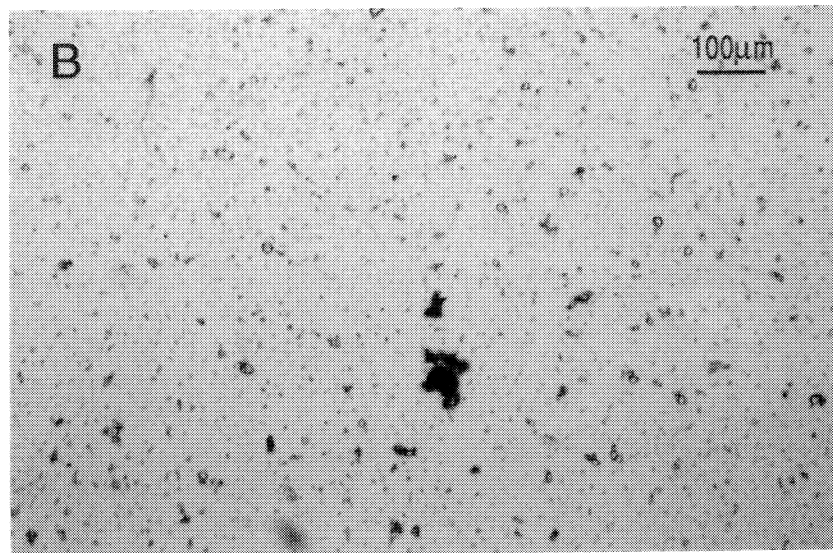
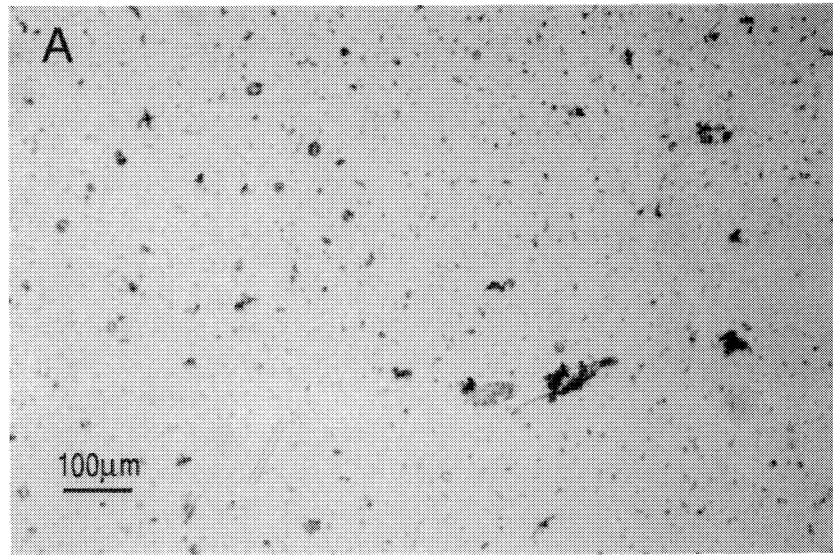
sediment-fecal coliform relationship, particularly during the winter runoff events, may result from a combination of factors, including different source-area contributions for snowmelt events, changes in sediment/floc properties and lower bacteria levels in the soil and river sediment during the winter.

### 14.3.3. Floc Analysis

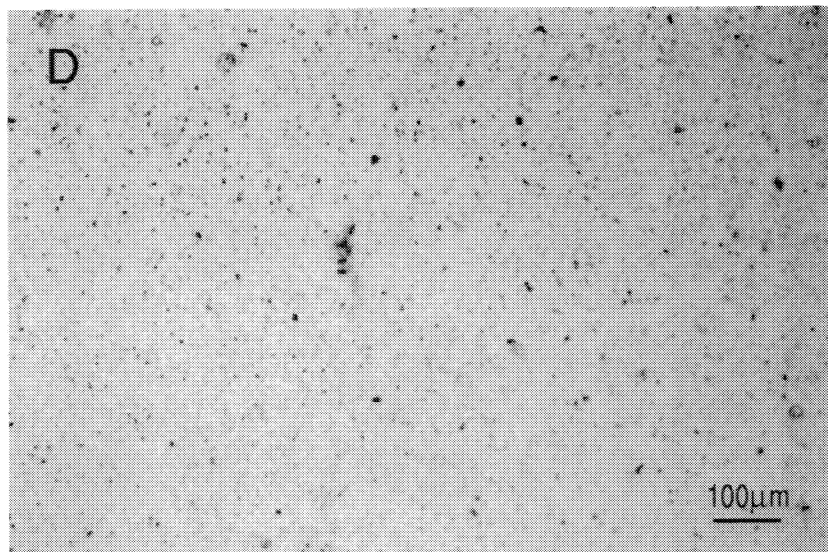
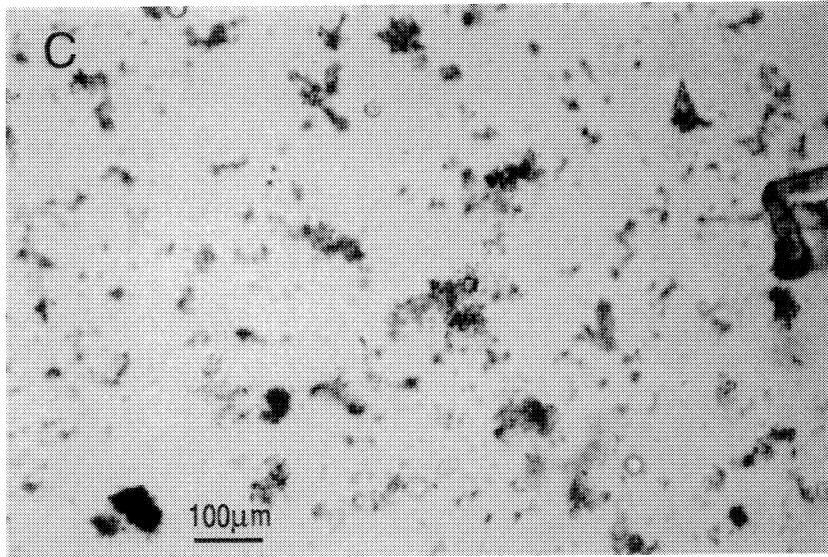
Plate 14.1 demonstrates for selected sites that the suspended sediment has a strong flocculated component. Observations of the effective size photos (Plate 14.1a, b, c) and distributions (Figures 14.4a, b, c) provide evidence that the floc characteristics differ between the sample environments. The degree of variability in size distribution and associated contaminant concentrations (including bacteria) is highly dependent on the origin of the sediment, the nature of the sediment and on the processes governing the erosion and transport of the sediment (Walling and Woodward, 1993).

For ease of comparison, the median diameters of the samples, by volume, ( $d_{50}$ ) are summarized in Table 14.3. Table 14.4 summarizes data on the suspended and dissolved sediment concentrations and bacteria levels. Table 14.3 demonstrates that the degree of flocculation at sites 10 and 11 is minimal as the ratio of effective to absolute  $d_{50}$  values is under 2. This low level of flocculation is likely related to the very shallow and fast flowing water at these sites resulting in a very high level of turbulence and fluid shear. Such conditions can contribute to floc breakage and limit aggregation. Although site 13 contains the smallest effective  $d_{50}$  value, the sediment was more highly flocculated than the upstream sites as is seen by the smaller  $d_{50}$  value of the absolute distribution. The reason for such a difference may be related to the different hydraulic and sedimentological properties at site 13. This site was slower-moving (lower shear velocity) than sites 10 and 11 and possessed slightly higher suspended sediment and bacteria levels and these conditions are more conducive to floc development (Krone, 1978; Partheniades, 1993).

Visual comparison of Plate X.1c and X.1d emphasizes the high degree to which the sewer sediment is flocculated. Plate X.1d represents the same sediment as in Plate X.1c, only the sample was sonicated to break the flocs into their absolute particle sizes. The effect of this disaggregation process on the whole sediment distribution is illustrated in Figure 14.4c and X.4d where the absolute particle size distribution is significantly



**Plate 14.1**  
Selected examples of suspended sediment images used to determine size distribution: (a) effective (floculated) size distribution, site 11; (b) effective (floculated) size distribution, site 13.



**Plate 14.1 (Continued)**  
Selected examples of suspended sediment images used to determine size distribution: (c) sanitary sewage (flocculated); (d) sanitary sewage (deflocculated).

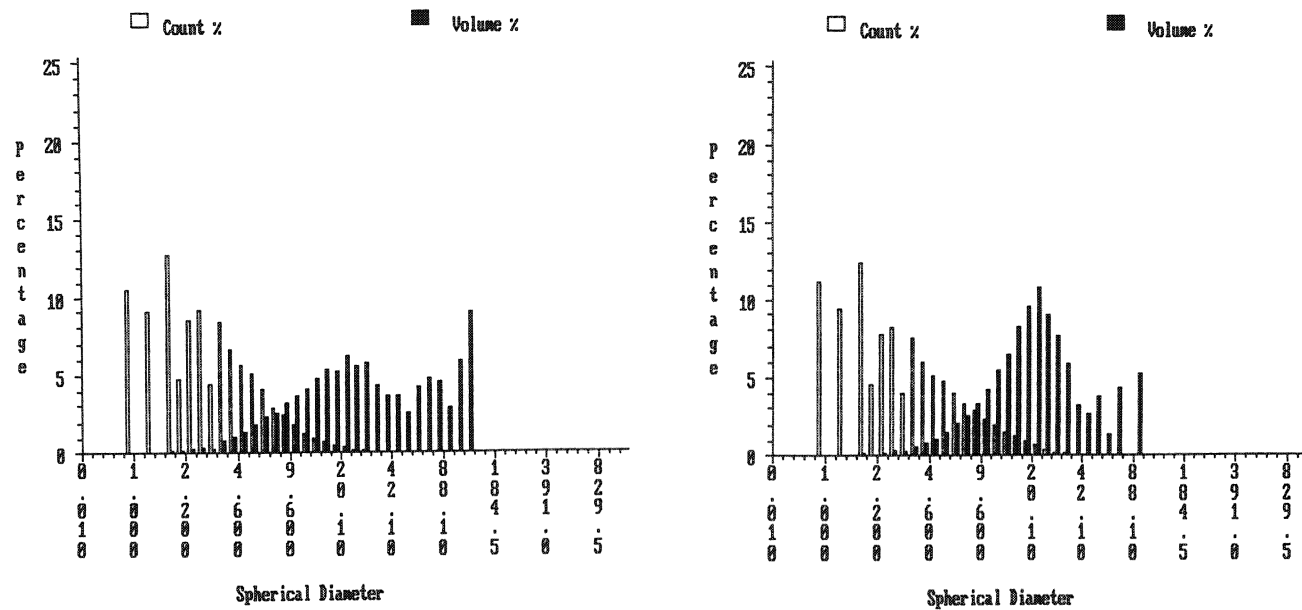


Figure 14.4 Size distributions of suspended sediment (in microns) determined through automated image analysis: (a) effective size distribution, site 11; (b) effective size distribution, site 13. Results for site 10 were similar to those of site 11.

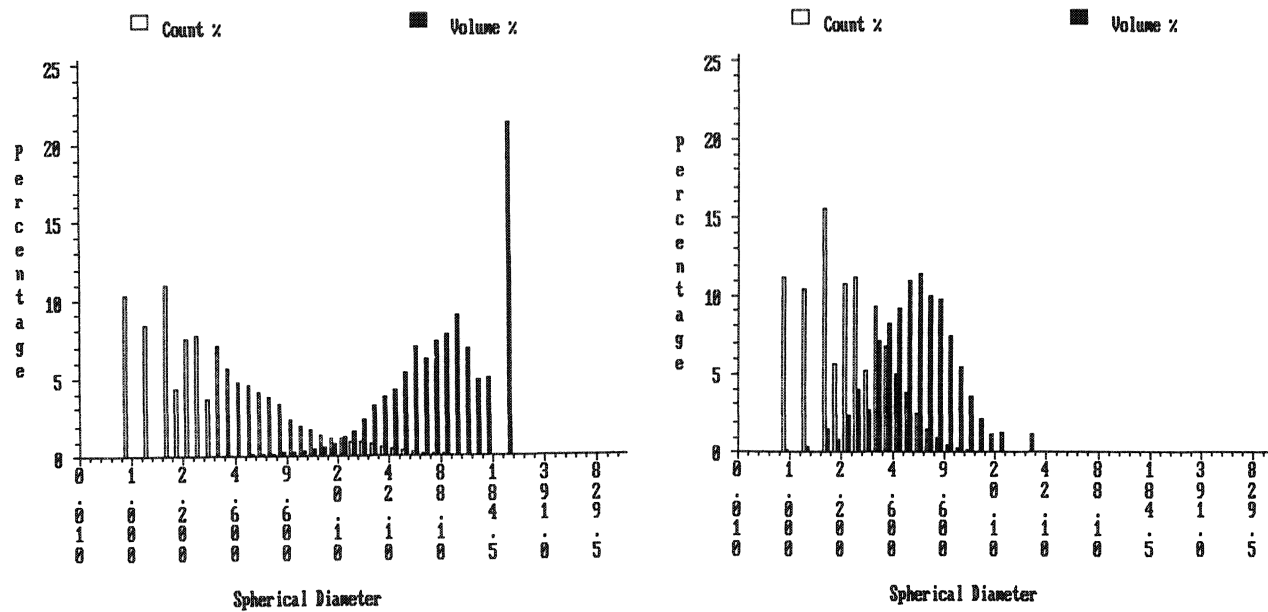


Figure 14.4 cont'd. Size distributions of suspended sediment (in microns) determined through automated image analysis: (c) effective size distribution, sanitary sewage; (d) absolute size distribution, sanitary sewage.

**Table 14.3**  
**Median diameter ( $d_{50}$ ) values (in microns), by volume, for effective and absolute sediment samples.**

	Site 10	Site 11	Site 13	Sewage
Effective (E)	23.1	27.9	21.2	96.4
Absolute (A)	16.7	14.9	8.8	6.4
Ratio (E/A)	1.4	1.9	2.4	14.8

**Table 14.4**  
**Solids and bacteria data for river and sewage samples.**

	Site 10	Site 11	Site 13	Sewage
<sup>1</sup> TSS, mg l <sup>-1</sup>	1.19	1.42	5.24	11.4 <sup>2</sup>
DS, mg l <sup>-1</sup>	186	171	188	288
FC, M.O. ml <sup>-1</sup>	3.5	1.1	3.6	42,000 <sup>3</sup>
HPC, M.O. ml <sup>-1</sup>	1.5 x 10 <sup>4</sup>	8.5 x 10 <sup>3</sup>	6.8 x 10 <sup>4</sup>	< 1 x 10 <sup>6</sup> <sup>4</sup>

<sup>1</sup> TSS - total suspended solids; DS - dissolved solids; FC - fecal coliforms; HPC - heterotrophic plate count

<sup>2</sup> average of 6 samples collected in 1993. The filter for TSS analysis of the 11/23/93 sample was damaged and results were not usable

<sup>3</sup> FC value represents average of samples collected by Irvine and Pettibone (1993) for the same site.

<sup>4</sup> HPC level for a sample collected 2/22/94 was 4 x 10<sup>4</sup>

shifted to smaller size classes. Table 14.3 demonstrates that the sanitary sewage sample was substantially more flocculated than any of the river samples. This is further emphasized by the fact that these large flocs are composed of primary particles that are smaller than those found in the river samples. These smaller floc constituent particles are likely due to differences in source area and to the nature of the sediment. Samples were collected in the sewer during dry weather which will constitute inputs primarily from residential sanitary and industrial waste discharges. Microscopic

observations indicate that this sediment has a high composition of cohesive organic material, including bacteria. Bacteria levels in the sanitary flow at the sample site typically are several orders of magnitude greater than in the river water (Table 14.4). Inorganic fines also made a significant contribution to the sediment texture and are likely introduced to the system through industrial discharges and winnowing of fines from deposited bottom sediments. Organic matter within the flocs is believed to be an important factor in stabilizing and promoting floc development (Ward et al., 1990; Droppo and Ongley, in press) and is likely the primary factor contributing to the large floc sizes in this sample environment. This is substantiated by the fact that the sewer possessed the highest velocity ( $0.5 \text{ m s}^{-1}$ ) and shear stress of the sample sites, yet exhibited the largest effective size distribution.

## 14.4 Conclusion

Results from this study and a survey of the literature reporting on different environments suggest indicator bacteria can survive in bed sediment at levels several orders of magnitude higher than in overlying water. These bacteria may be resuspended by natural or anthropogenic perturbations and can have a negative impact on water quality. Often, remediation of a water body involves modeling of pollutant sources and sinks. The role of bed sediment as a bacteria reservoir should be considered in remediation modeling efforts. When establishing sample sites for water quality monitoring, proximity to depositional areas and bed sediment characteristics should be considered. Resuspension of bacteria from upstream sediment pools may provide a biased picture of regional water quality.

Sediment flocs are common in freshwater fluvial and combined sewage systems. Sediment transport and contaminant fate modeling should consider the different hydrodynamic behaviour of a floc as compared to a discrete particle.

While the data demonstrate a distinct seasonality to the bacteria-sediment relationship, no data presently are available as to the influence of temporal changes in sediment structure (flocculation). As bacteria are known to be an integral part of the floc matrix, seasonal changes in the morphology and microbial ecology of a floc may result in significant changes in bacteria-sediment relationships. The effects of seasonal variations in floc size and structure on indicator bacteria populations in the suspended and bottom sediment will have to be evaluated in the future.

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