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TURBIDITY, SUSPENDED SOLIDS, AND BACTERIA RELATIONSHIPS IN THE BUFFALO RIVER WATERSHED

K.N. Irvine[1], E.L. Somogye[1], and G.W. Pettibone[2]
[1]Department of Geography/Planning
[2]Department of Biology
State University College at Buffalo
1300 Elmwood Ave.
Buffalo, NY 14222

ABSTRACT: *This paper summarizes the results of sampling that has been done in the Buffalo River, NY watershed over the past decade and specifically makes links between levels of turbidity, suspended solids, and fecal coliform using least squares regression. Fecal coliform levels in the Buffalo River are high enough to be of concern and there is local interest in developing Best Management Practices (BMPs) to improve water quality. An understanding of sediment and bacteria interactions is important in developing appropriate BMPs. Samples were collected at seven sites under both dry weather and storm event conditions, but the sampling did not occur at all sites contemporaneously. The correlations between suspended solids and turbidity or suspended solids and fecal coliform were strong, ranging between 0.46 and 1.0. The slopes of the regressions were significantly different from 0 ($\alpha=0.05$), although in the case of suspended solids vs. fecal coliform regressions some variability was observed in the slope and intercept of the equations for the different sites. Nonetheless, these turbidity-suspended solids-fecal coliform relationships can be used to produce reasonable planning level estimates of the frequency of high fecal coliform levels (>200/100 mL).*

INTRODUCTION

There is worldwide concern about fecal contamination of natural waterbodies and the resulting potential for human health impacts, but while there has been research on Best Management Practices (BMPs) to reduce untreated human and domestic animal waste discharge, our understanding of bacteria dynamics within a watershed remains imperfect (Geldreich, 1989; Embry, 2001; Inamdar et al., 2002; Frenzel and Couvillon, 2002). For example, there is ongoing discussion about the principal mode of transportation for fecal bacteria within a watershed. Some indicate that bacteria, such as fecal coliform, move primarily as free-floating organisms, while others have suggested that sediment plays an important role in the transport and dynamics of bacteria in a stream (e.g. Irvine et al., 1995).

Numerous studies have examined the relationship between turbidity and total suspended solids (TSS) in an effort to improve our ability to evaluate watershed-scale geomorphological responses (e.g. Walling, 1977; Lewis, 1996; Sun et al., 2001; Davies-Colley and Smith, 2001). There can be several advantages to using automated turbidity measurements as a surrogate for TSS sampling in the examination of sediment erosion and transport. These advantages include the capability of providing fine time resolution measurements (e.g. 15 minutes) for extended periods, without having to rely on sampling teams to catch transient storm events with minimal notice (i.e. keeping teams "on call" to chase storms), and elimination of laboratory costs for the analysis of TSS. Ultimately, the success of using turbidity measurements in place of TSS sampling relies on the accuracy of the TSS-turbidity rating curve. While these rating curves can be accurate, several environmental variables, including different particle size distribution, particle shape distribution, particle composition, and presence of humic acids can produce scatter in the relationship (Walling, 1977; Lewis, 1996; Davies-Colley and Smith, 2001). As such, Sun et al. (2001) concluded that TSS-turbidity relationships may be both site and time specific, so that a relationship is normally unique for a particular catchment and within a particular period of time.

Although bacteria-TSS and turbidity-TSS relationships have been examined separately by different research teams (e.g. Irvine et al., 1995; Sun et al., 2001) we are not aware of any work that has examined the inter-relation of bacteria, turibidity, and TSS. If these relationships were sufficiently strong, it may be possible to develop planning level estimates of indicator bacteria (e.g. fecal coliform) levels on a continuous basis using turbidity measurement. This could help to reduce the costs and time-constraints of fecal coliform sampling and analysis, be used as direct evidence for the effect of BMPs, or used as a tool for deterministic model calibration to help predict the effect of BMPs.

The objective of this paper is to summarize the results of sampling conducted within the Buffalo River, NY watershed over the past decade and specifically make links between levels of turbidity, TSS, and fecal coliform using least squares regression. Fecal coliform levels in the Buffalo River are high enough to be of concern and there is local interest in applying BMPs to improve water quality. An understanding of sediment-bacteria interactions is important in identifying appropriate BMPs.

METHODS

Study Area

The Buffalo River watershed has a total drainage area of 1,155 km^2 (Figure 1). Land use within the watershed varies, with much of the upper portion of the watershed being characterized by woods and farmland. The watershed exhibits a distinct urban gradient, as the major tributaries pass through several small communities and receive industrial, commercial, residential, and municipal discharges. Much of the lower Buffalo River is dredged to accommodate lake-going ships and as such the hydraulic nature of the river changes dramatically, as it becomes wider and deeper (dredging maintains a minimum depth of 6.7 m, with a shallower gradient (Irvine et al., in press). The lower 9.6 km of the Buffalo River also have been designated a Great Lakes "Area of Concern" by the International Joint Commission due to water quality and habitat impairments (e.g. New York State Department of Environmental Conservation, 1989).

Sample Sites and Analytical Procedures

Because of its designation as an Area of Concern, we have conducted several sampling projects in the watershed over the past decade. The results of sampling done in 1992-93 were reported by Irvine and Pettibone (1996) and Pettibone and Irvine (1996). Irvine (1997) and Wills and Irvine (1997) summarized the sampling effort conducted during 1996. The most recent sampling effort was done in 2000 and results have been reported by Irvine (2001) and Malcolm Pirnie, Inc. (2001). This paper draws on the results of these projects.

Samples for fecal coliform and TSS analysis were collected at seven sites (sites 1 through 7, Figure 1) under both dry weather and storm conditions. In 1992-93 sampling was done on a routine schedule, one day each week, and this schedule captured both dry and wet weather conditions. In 1996, samples were collected during four storm events (multiple samples through each event at site 2) and two dry weather periods. The 2000 sampling represented multiple samples through two storm events as well as single samples on two dry weather dates. In all cases, samples were grab samples that were kept on ice in the field. Sampling for fecal coliform was done asceptically and the samples were preserved with sodium thiosulfate to neutralize any possible effects of chlorinated discharges to the river. No preservation (except cooling) was required for the TSS samples.

All samples for fecal coliform analysis were processed in the laboratory within six hours of collection. Fecal coliform samples collected in 1992-93 were analyzed in the Microbiology Laboratory at Buffalo State using membrane filtration following Standard Method 9222 D (APHA, 1989). Samples collected in 1996 were analyzed using the same procedure (Standard Method 9222 D) by the Erie County Public Health Laboratory and the 2000 samples also were analyzed using the same procedure, but by Lozier Laboratories, Inc., of Rochester, NY.

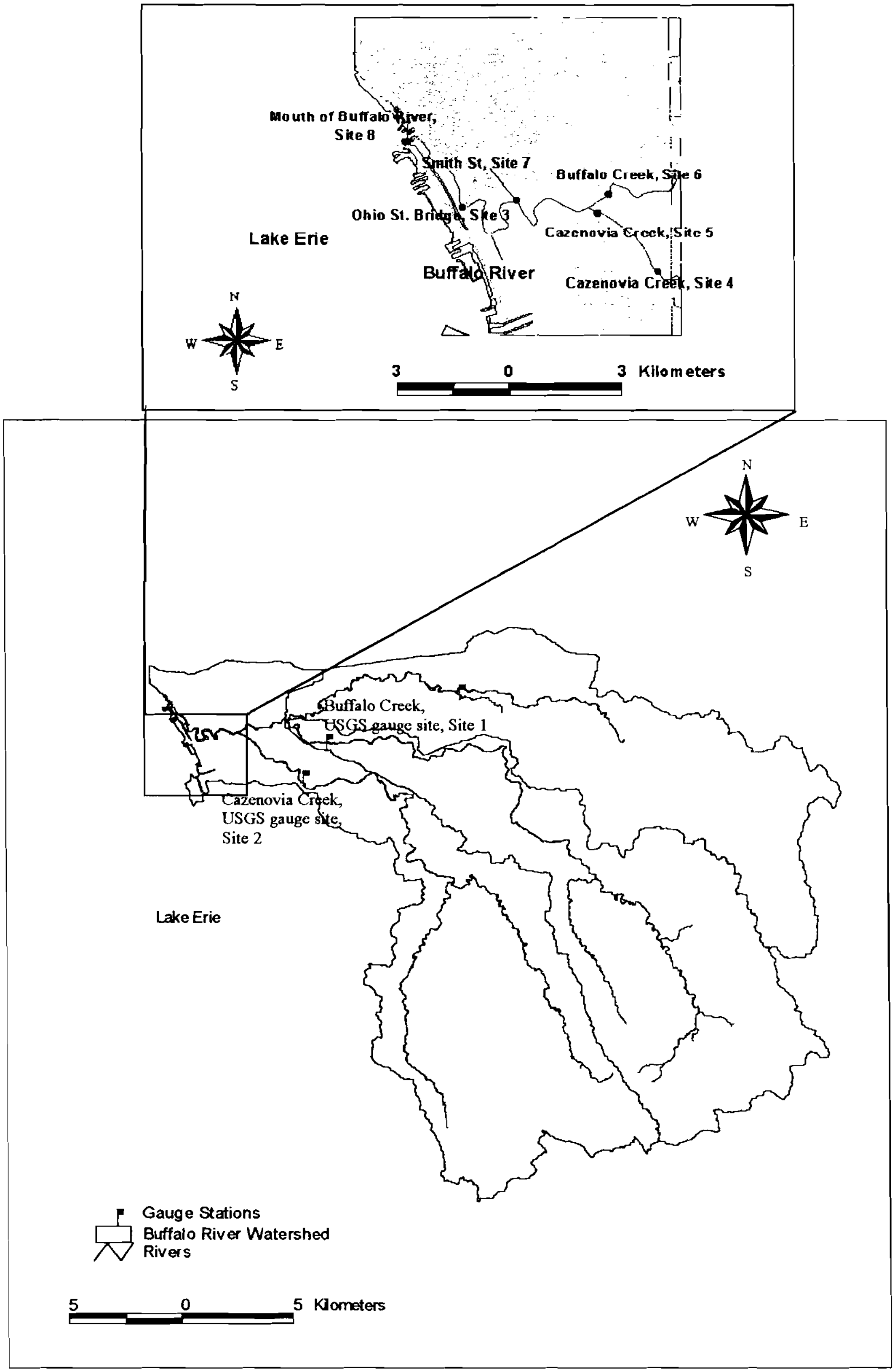


Figure 1 The Buffalo River Watershed and sample site locations.

The total suspended solids concentrations for the 1992-93 samples were determined at the Buffalo State Soils Laboratory using the general filtration procedure as described under Standard Method 2540 D (APHA, 1989), although 0.45 μm Millipore filters were used rather than glass fiber filters. It is not expected that use of Millipore filters had a large impact on results (e.g. Irvine, 1985). The identical analytical procedure (including use of filters) was followed for the 1996 samples, with the work being done by the Erie County Public Health Laboratory. The TSS samples in 2000 were analyzed following U.S. EPA Method 160.2 at either Waste Stream Technology, Inc. of Buffalo, NY or Phillip Analytical Services Inc., Burlington, ON.

In 2000, Hydrolab Datasonde 4a multiprobe sensors were deployed at 10 sites along the Buffalo River, Buffalo Harbor, and Black Rock Canal to monitor dissolved oxygen, turbidity, pH, conductivity, and temperature. Measurements at each site were recorded at 15 minute intervals and the monitoring program was conducted between 4/17/00 and 11/18/00. The Hydrolabs were cleaned and the data uploaded on a weekly basis. Sensor calibration throughout the study followed manufacturers recommendations (Irvine, 2001). All Hydrolabs were installed so that they were contained within a capped PVC tube. The lower section of the PVC tube had holes drilled through to allow the water to move freely past the sensors. The PVC tubes protected the Hydrolabs from damage due to floating storm debris in the river and the locked caps provided a level of security from tampering. At all sites (except site 8 in this paper), the PVC tube was fixed to a stationary object so that the sensors would be approximately 1.0 m below the March low water datum. During storm events the water depth above the sensor was greater. Site 8 was attached to a buoy so that the depth of measurement always was 1.0 m below the surface.

Table 1 Range of Fecal Coliform and TSS Values

Sample Site	Sample Site Number	Sample Dates	Fecal Coliform Range/100 mL	n	TSS Range, mg/L
Buffalo Creek, USGS gauge site	1	1992-93	50-14,000	13	0.4-68
Cazenovia Creek, USGS gauge site	2	1992-93	150-18,000	13	1-369
		1992-93	70-18,000	13	5-166
Buffalo River, Ohio Street Bridge	3				
		1996	148-5,400	20	1-90
Cazenovia Creek, USGS gauge site	2	1996	190-7,350	6	3-326
Cazenovia Creek in Cazenovia Park	4	2000	224-2,400	8	5-36
Buffalo River, Ohio Street Bridge	3	2000	80-53,000	18	1-199
Cazenovia Creek in Cazenovia Park	4	2000	224-38,000	6	2-36
		2000	304-53,000	22	5-136
Cazenovia Creek near mouth	5				
		2000	72-23,000	22	7-39
Buffalo River, South Ogden Bridge	6				
Buffalo River at Smith St. CSO	7				

Table 2 Regression Results for Fecal Coliform (FC) vs. TSS

Sample Site	Sample Site Number	Sample Date	Regression Equation	Correlation (r)
Buffalo Creek, USGS gauge site	1	1992-93	LogFC = 1.92 + 1.27(LogTSS)	0.97
Cazenovia Creek, USGS gauge site	2	1992-93	LogFC = 2.12 + 0.83(LogTSS)	0.97
Buffalo River, Ohio Street Bridge	3	1992-93	LogFC = 1.06 + 1.67(LogTSS)	0.85
Cazenovia Creek, USGS gauge site	2	1996	LogFC = 2.58 + 0.52(LogTSS)	0.62
Cazenovia Creek in Cazenovia Park	4	1996	LogFC = 2.46 + 0.43(LogTSS)	0.71
Buffalo River, Ohio Street Bridge	3	2000	LogFC = 0.0 + 1.0(LogTSS)	1.0
Cazenovia Creek in Cazenovia Park	4	2000	LogFC = 2.06 + 1.04(LogTSS)	0.68
Cazenovia Creek near mouth	5	2000	LogFC = 2.60 + 0.74(LogTSS)	0.46
Buffalo River, South Ogden Bridge	6	2000	LogFC = 2.35 + 0.94(LogTSS)	0.54
Buffalo River at Smith St. CSO	7	2000	LogFC = -0.004 + 2.49(LogTSS)	0.50

RESULTS

The ranges of fecal coliform and TSS values are summarized in Table 1. Least squares regression was performed on the fecal coliform and TSS data and residual analysis (cf. Draper and Smith, 1981) consistently showed that a log-log transformation of the data was appropriate. Results of the regression analyses are summarized in Table 2 and in all cases, the slope of the regression line was significantly different from 0 (α=0.05).

Least squares regression also was performed on the TSS and turbidity data recorded in 2000. Residual anlaysis indicated that a log-log transformation was appropriate for sites 4 and 6, while regression with the raw (untransformed) data was appropriate for sites 3 and 5. Results of the regression analysis are summarized in Table 3 and in all cases, the slope of the regression line was significantly different from 0 (α=0.05). Often a log transformation is automatically done for environmental data, but backtransformation can introduce bias into the estimate of the dependent variable. Although correction factors have been developed (e.g. Ferguson, 1986; Newman, 1993), our preferred approach is to use the raw (untransformed) data when residual analysis deems it appropriate. The reason why a log-log transformation was appropriate for some sites and not others has not been fully resolved. There may be some underlying physical reasons (see discussion next section), but it also could be the result of a small data set.

DISCUSSION

The results in Tables 2 and 3 show that TSS is significantly correlated (α=0.05) with fecal coliform levels and turbidity. Murray et al. (2001) also found a strong correlation between TSS and fecal coliform for the Rouge River, MI (r=0.79). 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. Pettibone et al. (1996) also found that fecal coliform levels in the Buffalo River increased by a factor of 2-11 times immediately after the passage of a lake going ship resuspended sediment into the water column. Numerous researchers have shown the levels of fecal coliforms in bed sediment can be 1 to 4 orders of magnitude greater than in overlying water, including the Buffalo River (e.g. Matson et al., 1978; Irvine and Pettibone, 1993; Center for Watershed Protection, 1999). It therefore seems that part of the correlation between TSS and fecal coliform is related to resuspension of inoculated bed sediment. The other major factor that would influence the correlation is storm event runoff inputs (including failing septic system discharges, combined sewer overflows, and runoff from urban and agricultural land).

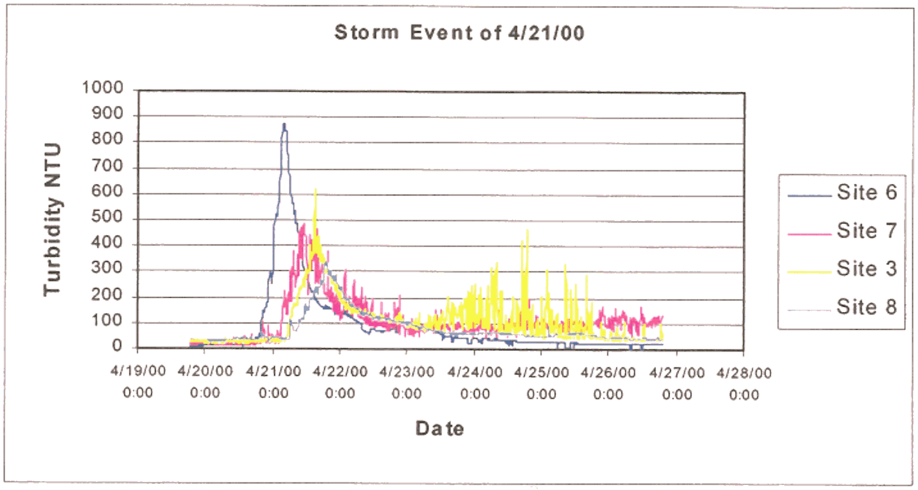
While the correlation between TSS and fecal coliform levels generally is good, there is considerable variation in the slope and intercept of the regression equations between the different sites (Table 2). Part of this variation may be the result of a small data set. However, it is interesting to note that the slope for site 7 is steeper than any other site for the 2000 data. The relationship at this site may be strongly impacted by the discharge from a large combined sewer outfall immediately upstream as well as the change in hydraulic geometry of the dredged portion of the Buffalo River. The regressions for sites 4, 5, and 6 (2000 data), which are located in the tributary creeks upstream of the dredged channel, are similar. The regressions for site 2 (1992 and 1996 data) also are similar to each other.

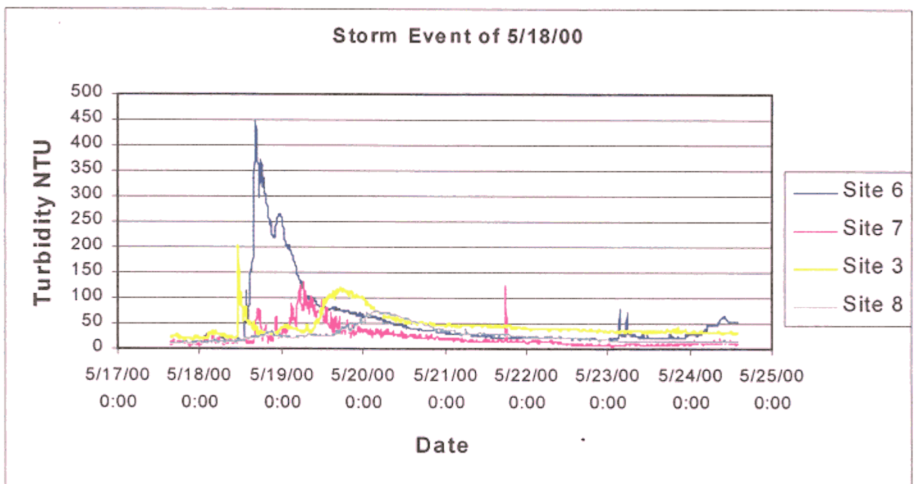
Past modeling studies (e.g. Wen et al., 1994) have shown that the Buffalo River is not in morphological equilibrium and, in fact, it is a net sediment sink. Figure 2 presents the turbidity data for three different storm events observed in 2000. Clearly, turbidity decreased in the downstream direction and it also is possible to trace the movement of the storm wave by examining the lag in the peaks between the sites. The decrease in turbidity is consistent with model results that show deposition occurs along the dredged section of the river. Deposition occurs due to the change in hydraulic geometry of the dredged portion of the river, as noted previously. In general, fecal coliform levels also decreased in the downstream direction (e.g. compare the 2000 results at sites 4, 5 and 6, with the downstream sites 7 (Smith St.) and 3 (Ohio St. Bridge)). The decrease in fecal coliform levels is consistent with the deposition of bacteria bound to suspended sediment.

Although the turbidity data provided useful insight to system dynamics and particularly the response to storm events, it is important to transform the turbidity data into concentration or mass-based units to maximize information about sediment transport and deposition. As noted, Sun et al. (2001) concluded that TSS-turbidity relationships may be both site and time specific, so that a relationship is normally unique for a particular catchment and within a particular period of time. In fact, even

Table 3 Regression Results for TSS vs. Turbidity (Turb)

Sample Site	Sample Site No.	Data Used	Regression Equation	Correlation (r)
Buffalo River, Ohio Street Bridge	3	Raw Data	TSS = 1.78 + 0.26(Turb)	0.86
Cazenovia Creek in Cazenovia Park	4	Log_{10}	TSS = -2.19 + 1.97(Turb)	0.86
Cazenovia Creek, near mouth	5	Raw Data	TSS = -0.15 + 0.37(Turb)	0.85
Buffalo River, South Ogden Bridge	6	Log_{10}	TSS = -0.40 + 1.12(Turb)	0.82





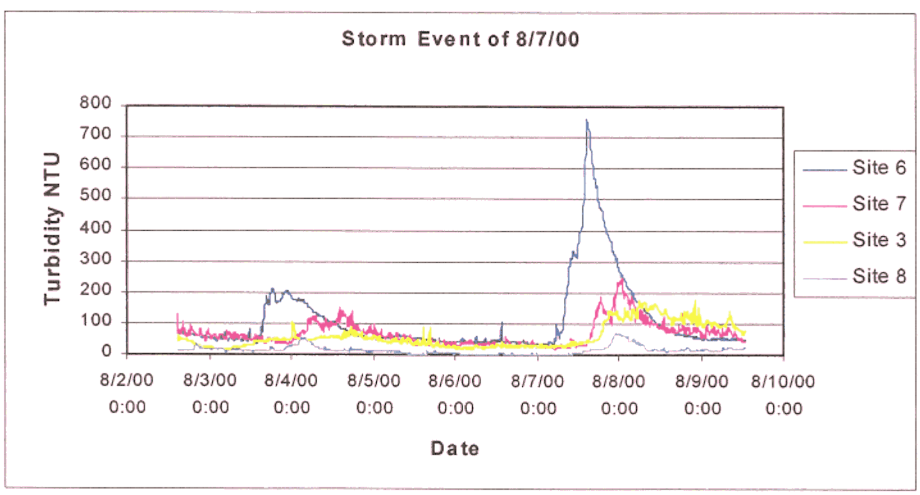


Figure 2 Turbidity for selected storm events. The noise in the data for site 3, 4/23-4/26/00 is unexplained but atypical.

within the same catchment our data indicate the TSS-turbidity relationship varies spatially (Table 3). Part of this variability may be related to the river characteristics at the particular sites. For example, sites 4 and 6 (log 10 transformation needed) are more natural, shallower, and faster flowing, as compared to site 5 which is deeper and channelized, or site 3, which is within the dredged portion of the Buffalo River. Lewis (1996) found that the nature of the relationship between TSS and turbidity could even vary between storms for the same site (some storms exhibited a linear relationship and others had a curvilinear relationship).

While there clearly can be variability in the exact nature of the TSS-turbidity relationship from site to site, Table 3 shows that the relationship for the individual sites can be strong (r between 0.82 and 0.86). Sun et al. (2001) used a fourth order polynomial function to describe the TSS-turbidity relationship for a small catchment in Australia and the resulting correlation was 0.9. Lewis (1996) cautioned the use of applying nonlinear fits or multiple fits, particularly in the presence of outliers and it did not appear that our data warranted a higher order function.

The relationships developed for TSS and fecal coliform (Table 2) and TSS and turbidity (Table 3) are strong, although they also exhibit spatial and temporal variability. This variability understandably places greater uncertainty on the application of the equations. However, we have proceeded cautiously and begun to use the equations in several ways to develop planning level evaluations of sediment and bacteria transport within the Buffalo River watershed. For example, work still in progress has used the TSS-turbidity rating curve to produce a TSS time series for the year 2000 to support the calibration of the NPSM/HSPF (Nonpoint Source Model/Hydrologic Simulation Program Fortran) sediment transport module. The NPSM/HSPF estimates of sediment concentration for the watershed also are being used with the TSS-fecal coliform rating curves to provide an estimate of the frequency of high fecal coliform levels (>200/100 mL).

CONCLUSION

The results of several projects conducted within the Buffalo River watershed over the past decade have shown that strong positive relationships exist between total suspended solids and turbidity as well as total suspended solids and fecal coliform. However, the nature of the regression equations that best describe these relationships can vary temporally and spatially. For planning level purposes, these relationships can be used, provided the uncertainty due to temporal and spatial variability are understood. Automated sampling instrumentation, such a Hydrolab Datasonde 4a's, provided turbidity data at a good temporal resolution, and minimized the level of manual field work that was needed to understand erosion dynamics within a watershed.

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