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FISP EVALUATION OF THE LISST-SL, AN INTERIM REPORT

October, 2008

Introduction

The US Geological Survey (USGS) entered a Cooperative Research And Development Agreement (CRADA) with Sequoia Scientific, Inc., in 2002 to develop a river-deployable version of the LISST-100. The LISST-100 measures particle size distribution and suspended-sediment concentration in-situ in real-time. It is a laser based instrument that measures forward scattered laser light intensity distribution through a 5 cm laser path length utilizing a series of 32 annular ring-detectors that are logarithmically spaced in an angular range of 0.0017-0.34 radians. Each ring represents a particle size class. Ring-detector information is used to determine particle size distribution and suspended-sediment concentration in real-time. The new river-deployable instrument is designated "LISST-SL" (StreamLined) and the CRADA states it should be capable of deploying from a standard single-conductor cable from a USGS B-reel, stable in flows up to 10 ft/sec, and weigh 100 lbs or less. It should also be capable of measuring sediment particles in a range from 0.002 to 0.5 mm median diameter within 25 percent, and to compute suspended-sediment concentrations to within:

a. 50 percent of actual concentration values less than 10 mg/L,
b. From 50 percent of actual concentrations of 10 mg/L to 25 percent at actual concentrations of 100 mg/L, computed linearly,
c. 25 percent of actual concentration values at 100 mg/L to 15 percent at actual concentrations of 1,000 mg/L, computed linearly, and
d. 15 percent of actual concentration values above 1,000 mg/L.

Maximum sediment-concentration values to be measured by the LISST-SL are at least 5,000 mg/L.

The current version of the LISST-SL has a streamlined body that has a maximum diameter of 5.2 in, length of 29.5 in, and weighs 35 lbs. It has a Pitot Static tube acting against a pressure transducer that senses the stream velocity and controls a pump that draws the water/sediment mixture through a 1/4 in inside diameter brass nozzle. The instrument also includes sensors to determine depth and water temperature. The sensors are contained in a chamber in the instrument body that is open to the outside through three small ports. The LISST-SL communicates through a single conductor with a Topside Controller Box (TCB). A laptop computer with operating software also connects to the TCB, which contains batteries to supply power to the instrument. The operating software displays real-time suspended-sediment concentration (volume concentration), particle size distribution, stream velocity, instrument depth, water temperature, and detector ring information. The LISST-SL measures sediment particles in a range from 0.002 to 0.5 mm median diameter and suspended-sediment concentration up to 3,000 mg/L. Figure 1 is a photograph of the instrument and TCB. Figure 2 is a photograph of the laptop display during operation of the instrument.

The instrument was received by the FISP for testing and evaluation. The remainder of this report summarizes results obtained through September 2008.

Laboratory Test Apparatus

A laboratory test apparatus was devised in which the instrument could be operated in a steady-state, continuous mode. A cylindrical tank 18 in inside diameter by 24 in tall was fitted with two variable-speed mixers. The mixers utilized an impeller designed for use in mixing paint. Four baffles spaced 90 degrees apart on the wall of the tank prevented the water/sediment mix from swirling in a centrifugal motion around the wall of the tank. The tank was fitted with a 1/4 in ball valve near the bottom and a short length of plastic tube connected the valve to the nozzle of the LISST-SL. The distance from the tank to the instrument nozzle was only 3 in. An approximately 12 in length of plastic tube was attached to the LISST-SL pump outlet. The tube opened to the atmosphere and allowed the pump discharge to freely flow into a small sump attached to a peristaltic pump. The peristaltic pump returned the water/sediment mix through plastic tubing back to the mixing tank to complete the circuit. A length of plastic tubing was attached to the Pitot Static tube on the instrument and fixed to a vertical upright. Water added to the tube produced a static head which induced the instrument pump operate. Figure 3 shows a schematic of the setup. Figure 4 is a photograph of the operation.

The test procedure included placing either 42 or 50 L of distilled or filtered water in the tank. The mixers were started and the valve opened to allow the water to flow through the instrument. The speed of the peristaltic pump was adjusted to maintain a fairly consistent level in the sump. The software was started and a background reading taken with only water in the system. The mixers were adjusted to the maximum speed that did not generate air bubbles. The presence of air bubbles in the test system was detrimental, as the LISST-SL perceived them as large particles. Adjusting the mixers speed to keep sediment suspended in the tank without inducing air bubbles was a challenge. Once the system was at steady-state and a background taken, a pre-weighed amount of material was added to the tank to make a known suspended-sediment concentration. The LISST-SL software was started and allowed to operate until the real-time volume concentration reading was consistent. Physical samples were taken from the LISST-SL pump discharge tube and the corresponding LISST-SL sample numbers recorded. Physical samples were analyzed at the Coastal and Hydraulic Laboratory (CHL) sediment laboratory at US Army Corp of Engineer Engineering Research Development Center (ERDC), Vicksburg, MS.

Materials (Table 1) used to make the suspended-sediment mixtures were obtained from Powder Technology, Inc (PTI). Three different materials were used, AC Spark Plug Dust (ACSPD), Arizona Test Dust (ATD) 12103-1 A4, and ground silica dust (PTI SD). The ACSPD and ATD were essentially ground granite and the PTI SD ground silica, 99 to 99.9 pct SiO_2. The ACSPD was 100 pct finer than 62 microns, the ATD 100 pct finer than 200 microns, and the PTI SD 100 pct finer than 150 microns. In addition, sieved sand fractions were added for some tests.

Results

Suspended-sediment Concentration

After preliminary tests to learn the operation of the instrument, a series of suspended-sediment concentration tests was conducted. The test mixtures were: 10 mg/L concentration using ACSPD; 100 mg/L concentration using 95 pct ACSPD and 5 pct 62/125 micron sand; 1,000 mg/L concentration using 95 pct PTI SD and 5 pct 125/250 micron sand; 3,000 mg/L concentration using 87 pct PTI SD and 13 pct 125/250 micron sand, all by dry weight (Table 2). Table 3 presents the results of Series 1. The LISST-SL concentration measurements were all lower than the prepared concentrations, but with the exception of the 1,000 mg/L were within the target range of the CRADA. Of obvious concern was the low concentration of the physical samples and the fact that the 1,000 mg/L LISST-SL concentration was out of range, although the concentrations immediately below it (100 mg/L) and above it (3,000 mg/L) were within range. These results pointed to a less than ideal mixing of the sediment in the test system and the possibility of sediment being trapped in the LISST-SL pump. An examination of the LISST-SL size analysis of one of the 1,000 mg/L samples (Figure 5) seems to confirm that the sand was not efficiently suspended in the mixing tank. The prepared water/sediment mixture contained 5 pct by dry weight 125/250 micron sand, yet the size analysis from the instrument showed no material larger than 100 microns. The difficulty encountered was that a mixer speed sufficient to keep the sand suspended resulted in the introduction of detrimental air bubbles in the system. Also of note from Table 3 is that the concentration trended down from the first to the last sample, indicating that material was being “lost” during a test run. It is speculated some of the sediment was being trapped in the LISST-SL pump cavity due to the type and orientation of the pump. This would be of no consequence in field use, as any sediment trapped in the pump cavity would eventually be flushed out. However, it could partly account for the low concentration of the physical samples collected from the pump discharge.

A second series of concentration tests was conducted using only PTI SD. The concentrations tested were 10, 100, 500, 1,000, 2,000 and 3,000 mg/L. Care was taken to adjust the mixers to the maximum speed without creating air bubbles. Table 4 presents the results. The LISST-SL produced excellent results compared to the prepared mixture, i.e., within 10 pct for all concentrations. However, the laboratory analysis of physical samples collected from the LISST-SL pump discharge was still low.

A third series of concentration tests was conducted with the orientation of the LISST-SL pump changed in an attempt to lessen the possibility of material getting trapped in the pump. The pump was rotated 180 degrees so the pump discharge was oriented downward instead of upward. Concentrations of 50, 100, 250, 500, 1,000, 2,000 and 3,000 mg/L were prepared using PTI SD. Table 5 shows the results. Again, the LISST-SL measured concentrations well within the range specified by the CRADA compared to the prepared concentrations. Changing the LISST-SL pump orientation did improve the correlation between the LISST-SL measurements and physical samples for the 50, 100 and 250 mg/L mixtures. However, at the higher concentrations it appears some sediment was still being trapped in the pump.

During a typical concentration test, between 200 and 700 measurements were made and recorded by the LISST-SL. Figure 6 shows the run-time concentration for 100, 500 and 1,000 mg/L tests from Series 3 concentration test. The concentration reading remained mostly constant with a slight decrease from the beginning to the end of the test as has already been noted and attributed to the possibility of sediment being trapped in the pump.

Size Analysis

Beaker tests were conducted to determine how varying size distributions would effect concentration measurements by the LISST-SL. A known concentration was mixed in a one liter beaker and the mixture stirred on a magnetic stirring plate. Plastic tube was attached to the LISST-SL nozzle with the intake in the beaker. A plastic tube connected the LISST-SL pump discharge to a peristaltic pump with a return tube to the beaker, so it was a closed loop system. The peristaltic pump served to move the water/sediment mixture through the instrument without the LISST-SL pump running. ACSPD, PTI SD and ATD materials were mixed at concentrations of 200 and 1,000 mg/L. Figures 7 and 8 present the results. It is apparent from the volume distribution of each size class that the ACSPD is much finer than the PTI SD and ATD, and the PTI SD slightly finer than the ATD, which agrees with the size analysis reported by the supplier and previously stated. The concentration measurements by the LISST-SL for the 200 mg/L mixture were: ACSPD 175 mg/L, PTI SD 166 mg/L, ATD 147 mg/L. Although all the measurements were less than 200 mg/L, they were fairly close to each other. The concentration measurements for the 1,000 mg/L mixture were: ACSPD 1080 mg/L, PTI SD 985 mg/L, ATD 985 mg/L. These results show that for a known concentration, the LISST-SL concentration measurement is independent of particle size distribution. It should be noted that the suspended-sediment concentration/particle size distribution relationship is a major hurdle for acoustic-based suspended-sediment concentration surrogate technology.

As reported in the concentration results section, the tank mixer system could not be operated at a mixer speed to keep sand in suspension without introducing air bubbles into the system. To determine the LISST-SL's ability to measure sand size particles, additional beaker tests were conducted with sand sized material. Commercially available silica sand was sieved using a conventional Ro-Tap machine into the following size fractions: 62/125 microns, 125/212 microns, 212/300 microns, and 300/500 microns. Although the sand could not be efficiently mixed in the beaker to make concentration measurements, the intake tube to the LISST-SL nozzle could be adjusted to insure that the sand was being pulled through the instrument by the peristaltic pump. Figure 9 presents the cumulative particle size distribution plot for the four sand-sized fractions.

The chart shows the four distinct size fractions, and also shows that the sieving operation was less than perfectly efficient.

A size analysis of the PTI SD was performed by the CHL sediment laboratory using a laboratory laser instrument. The size analysis from the laboratory was compared to the size analysis from LISST-SL measurements for all concentrations tested. Figures 10-17 show the cumulative particle size distribution measured by the two instruments. Although the laboratory measurement is listed as the "control" in the charts, it should be recognized that the comparison is between two laser instruments and not between the LISST-SL measurements and an absolute "true" particle size distribution. None the less, the correlation between the two was excellent, with a slight variation at the lower and upper end of the LISST-SL operating range (10 and 3,000 mg/L).

Hydraulic Efficiency

Determining the hydraulic efficiency of the LISST-SL is not as straight forward as with FISP samplers in which a timed volume of water is collected and measured. The ideal approach would be a technique to directly measure the water velocity through the nozzle. To expedite evaluation of the instrument, such a technique was not pursued. Two techniques were employed to make indirect cursory hydraulic efficiency measurements. In the first, the LISST-SL was submerged in a tank of water with a constant head tank connected to the intake nozzle and the Pitot Static tube. The constant head tank's elevation could be adjusted to produce a static head of 1 to 17 in of water, the range which represent velocities of approximately 2 to 10 ft/sec through a 1/4 in inside diameter tube. A plastic tube was attached to the LISST-SL pump discharge. A container was submerged in the tank to the point that only about a one-inch lip remained above the waterline. A timed volume of water was collected from the pump discharge at each static head. Table 6 presents the results. The "LISST-SL velocity" column is the reading from the LISST-SL software display. The column "Nozzle velocity" is the velocity calculated from the timed volume of water collected from the pump discharge. The "Hydraulic efficiency" column is the "Nozzle velocity" divided by the "LISST-SL velocity" reading. FISP suspended-sediment samplers are designed to sample within plus or minus 10 pct of ideal (isokinetic). The hydraulic efficiency values from the static head tests of the LISST-SL indicate that the instrument is certainly close to plus or minus 10 pct from ideal with the exception of the results from the 12 in static head test. It appears that the low efficiency at 12 in static head is an anomaly compared to the other results, but probably warrants a second test, which has not been conducted.

A second hydraulic efficiency test was conducted in the US Geological Survey Hydrologic Instrumentation Facility Hydraulic Laboratory's flume. The flume is capable of a maximum water velocity of approximately 3.7 ft/sec, so only the lower velocity range of the LISST-SL could be tested. The procedure was to set a flume water velocity and measure the velocity with a Price AA velocity meter. The LISST-SL was suspended to the same vertical elevation in the water column as the Price AA meter. The flume water velocity reading from the Price AA meter and LISST-SL software velocity display were recorded. The LISST-SL was raised to the point that it was still totally submerged, but near the water surface and a plastic tube attached to the pump discharge. A timed volume of water was collected in the same manner as in the static head tests. The water velocity through the nozzle was calculated from the timed water sample. Table 7 shows the results. The "LISST-SL velocity" column is the velocity reading recorded from the software display. The "LISST-SL / Flume" column is the instrument reading divided by the Price AA reading. The "Hydraulic efficiency" column is the nozzle velocity calculated from the timed volume sample divided by the Price AA reading. In most cases, the hydraulic efficiency was above ideal, but not too far out of range.

The conclusion of the hydraulic efficiency tests is that since the static head test resulted in efficiencies that were low and the flume test resulted in efficiencies that were high, the true efficiency is probably somewhere in between. However, further hydraulic efficiency testing is probably warranted.

Need for Field Testing

Integral to the FISP evaluation of the LISST-SL are plans to field test the instrument in cooperation with one or more USGS Water Science Centers. These plans have been delayed because of hurricane activity along the southern gulf coast. The plan is for side by side testing between the LISST-SL and FISP point and depth integrated samplers. These tests will be completed. The purpose of the tests is to determine if LISST-SL measurements compare favorably with physical samples, to determine how the instrument handles river environments and to determine how user friendly it is. Background with clean water in the instrument must be recorded before measurements are made. The chamber containing the pressure transducers for measuring stream velocity and water depth must be full of water with no air trapped in the chamber. The instruction manual states that filling the chamber with water requires the nose of the sampler be removed and the instrument reassembled under water, using a brush and/or syringe to insure no air is trapped in the chamber. These operations could prove challenging in the field.

Conclusion

Laboratory tests to date of the LISST-SL show that measurements of suspended-sediment concentration and particle size distribution made by the laser optics employed in the instrument compare favorably with prepared water/sediment mixtures. Different materials and particle size distributions were tested and the LISST-SL performed well within the criteria stated in the CRADA.

Rudimentary hydraulic efficiency tests indicate the LISST-SL water velocity sensor and pump system draw water through the nozzle at near isokinetic.

Rigorous field testing needs to be completed.

Table 1-- Material used in laboratory tests

Material	Content	Size
AC Spark Plug Dust (ACSP)	Granite	100 pct < 62 microns
Arizona Test Dust (ATD)	Granite	100 pct < 200 microns
PTI Silica Dust (PTI SD)	Silica	100 pct < 150 microns

Table 2-- Material use in Series 1 concentration test

Concentration	Material
10 mg/L	ACSPD
100 mg/L	95 pct ACSPD, 5 pct 62/125 micron sand
1,000 mg/L	95 pct PTI SD, 5 pct 125/250 micron sand
3,000 mg/L	87 pct PTI SD, 13 pct 125/250 micron sand

Figure 1-- The LISST-SL and Topside Control Box

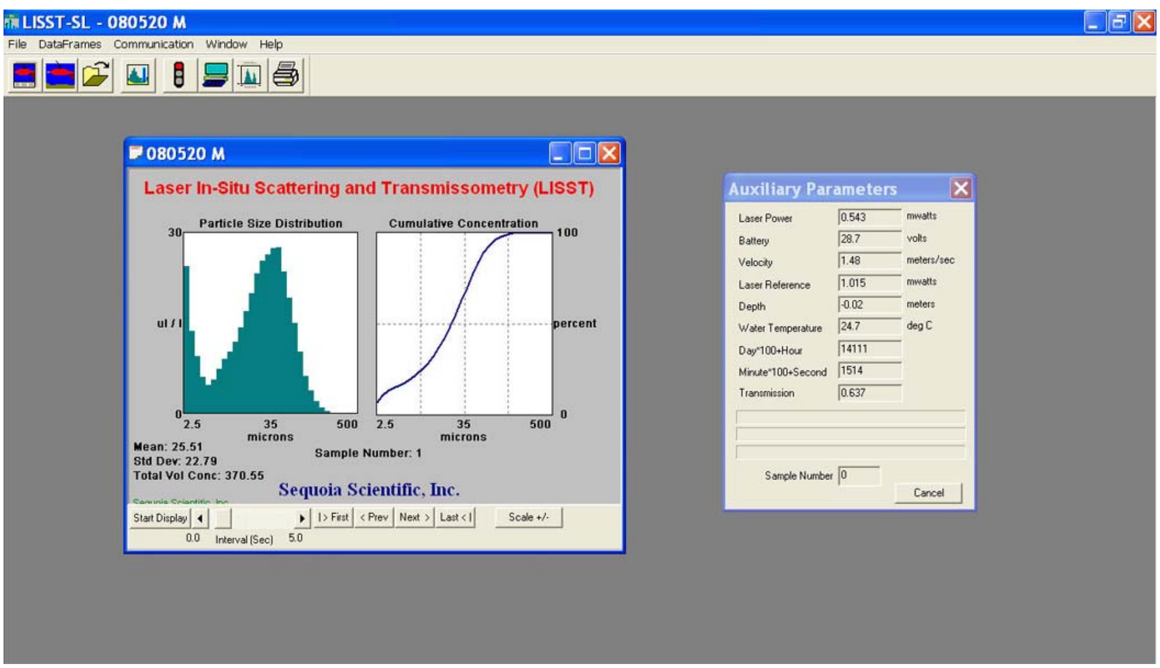

Figure 2-- Laptop computer display during instrument operation

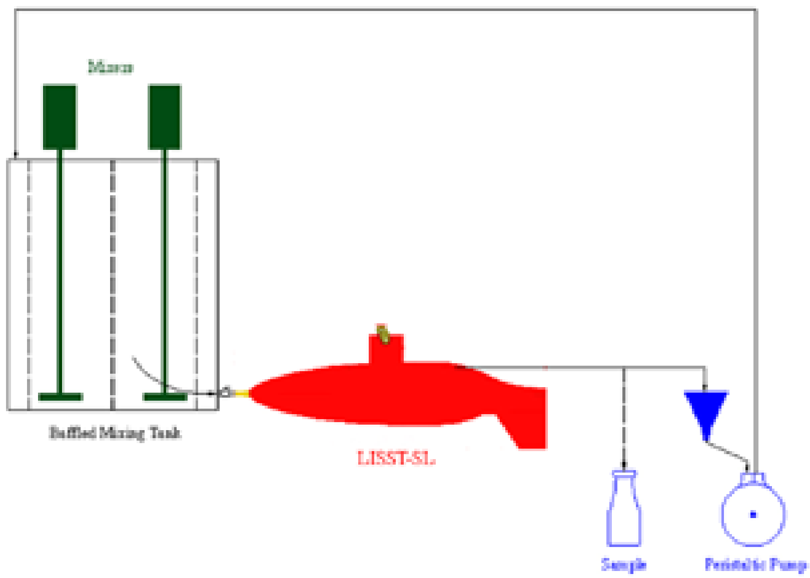

Figure 3-- Schematic of laboratory test system

Figure 4-- Photograph of laboratory test system

Table 3-- Series 1 suspended-sediment concentration test results

Sample Number	Prepared Conc, mg/L	LISST-SL Conc, mg/L	Lab analysis Conc, mg/L	LISST-SL / Prepared	Lab analysis / Prepared
X-1	10	7.05	8.32	0.71	0.83
X-2	10	7.23	6.80	0.72	0.68
X-3	10	7.41	7.64	0.74	0.76
X-4	10	7.14	7.99	0.71	0.80
X-5	10	7.08	11.86	0.71	1.19
X-6	10	6.65	8.12	0.67	0.81
X-7	10	6.7	9.85	0.67	0.98
X-8	10	7.05	8.05	0.71	0.81
X-9	10	6.7	6.93	0.67	0.69
X-10	10	6.23	8.14	0.62	0.81
C-1	100	84	64	0.84	0.64
C-2	100	80	62	0.80	0.62
C-3	100	87	63	0.87	0.63
C-4	100	89	70	0.89	0.70
C-5	100	91	67	0.91	0.67
C-6	100	78	56	0.78	0.56
C-7	100	74	54	0.74	0.54
C-8	100	76	52	0.76	0.52
C-9	100	75	53	0.75	0.53
C-10	100	73	55	0.73	0.55
M-1	1000	714	606	0.71	0.61
M-2	1000	704	599	0.70	0.60
M-3	1000	690	563	0.69	0.56
M-4	1000	681	552	0.68	0.55
M-5	1000	679	554	0.68	0.55
M-6	1000	676	539	0.68	0.54
M-7	1000	679	548	0.68	0.55
M-8	1000	686	570	0.69	0.57
M-9	1000	689	543	0.69	0.54
M-10	1000	619	500	0.62	0.50
3M-1	3000	2782	2057	0.93	0.69
3M-2	3000	2762	2062	0.92	0.69
3M-3	3000	2700	2017	0.90	0.67
3M-4	3000	2661	1986	0.89	0.66
3M-5	3000	2667	1998	0.89	0.67
3M-6	3000	2638	1974	0.88	0.66
3M-7	3000	2621	1974	0.87	0.66
3M-8	3000	2601	2010	0.87	0.67
3M-9	3000	2598	1948	0.87	0.65
3M-10	3000	2576	1919	0.86	0.64

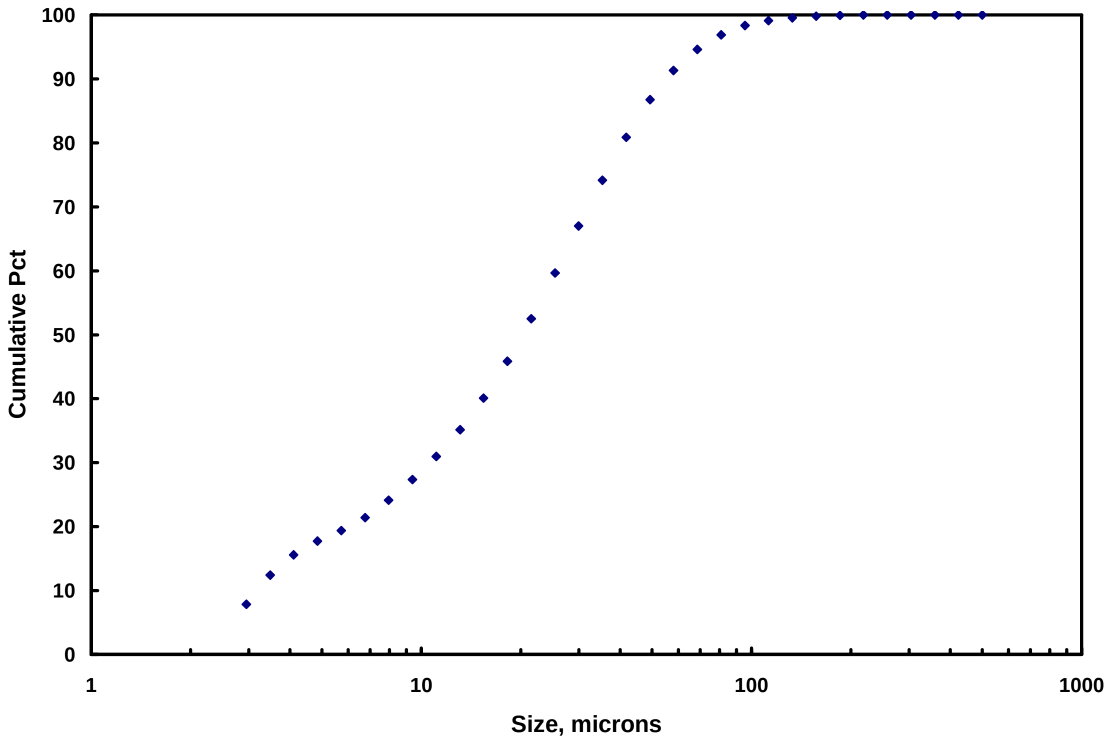

Figure 5-- Cumulative size distribution for Series 1 1,000 mg/L test sample

Table 4-- Series 2 suspended-sediment concentration test results

Sample Number	Prepared Conc, mg/L	LISST-SL Conc, mg/L	Lab analysis Conc, mg/L	LISST-SL / Prepared	Lab analysis / Prepared
X-1	10	9.9	8.3	0.99	0.83
X-2	10	9.2	7.8	0.92	0.78
X-3	10	7.9	7.4	0.79	0.74
C-1	100	98	74	0.98	0.74
C-2	100	97.8	86	0.98	0.86
C-3	100	99.2	80	0.99	0.80
C-4	100	100.8	80	1.01	0.80
C-5	100	101.2	82	1.01	0.82
5C-1	500	526	383	1.05	0.77
5C-2	500	526	466	1.05	0.93
5C-3	500	526	418	1.05	0.84
5C-4	500	525	442	1.05	0.88
5C-5	500	527	392	1.05	0.78
5C-6	500	518	439	1.04	0.88
M-1	1000	961	805	0.96	0.81
M-2	1000	950	797	0.95	0.80
M-3	1000	937	773	0.94	0.77
M-4	1000	927	773	0.93	0.77
M-5	1000	918	743	0.92	0.74
M-6	1000	1002	842	1.00	0.84
2M-1	2000	2217	1691	1.11	0.85
2M-2	2000	2205	1714	1.10	0.86
2M-3	2000	2203	1694	1.10	0.85
2M-4	2000	2199	1703	1.10	0.85
2M-5	2000	2198	1690	1.10	0.85
3M-1	3000	3008	2245	1.00	0.75
3M-2	3000	3059	2304	1.02	0.77
3M-3	3000	3074	2292	1.02	0.76
3M-4	3000	3090	2361	1.03	0.79
3M-5	3000	3096	2327	1.03	0.78

Table 5-- Series 3 suspended-sediment concentration test results

Sample Number	Prepared Conc, mg/L	LISST-SL Conc, mg/L	Lab analysis Conc, mg/L	LISST-SL / Prepared	Lab analysis / Prepared
L-1	50	42.7	42.4	0.85	0.85
L-2	50	43.2	42.4	0.86	0.85
L-3	50	44.5	43.3	0.89	0.87
L-4	50	44	44.3	0.88	0.89
L-5	50	44	43.9	0.88	0.88
C-1	100	83.2	78.2	0.83	0.78
C-2	100	82.2	81.9	0.82	0.82
C-3	100	80.8	84.6	0.81	0.85
C-4	100	79.5	83.7	0.80	0.84
C-5	100	77.7	80.7	0.78	0.81
CCL-1	250	224.2	207.4	0.90	0.83
CCL-2	250	222.6	213	0.89	0.85
CCL-3	250	222.1	214.6	0.89	0.86
CCL-4	250	220.7	216.7	0.88	0.87
CCL-5	250	221.5	214	0.89	0.86
5C-1	500	525	414	1.05	0.83
5C-2	500	511.2	391.1	1.02	0.78
5C-3	500	497.1	400.3	0.99	0.80
5C-4	500	483.2	379.2	0.97	0.76
5C-5	500	469.1	365.8	0.94	0.73
M-1	1000	1039.9	831.1	1.04	0.83
M-2	1000	1040.1	812.4	1.04	0.81
M-3	1000	1034.3	828.1	1.03	0.83
M-4	1000	1024	817.4	1.02	0.82
M-5	1000	1016	777	1.02	0.78
M-6	1000	985.3	831.5	0.99	0.83
2M-1	2000	2290.9	1724.1	1.15	0.86
2M-2	2000	2269.5	1725.7	1.13	0.86
2M-3	2000	2259.9	1705.1	1.13	0.85
2M-4	2000	2249.9	1660.9	1.12	0.83
2M-5	2000	2231.3	1701.9	1.12	0.85
3M-1	3000	3244.1	2406.5	1.08	0.80
3M-2	3000	3207.8	2368.4	1.07	0.79
3M-3	3000	3180.5	2386.3	1.06	0.80
3M-4	3000	3136.5	2244	1.05	0.75
3M-5	3000	3097.3	2305.7	1.03	0.77

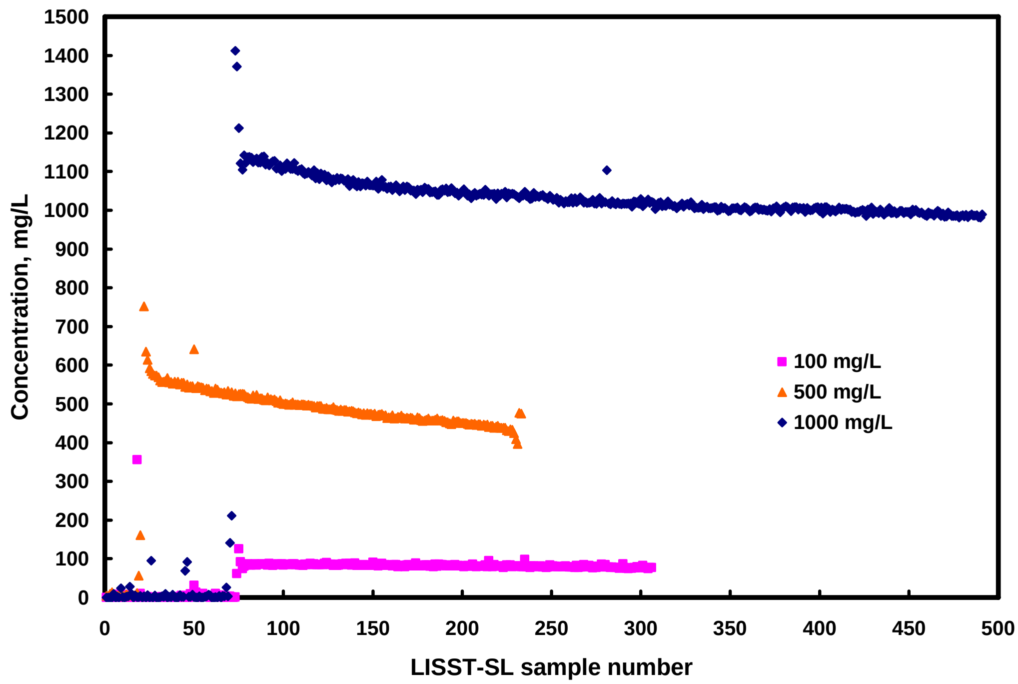

Figure 6-- Runtime concentration results

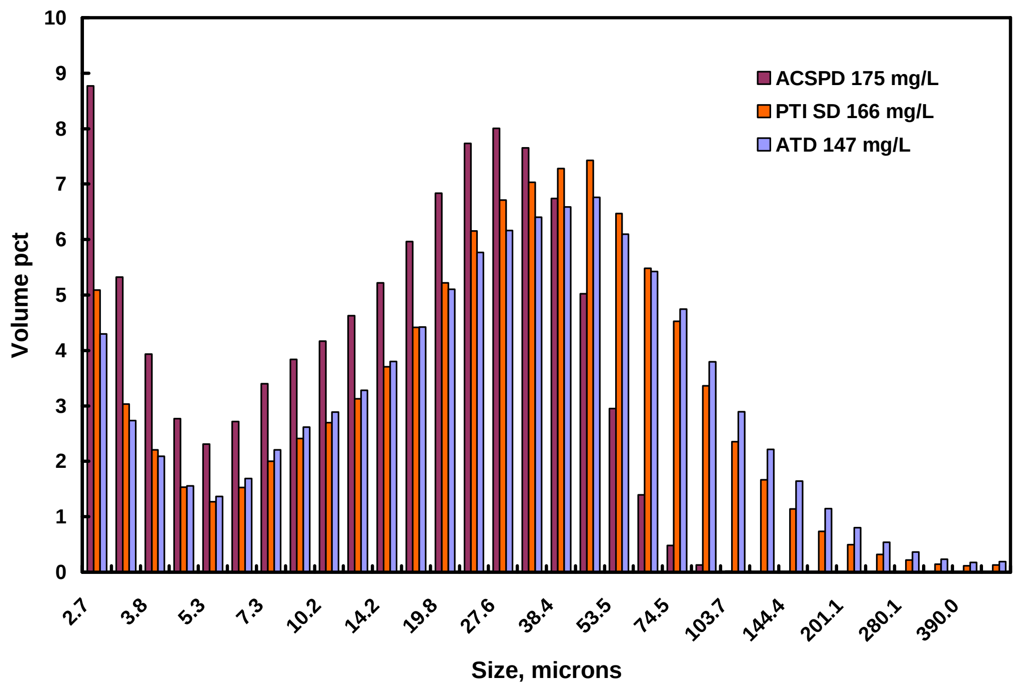

Figure 7-- 200 mg/L concentration beaker test results

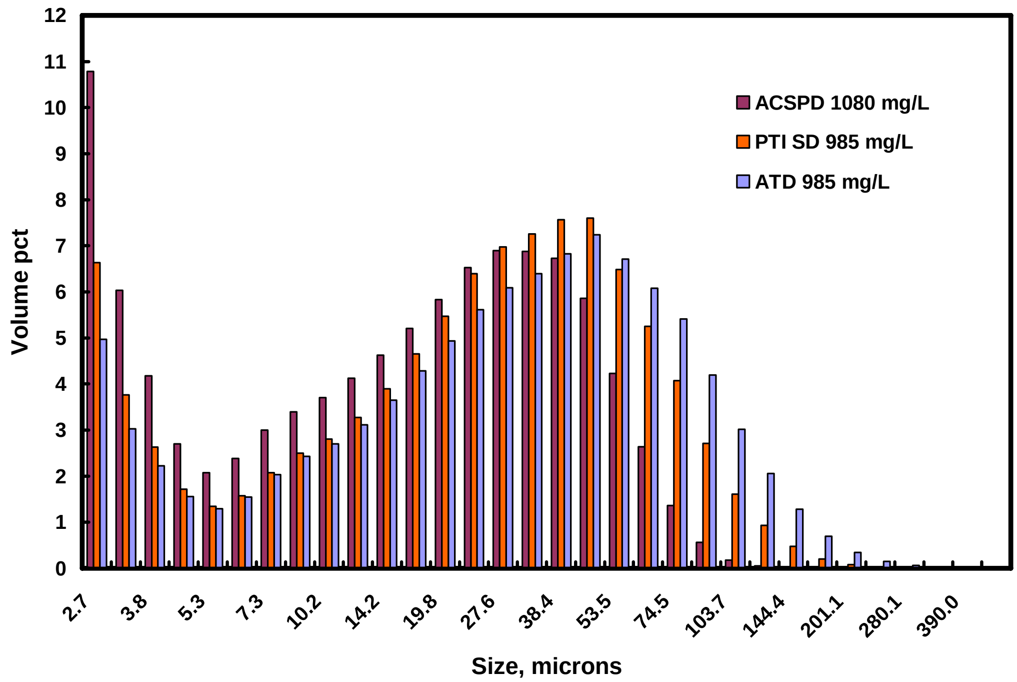

Figure 8-- 1,000 mg/L concentration beaker test results

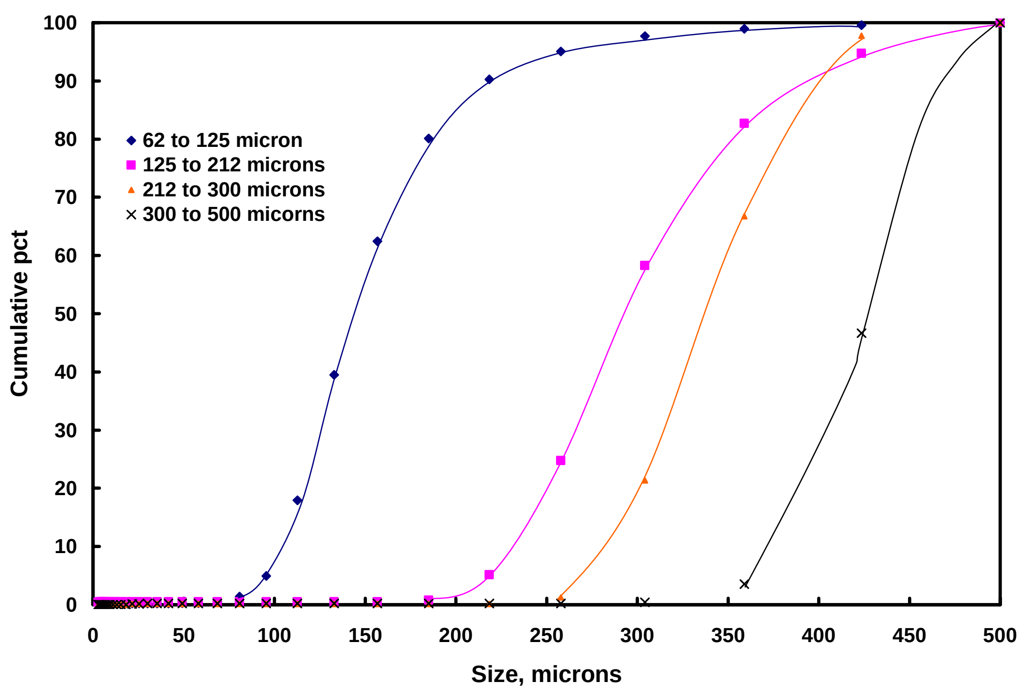

Figure 9-- Sand-size fraction beaker test results

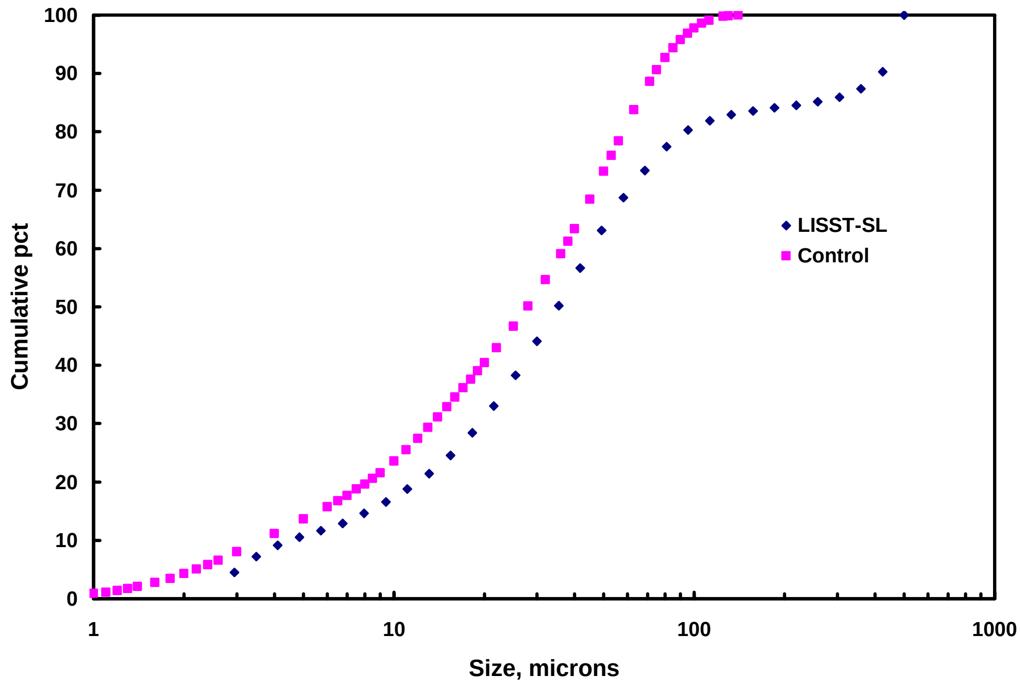

Figure 10-- Cumulative size distribution for 10 mg/L sample

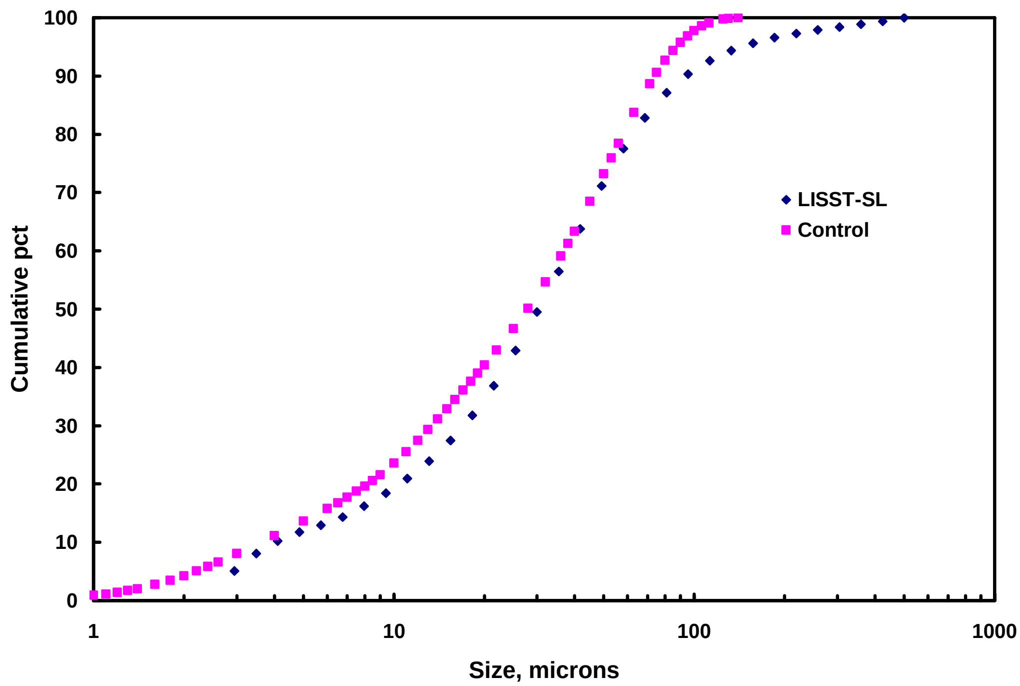

Figure 11-- Cumulative size distribution for 50 mg/L sample

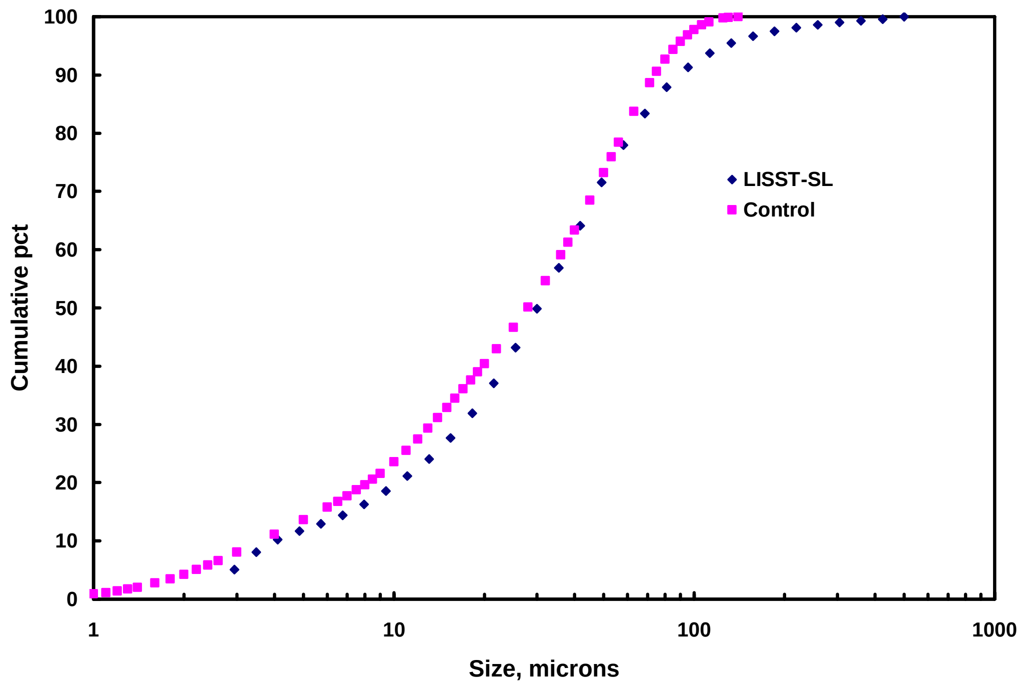

Figure 12-- Cumulative size distribution for 100 mg/L sample

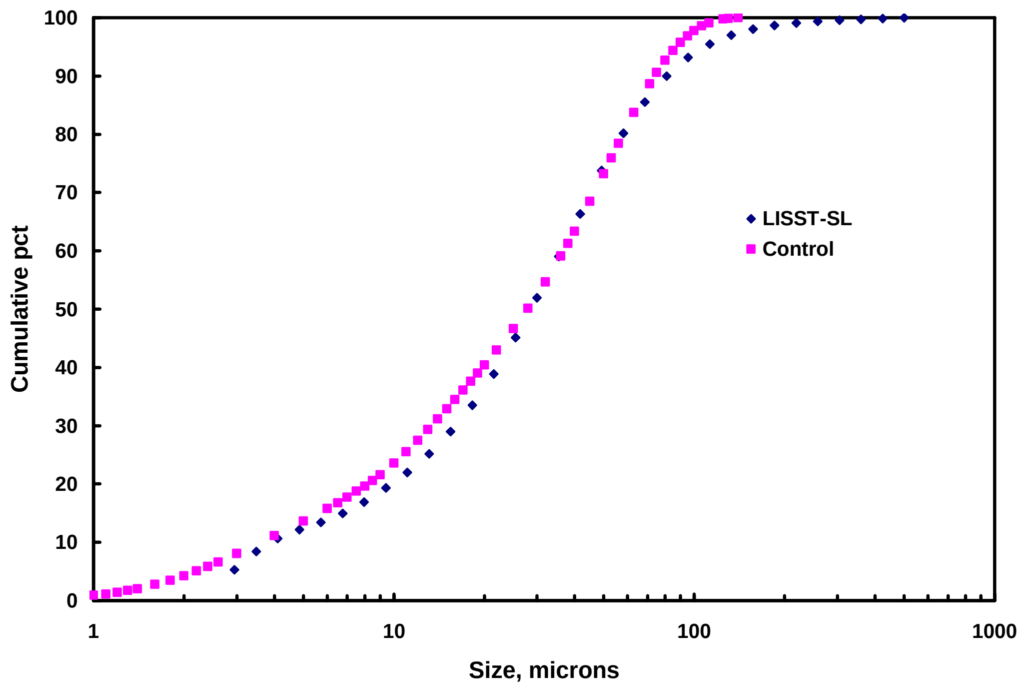

Figure 13-- Cumulative size distribution for 250 mg/L sample

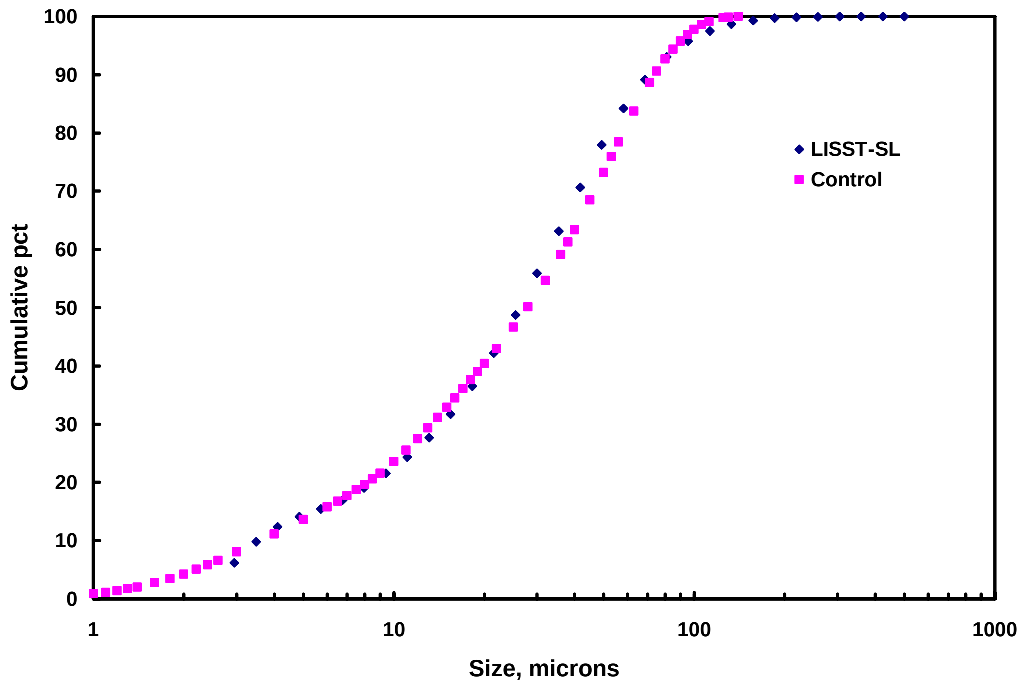

Figure 14-- Cumulative size distribution for 500 mg/L sample

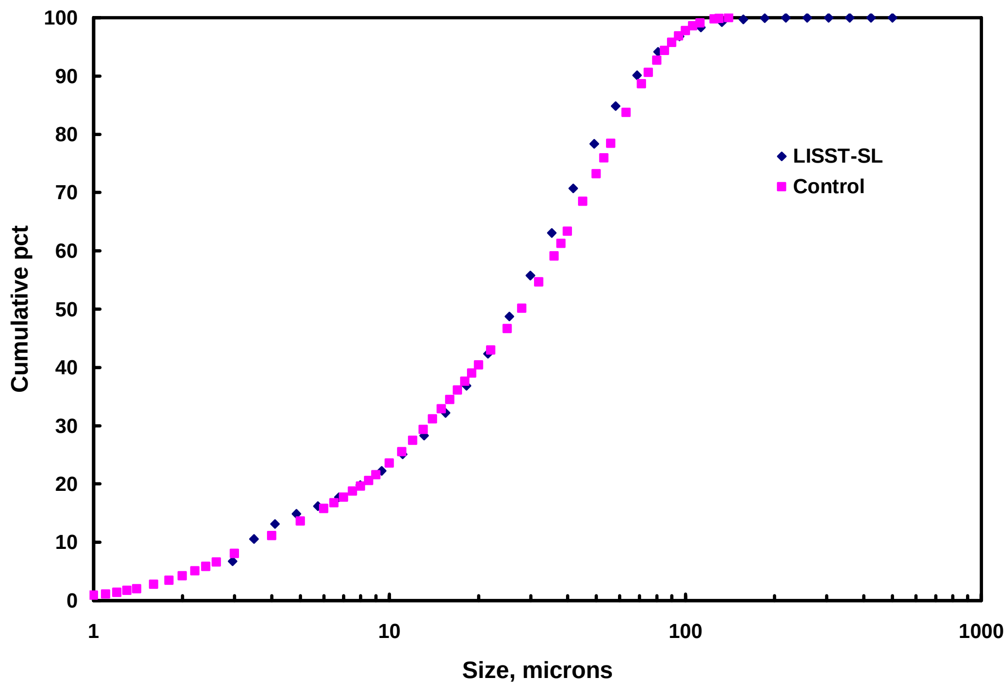

Figure 15-- Cumulative size distribution for 1,000 mg/L sample

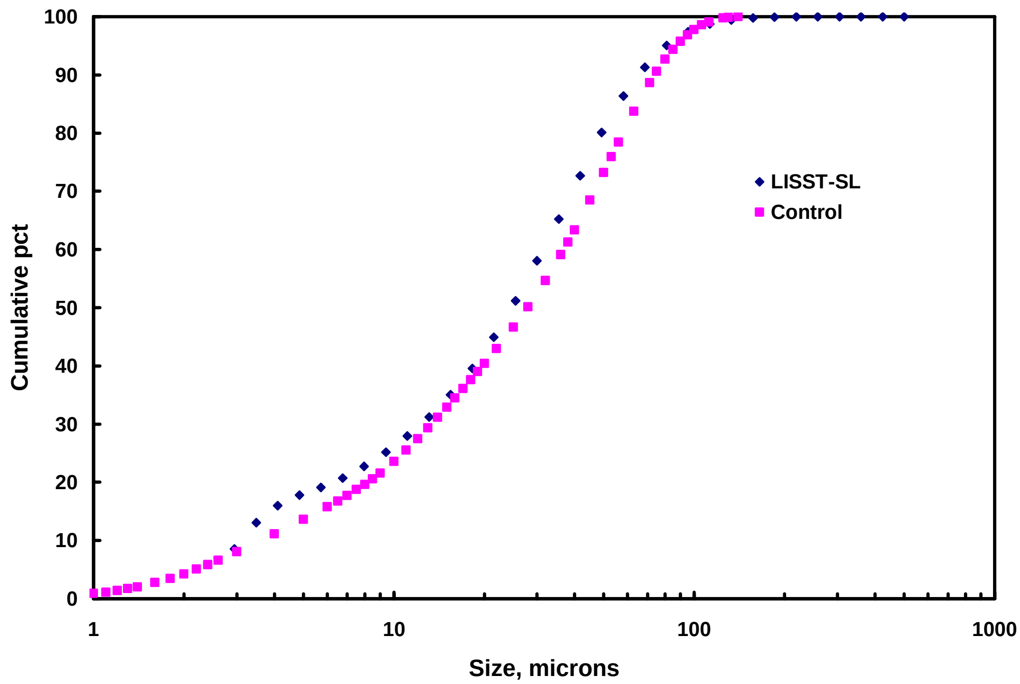

Figure 16-- Cumulative size distribution for 2,000 mg/L sample

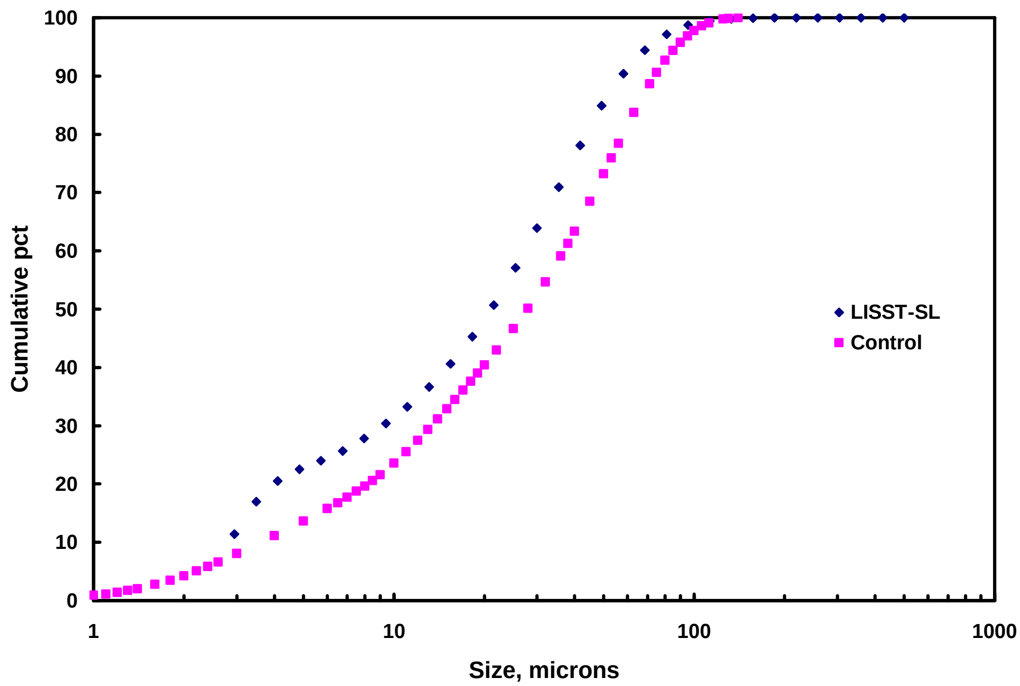

Figure 17-- Cumulative size distribution for 3,000 mg/L sample

Table 6-- Hydrostatic head hydraulic efficiency test results

Hydrostatic head on Pitot Static Tube, in	LISST-SL velocity, m/sec (ft/sec)	Nozzle velocity, ft/sec	Hydraulic efficiency
1	0.82 (2.69)	2.30	0.85
1	0.81 (2.66)	2.36	0.89
1	0.82 (2.69)	2.40	0.89
2	1.15 (3.77)	3.37	0.90
2	1.16 (3.80)	3.32	0.87
2	1.17 (3.84)	3.29	0.86
7	1.99 (6.5)	5.39	0.83
7	1.99 (6.5)	5.43	0.83
7	1.99 (6.5)	5.34	0.82
12	2.54 (8.33)	6.02	0.72
12	2.55 (8.36)	5.99	0.72
12	2.55 (8.36)	5.97	0.71
12	2.55 (8.36)	6.70	0.80
17	3.04 (9.97	10.96	1.10
17	3.04 (9.97)	10.88	1.09
17	3.04 (9.97)	10.76	1.08

Table 7-- Flume hydraulic efficiency test results

Flume velocity, ft/sec	LISST-SL velocity, m/sec (ft/sec)	LISST-SL / Flume	Nozzle velocity, ft/sec	Hydraulic efficiency
1.97	0.77 (2.53)	1.28	2.42	1.23
1.96	0.74 (2.43)	1.24	2.38	1.21
2.49	0.89 (2.91)	1.17	2.83	1.14
2.4	0.89 (2.91)	1.21	No sample	
2.4	0.90 (2.96)	1.23	2.69	1.12
2.47	0.86 (2.82)	1.14	2.94	1.19
2.44	0.86 (2.83)	1.16	2.49	1.02
2.95	1.00 (3.28)	1.11	3.25	1.10
2.95	0.99 (3.26)	1.10	3.32	1.13
2.95	1.00 (3.28)	1.11	3.45	1.17
2.9	1.05 (3.44)	1.19	2.25	0.78
3.4	1.16 (3.81)	1.12	3.18	0.94
3.43	1.17 (3.84)	1.12	3.11	0.91
3.46	1.14 (3.75)	1.08	3.87	1.12
3.46	1.16 (3.82)	1.10	3.9	1.13
3.68	1.25 (4.09)	1.11	4	1.09
3.66	1.26 (4.15)	1.13	4.14	1.13
3.63	1.21 (3.98)	1.10	4.21	1.16
3.64	1.23 (4.02)	1.10	4.21	1.16