Middle States Geographer, 1999, 32: 99-109

NON-DESTRUCTIVE IMAGE ANALYSIS TO DETERMINE SUSPENDED SEDIMENT SIZE DISTRIBUTION CHARACTERISTICS UNDER VARYING FLOW CONDITIONS, CAZENOVIA CREEK, NY

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ABSTRACT: *Recent studies suggest that suspended sediment in rivers may move predominantly as flocs rather than as individual (discrete) particles. Research on flocculation has been facilitated by improved analytical technologies, including image analysis. Because image analysis is a relatively new analytical approach, there is limited information on quality assurance/quality control (QA/QC) procedures. Non-destructive image analysis was used to determine size distribution characteristics of suspended sediment samples collected from a site on Cazenovia Creek, NY, during storm and non-storm events. An important focus of the study was refinement of QA/QC procedures. Samples could be refrigerated for up to 22 days without significant change in size distribution. Imaging approximately 1,000 particles appears optimum in providing a reliable size distribution and minimizing analytical time. The Pearson Type VI probability distribution typically provided the best fit for the flocculated sediment, while the Extreme Value Type 1 was best for the primary particle size distributions and the lognormal was best for watershed soils (i.e. source material). Differences between the flocculated size distribution, primary particle size distribution, and soil size distributions may be related to hydraulic sorting and the flocculation process. There was relatively little difference in the flocculated size characteristics of the event and non-event samples and the suspended sediment samples from Cazenovia Creek were not as highly flocculated as samples collected in other rivers. Previous studies have shown environmental factors such as total bacteria, dissolved organic carbon content, and suspended sediment concentration, were related to floc size characteristics, but this typically was not the case for Cazenovia Creek. Cazenovia Creek is located in a highlands region and even during non-events the flow is very turbulent. The most important factor governing floc size characteristics for the creek therefore seems to be flow hydraulics.*

INTRODUCTION

The literature is replete on sediment flocculation characteristics in marine and urban sewage systems (e.g. Kranck, 1984; Muschenheim et al., 1989; Urbain et al., 1993; Li and Ganczarczyk, 1986), but it is only within the past decade that flocculation has been examined as a dominant mode of transport in freshwater fluvial systems (e.g. Ongley et al., 1992; Droppo and Ongley, 1992; Walling and Woodward, 1993; Droppo and Ongley, 1994; Droppo et al., 1998). Consideration of floc properties is important because flocs potentially have both a very different hydrodynamic behavior and bio-chemical structure as compared to discrete (primary) particles of a similar size (e.g. Irvine and Droppo, 1999). These differences between flocs and individual, discrete particles have important implications for the transport and fate of the suspended sediment and contaminants bound to the sediment. Lawler (1993) noted that mathematical approaches to describe the kinetics of flocculation were developed as early as 1917 and this work still serves as the foundation for understanding changes in particle size distribution due to flocculation. One reason that there has been limited progress in developing numerical expressions of flocculation dynamics is "the ability to measure the size distribution in practice is .... difficult" (Lawler, 1993). However, new developments in modelling the flocculation process and floc transport dynamics are being facilitated by the increasing sophistication of non-destructive analytical techniques to determine sediment (and floc) size characteristics (e.g. Lau and Krishnappan, 1992; Droppo and Ongley, 1992; Walling and Woodward, 1993; Droppo et al., 1997). These non-destructive techniques contrast with classical approaches (e.g. pipette, hydrometer, SediGraph) that purposely break flocs apart to obtain primary particle size distributions.

Because many of these non-destructive analytical sizing techniques are relatively new, literature on QA/QC measures is relatively scarce. One objective of this paper is to present the results of various QA/QC tests that were recently conducted in association with size distribution analyses of suspended sediment from Cazenovia Creek, NY. These QA/QC tests can be used to guide sampling and analytical procedures as well as provide insights into the level of confidence that can be obtained in determining and interpreting suspended sediment size distribution data.

Sediment size distribution characteristics have long been used to differentiate depositional environments and modes of transportation (e.g. Visher, 1969; Middleton, 1976; Viard and Breyer, 1979). Furthermore, hydrologists have used the characteristics of flood probability distributions to examine the regional nature of the flooding process (e.g. Irvine and Waylen, 1986; Irvine and Drake, 1987; Caissie and El-Jabi, 1991). In particular, the parameter values that are determined to operationalize the distributions may exhibit a regional trend that reflects the physical and hydrometeorological characteristics of the watersheds. A second objective of this paper follows from these earlier works, as theoretical probability distributions were fit to the suspended sediment size distributions determined for storm and non-storm events from Cazenovia Creek and to source soils. This is a preliminary effort to: identify appropriate theoretical distributions to fit the size data; and examine how size distribution may evolve from soil source, through transportation within a river channel. Information on suspended sediment size distributions ultimately can be useful input for sediment/contaminant transport models (e.g. Gailani et al., 1991; Ongley et al., 1992) and to make spatial comparisons of erosion dynamics within and between watersheds, using regional approaches as has been done in hydrology (see also, Walling and Moorehead, 1987; Stone and Saunderson, 1992).

METHODS

Study Area

Cazenovia Creek is one of three major tributaries to the Buffalo River (Figure 1). The International Joint Commission (IJC) designated the lower 9 km of the Buffalo River as a Great Lakes Area of Concern due to a variety of environmental impairments (New York State Department of Environmental Conservation (NYSDEC), 1989) and there has been a great deal of interest and effort expended in developing and implementing remediation strategies. More recent studies (e.g. DePinto et al., 1995; Irvine and Pettibone, 1996) indicated that there are important point and non-point pollutant sources in the watershed above the IJC-designated Area of Concern and the Erie County Department of Environment and Planning has initiated a pilot watershed management project for Cazenovia Creek. Refinement of available water quality models for Cazenovia Creek requires information on the suspended sediment characteristics, as some of the contaminants of

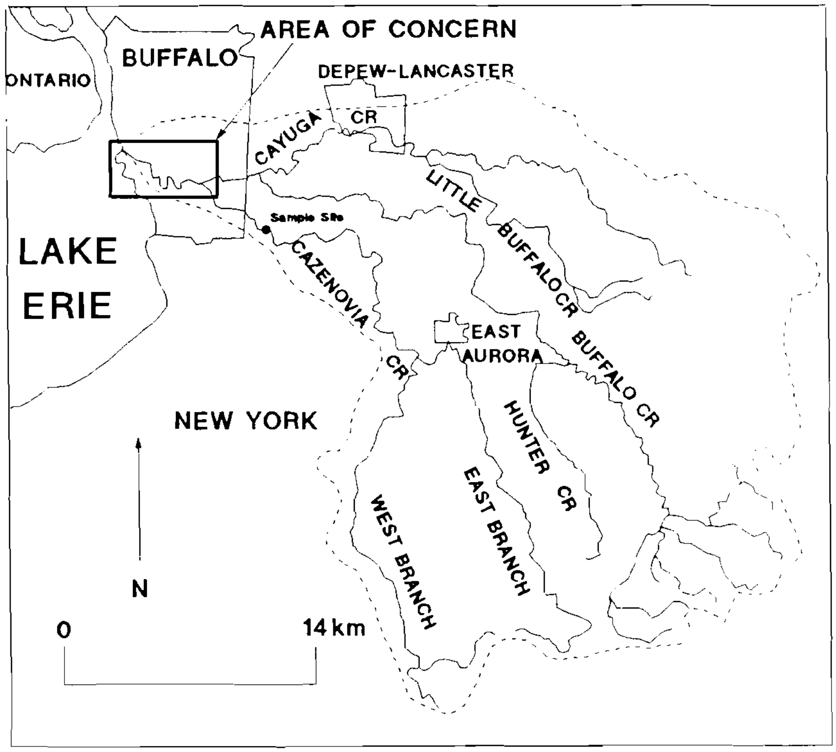

Figure 1. The Buffalo River watershed and sample site location on Cazenovia Creek.

concern (fecal coliforms, metals, and semi-volatile organic compounds) tend to be particle-bound.

Cazenovia Creek drains an area of 350 km^2 and land use in the watershed varies. The upper portion of the watershed flows through the Alleghany Plateau area and is characterized primarily by woods and farmland, although small communities also are scattered through the upper watershed. The creek flows through a progressively more suburban landscape as it enters a glacial lake plain area and thence discharges to the Buffalo River.

All samples were collected at the USGS gauge station (#04215500), which is located in suburban West Seneca, NY (Figure 1). Flows in the range of 0.03 to 1.4 m^3s^{-1} are equalled or exceeded at this site essentially 100% of the time, while discharges larger than 28 m^3s^{-1} are equalled or exceeded approximately 8% of the time (Monahan, 1997).

Sampling Methods

Samples for analysis of suspended sediment size, suspended sediment concentration, and bacteria levels, were collected for events and non-event periods between July, 1994 and June, 1996. In past studies (e.g. Droppo and Ongley, 1992), storm event and non-event samples for floc analysis were collected by directly inserting a plankton settling column to a depth of 30 cm below the water surface and parallel to flow. The upper end was then capped under water to trap the water-sediment mix. For safety reasons, this sampling method was not possible under high flow conditions at the study site on Cazenovia Creek. As a result, grab samples of water had to be collected in sterile glass sample bottles from a bridge during storm events. The sample depth for storm events was 30 cm. To be consistent, non-event samples also were collected in sterile glass bottles. River depth typically was less than 30 cm under non-event conditions and therefore a sample depth of 0.6 of the total depth below the surface was used. Samples for suspended solids concentration analysis were collected in a separate glass bottle, immediately after the sampling for floc and bacteria analysis

Samples for size analysis were poured immediately into plankton settling columns fitted with inverted microscope slides. Direct counts of bacteria were done on the samples in the inverted microscope slides. Water temperature, pH, conductivity, and flow velocity also were measured on site.

Laboratory Methods

Suspended sediment size distributions were determined at the National Water Research Institute using an Optomax V automated image analysis system interfaced with an IBM computer and a Zeiss Axiovert 100 inverted microscope (Irvine et al., 1995). The sediment settled through the plankton column and into the 3 ml reservoir of the inverted microscope slide (see Plate 1). The settling column was removed and the slide containing the water-sediment mix was placed on the movable stage of the inverted microscope. Particles in the microscope field of view were then imaged. To obtain an appropriate number of particles for distribution calculations, it was necessary to move the stage several times to image a new field of view (i.e. a view of a different part of the inverted microscope slide). Distributions were determined as a percent by both volume and number, based on equivalent spherical diameter. A subset of samples that were not analyzed for bacteria levels were sonicated to determine the primary particle size distribution. Samples for suspended sediment concentration analysis were filtered through 0.45 µm Millipore filters.

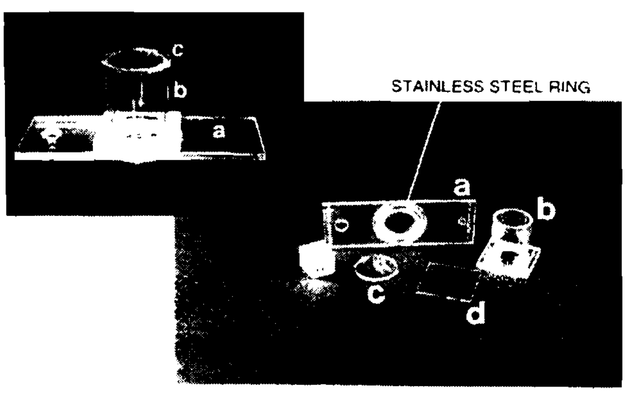

Plate 1. Plankton settling column system. a) inverted microscope slide with 3ml reservoir; b)settling column; c)top cap to cover settling column; d)square glass plate to cover 3 ml reservoir (in the absence of the settling column) (from Irvine and Droppo, 1999)

Direct counts of bacteria were determined using epifluorescence microscopy (e.g. Bitton et al., 1993; Monahan, 1997). The bacteria analysis was performed in the Microbiology Laboratory at SUNY College at Buffalo using an Olympus Vanox-T epifluorescent microscope equipped with an HBO light source, VG1 exciter filter, a 1420 barrier filter, and a DAPO 100x U.V. objective. Using this method, total bacteria were counted regardless of species.

RESULTS AND DISCUSSION

Quality Assurance/Quality Control

There are numerous QA/QC questions associated with the image analysis approach to analyzing suspended sediment size characteristics, in part because the technique is relatively new. This section summarizes various QA/QC tests that were conducted on the samples.

Sampling methodology comparison

To ensure that the results for samples collected in a bottle and poured into a plankton column were comparable to results for samples collected directly into a plankton column (thereby facilitating comparisons with past studies), sampling was conducted to test the effects of the two sampling methodologies. A total of 10 samples were collected on one day at a discharge of 16 m^3s^{-1} where five samples were collected directly into the plankton settling column (per the procedure outlined by Droppo and Ongley, 1992) and five samples were collected in bottles and poured into the columns. A total of four samples were collected at a discharge of 1 m^3s^{-1} on a different day, where two samples were collected directly into the settling column and two samples were collected in bottles and poured into the columns. The Mann-Whitney test and Student's t-test indicated that there was no significant difference (α=0.05) between the average of the mean spherical diameters (by number) determined for the two sampling methodologies. An "average" size distribution also was calculated for each sampling methodology on each sample date. A Kolmogorov-Smirnov (KS) test indicated that there was no significant difference in the size distributions (per cent by number) for the two methodologies (α=0.05).

Holding time

There is some question as to whether the size distribution of a sample may change within the inverted microscope slide, over a period of time prior to analysis. Two separate holding time studies therefore were conducted. For the first study, three replicate samples were imaged one and three days after collection. For the second study, a single sample was imaged one and 22 days after collection. For both studies, a KS test indicated that there was no significant (α=0.05) change in the size distribution (per cent by number) over the holding time. An analysis of variance also indicated that the mean spherical diameters for the replicates did not change significantly (α=0.05) over the three day holding time.

Optimum number of particles to image

In an effort to minimize imaging time and maintain confidence in the analytical results, two tests were conducted to determine an optimum number of particles to image. First, one sample was imaged eight times, with the number of particles imaged being progressively increased. Second, eight samples were collected under different flow conditions and 500 and 1,000 particles were imaged for each sample. Results of the first test are summarized in Table 1. Qualitatively, there is little difference in the summary statistics shown in Table 1 and a KS test indicated no difference (α=0.05) in the distributions for the 731 vs. 15,155 particle imaging or for the 1,094 vs. 15,155 particle imaging. For the second test involving the eight different samples, a KS test indicated no difference (α=0.05) in size distribution for any of the samples when 500 or 1,000 particles were imaged. It is important to note, however, that when fewer than 1,000 particles are imaged, the number of fields of view (i.e. the number of locations on the slide from which images are collected) is limited (Table 1). Imaging fewer fields of view would increase the probability of collecting a non-representative sample.

Suspended Sediment Size Characteristics of Event and Non-Event Samples

Data on the mean and median size characteristics for non-event and event samples are summarized in Table 2. Student's t-tests and Mann-Whitney tests indicated that there were no significant differences (α=0.05) between the averaged event and non-event mean spherical diameter (by number and volume) or between the averaged median event and non-event spherical diameter (number only was tested).

KS tests indicated that there were significant differences (α=0.05) in the per cent by number size distributions during two of the storm events. For the November 7, 1995 storm event three samples were collected through the storm and there was a significant difference between the samples collected at 10:00 and 18:00. A snowmelt event sample was collected on each of March 15 and 16, 1996 and there was a significant difference between the two size distributions (per cent by number). There were no significant differences in the remaining storm event distributions (per cent by number). There were significant differences (α=0.05) in the per cent by volume size distributions from all samples collected through storms.

The suspended sediment was flocculated and the size characteristics for the flocculated and sonicated samples are summarized in Table 3. The ratio between flocculated and sonicated median size is greatest for the volume data and this in part is a function of a few individual flocs making up the bulk of the sediment volume (see also, Figure 2). Droppo et al., (1998) reported flocculated to sonicated ratios for median size (per cent by number data) averaging 3.3 for samples from three rivers in the McKenzie River Delta, Northwest Territories. However, it also was noted that the sediment in these rivers tended to be more flocculated than for sampled rivers in southeastern Canada. Irvine et al. (1995) reported flocculated to sonicated ratios for median size (per cent by volume data) ranging between 1.4 and 1.9 for non-event samples from the Buffalo River and its three major tributaries. This ratio increased to 14.8

Table 1: Results of progressively increasing the number of particles imaged

No. of Particles Imaged	Mean Spherical Diameter, μm	Median Spherical Diameter, μm	Standard Deviation, μm	No. of Fields of View
124	5.39	3.80	4.70	1
290	5.34	4.19	4.12	2
731	5.23	4.00	4.95	4
1,094	5.60	4.23	5.07	6
2,172	5.51	4.16	5.52	12
5,257	5.61	4.17	5.70	27
10,133	5.59	4.19	5.66	49
15,155	5.57	4.21	5.45	68

Table 2: Summary of size analysis

Storm Event Results			Non-Event Results		
Range of Mean Spherical Diameter, μm, % by number	Range of Median Spherical Diameter, μm, % by number	Range of Median Spherical Diameter, μm, % by volume	Range of Mean Spherical Diameter, μm, % by number	Range of Median Spherical Diameter, μm, % by number	Range of Median Spherical Diameter, μm, % by volume
3.8-6.7	3.2-4.7	9.1-112.1	4.4-5.8	3.6-4.2	16.2-71.3

n=23 for event samples; n=11 for non-event samples

for dry weather sewage samples collected in the same study.

Various environmental factors may influence the size distribution of flocculated sediment, including exopolymer excretions from bacteria, suspended solids concentration, organic carbon, major ions, pH, water turbulence, and temperature (e.g. Tsai et al., 1987; Muschenheim et al., 1989; Dade et al., 1996; Droppo and Ongley, 1994; Droppo et al., 1997). Correlation results between size characteristics and environmental variables measured in this study are shown in Table 4. The results in Table 4 indicate no correlation between bacteria counts and particle size characteristics and weak (but not significant at $\alpha=0.05$) correlation between suspended solids concentration and particle size characteristics. There also were weak correlations (but not significant at $\alpha=0.05$) between velocity and particle size, indicating that as velocity (and shear) increases, the floc size generally becomes smaller. This is consistent with the results reported by Tsai et al., 1987. In flume experiments, Stone and Krishnappan (1998) showed that the median diameter of suspended solids changed as a function of time and shear stress. These experiments indicated that increased shear stress resulted in flocculation until a threshold stress was reached, above which the median diameter decreased (i.e. larger flocs broke up). It is not clear whether this "dual role" for shear stress that was observed in the flume experiments also operates in rivers, but more detailed sampling under greater flow variations for different rivers is warranted.

Fitting Theoretical Distributions

A lognormal distribution historically has played a central role in summarizing sedimentary textures and interpreting transportation characteristics and depositional environments (e.g. Viard and Breyer, 1979; Schleyer, 1987). We used the BestFit software, an Excel spreadsheet add-in (Palisade Corporation, 1997) to identify the distribution(s) that most likely produced the observed size data. BestFit compared the sample data with 25 theoretical probability distributions, using a maximum-likelihood estimator approach. Subsequently, Chi-square and KS test statistics were calculated to evaluate goodness-of-fit and BestFit ranked the fit of each distribution based on the test statistic results. For brevity, we have confined our analysis to the per cent by number size distribution data. In addition, we

Table 3: Summary of sonication results for mean and median spherical diameters (μm) and ratio of flocculated (F) to sonicated (S) sizes

	Floc Data, % by Number		Sonicated Data, % by Number		Floc Data, % by Volume	Sonicated Data, % by Volume	Ratio, F:S, by Number	Ratio, F:S, by Number	Ratio, F:S, by Volume
Sample Date	Mean	Median	Mean	Median	Median	Median	Mean	Median	Median
11/14/95	5.1	3.7	4.7	3.9	71.3	9.4	1.09	0.95	7.59
2/24/96	6.9	4.7	4.4	3.9	93.5	8.3	1.57	1.21	11.27
4/24/96	6.7	4.5	4.8	3.7	94.1	12.9	1.40	1.22	7.29
4/25/96	4.6	3.6	4.2	3.5	23.3	10.2	1.10	1.03	2.28
4/25/96	4.6	3.6	4.5	3.7	14.1	9.3	1.02	0.97	1.52
6/4/96	4.1	3.3	3.9	3.5	33.0	6.3	1.05	0.94	5.24
6/4/96	5.4	4.1	4.0	3.5	18.4	6.6	1.35	1.17	2.79
6/4/96	4.7	3.7	4.1	3.7	26.7	6.6	1.15	1.00	4.05

Table 4: correlation results (r) between particle size characteristics (μm) and environmental variables

Size	Bacteria, (m.o.)	Suspended Solids, mg l^{-1}	Water Temp. °C	pH	Conductivity, μs	Water Velocity, m s^{-1}
Mean Spherical Diameter, by Number	0.083	0.266	-0.317	-0.337	-0.182	-0.11
Median Spherical Diameter, by Number	0.002	0.112	-0.084	-0.121	-0.151	-0.21
Median Spherical Diameter, by Volume	0.042	-0.022	-0.385	-0.083	-0.151	-0.33

applied the software to fit the observed size distributions of eight different soil types found in the watershed, as reported by the U.S. Department of Agriculture (1986).

In general, the Pearson Type VI distribution best fit the flocculated event and non-event size distributions (e.g. Figure 3a), while a lognormal distribution clearly was best for the soils (Figure 3c). Best fit results were more variable for the primary particle distributions. The Extreme Value Type I distribution generally was best (e.g. Figure 3b), but the Gamma and Erlang distributions also provided a reasonable fit.

In an analysis of bed sediment samples from a river in Italy, Schleyer (1987) suggested that coarse, immature clastic sediments tended to be Rosin-distributed which was a source-rock-specific feature. With increasing maturity, the sediments became more lognormally-distributed and this change in distribution was attributed to hydraulic sorting. Meyer et al. (1992) found that sediment eroded from test soil plots generally was coarser than the parent soil due to the presence of water-stable aggregates. However, when the eroded sediment was dispersed, the primary particle size distribution was similar to that of the parent soil primary particle size distribution. Our results represent three different distributions, the Pearson Type VI, the Extreme Value Type I, and the lognormal. As such, it appears that both hydraulic sorting and the flocculation process may be modifying the lognormal distribution of the source-soil. It also is possible that entrained bed sediment sizes were mixing with eroded soil. This possibility should be investigated, but it is worth noting that much of the river bed in the upstream Allegheny Plateau consists entirely of bedrock.

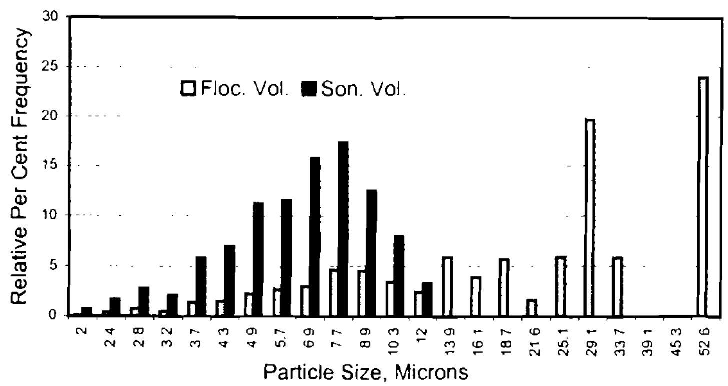

Figure 2. Relative frequency distribution (per cent by volume) for the flocculated and sonicated sample collected during the storm event of 6/4/96 at 11:30 a.m.

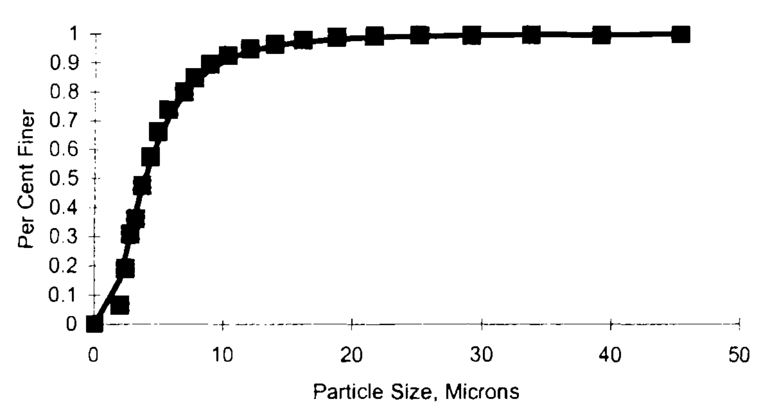

Figure 3(a). Observed (squares) and fitted Pearson Type VI (line) frequency distribution for the flocculated sample of 6/4/96 collected at 10:30 a.m. Plotted results were typical of all samples.

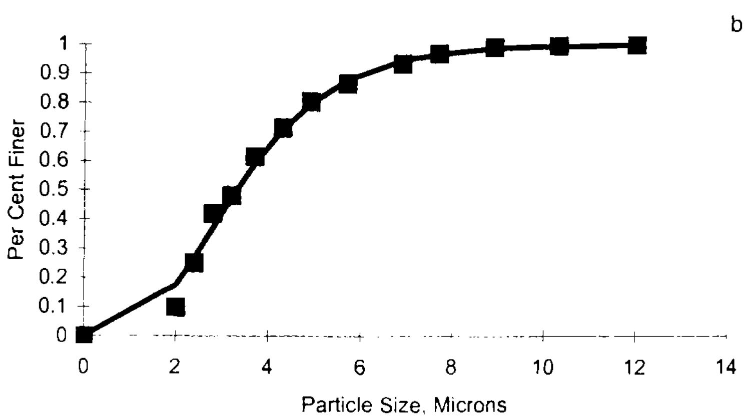

Figure 3(b). Observed (squares) and fitted Extreme Value Type I (line) frequency distribution for the sonicated sample of 6/4/96 collected at 10:30 a.m. Plotted results were typical of all samples.

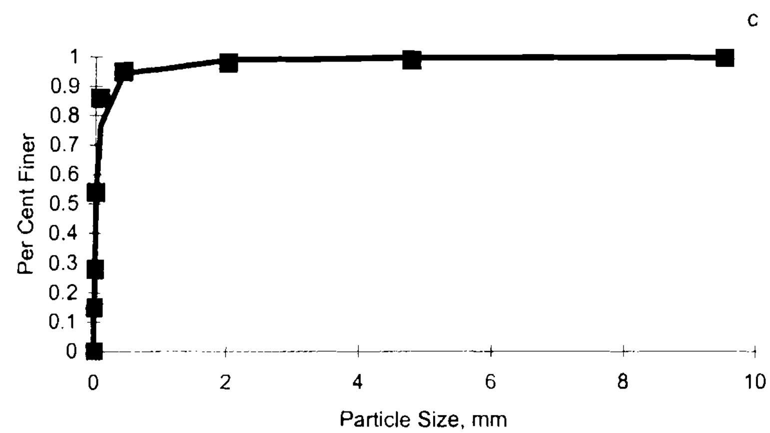

Figure 3(c). Observed (squares) and fitted lognormal (line) frequency distribution for the Derb Fine Silt soil. Plotted results were typical of all samples.

CONCLUSION

Suspended sediment flocs in Cazenovia Creek appear to be relatively stable, as pouring a sample from a bottle to a plankton settling column did not significantly change the size distribution. Provided samples are refrigerated, they may be held up to 22 days prior to imaging, without any significant change in the size distribution. The optimum number of particles to image is approximately 1,000, as this number provides stable size distribution results, minimizes analytical time, and represents multiple fields of view in the microscope.

The suspended sediment samples were flocculated, but not to the same extent that has been reported for other rivers. Furthermore, there were weak relations between environmental factors and size distribution characteristics. The lower level of flocculation and weak environment-size relations may indicate that the suspended sediment in Cazenovia Creek is influenced more by hydraulic factors. Because of the steep bed slope in the area, flow was highly turbulent, even during non-event sampling.

The Pearson Type VI distribution provided the best fit for the flocculated samples, while the Extreme Value Type I was best for the sonicated (primary particle) distributions, and the lognormal was best for source-soil distributions. It may be possible that both hydraulic sorting and the flocculation process were modifying the lognormal distribution of the source-soil. Additional study should be conducted to assess the evolution of flocculated, suspended sediment size distributions in the downstream direction and to quantitatively evaluate the possibility of regionalization of suspended sediment size distributions.

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